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The application of carbon fibres in ARALL Laminates

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CONTENTS

SUMMARY

Ongoing developments in the materials field concerning metal alloys, resin systems and fibre materials, will govern the developments of ARALL, and will generate a large family of laminated materials.
Starting with aramid fibres, glass fibres were introduced into the ARALL concept, leading to the commercialized GLARE (GLAss REinforced) material.
A logical and very interesting development is the use of carbon fibres in the ARALL concept. The carbon fibres offer a large variety of mechanical properties. Combined with a low density, considerable weight savings are possible. Combining carbon fibres together with aluminium alloys inherently causes a potential galvanic corrosion problem.

In this report, the mechanical properties of CARE (CArbon REinforced) are evaluated. Results on tensile strength, elastic modulus, blunt notch properties and several kinds of fatigue are demonstrated for CARE with six different carbon fibres. The results are compared with the existing aramid ARALL and GLARE materials. Solutions to solve the galvanic corrosion problem are discussed.
An investigation of Titanium alloys and thermoplastic adhesives, for elevated temperature ARALL (up to 250 °C) will be discussed.

CARE offers superior mechanical properties: high strength, high modulus materials with excellent fatigue performance. Isolating the carbon prepreg with a thermoplastic adhesive, or with a glass prepreg, solves the potential galvanic corrosion problem.
Good mechanical and fatigue properties are achieved up to 250 °C for ARALL with thermoplastic adhesive, carbon fibres and titanium alloy sheets.

CHAPTER 1

INTRODUCTION

In the aerospace ARALL concept (fig. 1.1), all kinds of fibres are applicable. In the early stages of the ARALL development, three types of fibres were compared with each other: E-Glass, Carbon Fibre T300 and High Modulus aramid fibres. From the first fatigue results, it appeared that the aramid fibre behaved best in the ARALL concept and it was chosen to become standardized. Later, with new developments of glass and carbon fibres, the possible disadvantages of the first fibres were overcome. This has led to two types of laminated materials, GLARE (GLass REinforced, ARALL with glass fibres) and CARE (ARALL with carbon fibres, CArbon REinforced).

For the glass fibre, S-Glass and R-Glass proved to behave very satisfactorily in the ARALL concept. These fibres have high static tensile strength properties combined with superior fatigue strength. One possible disadvantage is the slightly lower stiffness compared to aluminium and aramid ARALL. This is especially true for laminates with crossed fibre layers (biaxial GLARE) used for fuselage application.

New developments in carbon fibres also occurred, varying from high strength high strain to ultra high modulus fibres. Very strong and stiff fibres with relatively large failure strains, like TENAX IM 600 and Toray T 800, became available. The variety of mechanical properties within the carbon fibre family is quite large.
The application of the carbon fibre gives a large number of advantages over aramid and even over the above mentioned S- and R-Glass fibres. CARE also offers an advantage of the impact behaviour compared to full composite materials (ref. 8,12).

Galvanic corrosion appears to be a potential enemy of CARE. A preliminary investigation of this potential problem has been completed (ref. 3). Several ways of solving this problem seem realistic at the moment. That being the case, nothing should prevent the application of CARE which may be the best aerospace ARALL at present: it has higher stiffness, higher strength and better fatigue properties than aramid ARALL or GLARE. The density of CARE is even lower than that of GLARE, due to the lower density of the carbon fibres, which means that a greater weight reduction is possible.

Nevertheless aerospace ARALL will remain a family of materials with regard to various metals, fibres and lay-ups. Which ARALL variant should be used will strongly depend on the application.

In this report, the carbon fibre mechanical properties (strength and stiffness) are investigated by testing CARE with regard to static strength (chapter 2) and fatigue properties (chapter 3). Comparisons are made with both aramid ARALL and GLARE. In chapter 4, the mechanical behaviour of CARE with isolating layers is discussed.

For applications at elevated temperatures up to 250 °C, the aluminium layers have to be replaced by thin layers of titanium. Some mechanical (tensile and notch behaviour) and fatigue results on ARALL with titanium alloy layers and APC-2 are discussed in chapter 5. Carbon fibres were used (Hercules AS4 carbon fibres) in combination with a thermoset and thermoplastic (PEEK) adhesive. This carbon fibre/adhesive system has the trade name APC-2 and is delivered by ICI.
Chapter 6 ends with the final conclusions.

CHAPTER 2

STATIC PROPERTIES

2.1 Introduction

The possibilities with respect to mechanical properties within the carbon fibre family seem to be unlimited. They vary from fibres with high strength to fibres with high modulus while recent developments go towards fibres with both high strength and high modulus resulting, as a consequence, in carbon fibres with high strain capabilities.
For academic reasons, the comparison of the behaviour of these mechanically different carbon fibres in the ARALL concept is extremely interesting (fig. 2.1). ARALL with carbon fibres can be a better alternative than ARALL with aramid or glass fibres, for several applications.

In chapter 2.2, the materials used in the present investigation are discussed. Chapter 2.3 concentrates on the influence of the engineering constants: fibre modulus, fibre strength and strain. During plastic deformation of the aluminium layers, all CARE materials still have an extremely high modulus of elasticity. In chapter 2.4 a new yield criterion is introduced.
The CARE blunt notch behaviour is dealt with in chapter 2.5. General conclusions are given in chapter 2.6.

2.2 Materials

Fibres

Table 2.1 shows the carbon fibres that have been investigated. This table shows industry provided fibre properties. These values are always lower than the virgin fibre properties which are found in laboratory tests (see also chapter 2.3). The virgin fibre properties, as provided in specific lot information sheets, table 2.2, were used for the calculation of mechanical properties of ARALL. The results are fairly satisfactory.

Epoxy resin

In the present investigation, prepregs have been used with different adhesive systems (see table 2.3): For HM 35, HTA and FT 700 carbon fibres, 3M adhesive AF 163-2 has been used. Those laminates were made in the b2-laboratory (the Structures and Materials laboratory of the faculty of Aerospace Engineering of Delft University of Technology) by filament winding and adhesive film hand lay-up. For all other fibres, a Ciba-Geigy prepreg system was available. T300 carbon fibre and R-Glass were impregnated with a 120 °C cure epoxy adhesive, IM 600 and T800 carbon fibres with a 180 °C cure epoxy adhesive.

The prepreg materials used in the present investigation can be found in table 2.3. The table gives each fibre/resin combination together with the fibre volume content and prepreg thickness. The three different epoxy resin systems are used because of their availability in the b2-laboratory. The 3M AF 163-2 system was used for a long time. Aramid ARALL is standardized with this resin. The DLS 1095 from Ciba-Geigy is an experimental epoxy, mainly used during the development of GLARE. The experimental results on this resin resulted in the newly standardized Ciba-Geigy Aramid ARALL and GLARE prepregs. Both the 3M and Ciba-Geigy systems are 120 °C cure epoxy systems. The Ciba-Geigy product Fibredux 924C is a 180 °C cure epoxy. Materials with this system can also be used at 180°C for a considerable length of time.

Aluminium

Aluminium 2024-T3 alloy, in sheets of 0.3 mm, has been used for all specimens. One exception is made, where 7075-T6 material was used, also in 0.3 mm thickness, with IM600 carbon fibre.

Material codes

The codes used in this report for different versions of CARE are given with the additive of the Carbon fibre code 'CARE HTA', where CARE is meant with HTA Carbon fibre.

2.3 Results of the tensile tests

Fibre tensile strength

In table 2.1, the tensile properties of several carbon fibres are given. These fibres have been used in the present investigation. The carbon fibres cover a wide range of tensile properties, from intermediate to ultra high modulus fibres, and from low to high strength fibres. The properties given in table 2.1 are those given in brochures by the industry. The values are usually lower than the virgin fibre properties found in tests performed in the laboratory. The lower values are given by the industry because the fibres are used in real structures, where the fibres are often twined or woven. A considerable part of the fibre properties is then lost.

In the ARALL concept, only UD fibre prepregs are used. The concept is very tolerant of material inconsistencies. The laminate, where every prepreg is supported by two metal layers, results in a very damage tolerant material: weaker parts in the prepreg or flaws in the aluminium, if there are any, are efficiently supported by the surrounding material, and will not cause premature failure of the specimen. Therefore the mechanical properties of the individual (virgin) fibres are used to calculate the ARALL tensile strength and modulus. In table 2.2, the fibre tensile properties are given, as provided in data sheets on the specific fibre lots measured in laboratory tests (except for the T300 and T800 carbon fibres for which no data were available).

The tensile strength of ARALL is an important property; theoretically, this strength is easily calculated with the rule of mixtures. In the past, the results of such calculations were always in agreement with test results. In table 2.4, the calculated values are shown alongside the test results, both for tensile strength and modulus. Especially for the tensile modulus, the agreement between calculated values and test results is good. One exception concerns the FT700 fibre with an extremely high fibre modulus of 705 GPa. Two batches of material were made in the Structures and Materials Laboratory. The results for both static and fatigue testing were better for the second batch. The calculated modulus is lower than the modulus that was found in the tensile tests. The strength found in the second batch agrees with the calculated value.

Comparison of carbon fibres with aramid and R-Glass fibres

The fibre strength is the most important factor in determining the tensile strength of ARALL (ref. 2). The results found in the present investigation confirm this conclusion: in table 2.4, the results for ARALL are compared with aramid and R-Glass fibres. An important conclusion is that the tensile strength of CARE can be considerably higher than for aramid ARALL or GLARE, because the fibre strength of some carbon fibres is much higher. This high strength is combined with a much higher stiffness. In this way, CARE can be tailored to any application that is strength or modulus dominated.

2.4 The yield stress for CARE: $\sigma_{0.05}$

For monolithic aluminium the yield stress is $\sigma_{0.2}$ (sometimes also $\sigma_{0.1}$ is used). This means that for practical purposes, the yield limit is chosen at 0.2% (or 0.1 %) plastic strain. The difference between $\sigma_{0.0}$ (elastic limit) and $\sigma_{0.2}$, is relatively small for aluminium alloys, due to the highly reduced stiffness during plastic deformation.
For ARALL, this $\sigma_{0.2}$ criterion was also adopted because a significant part of the material consists of aluminium alloy. As can be seen from fig 2.2, the difference between $\sigma_{0.0}$ and $\sigma_{0.2}$ for both ARALL and GLARE are small. However, when CARE is considered, the difference is significant. This is due to the very high stiffness of CARE in the region of plastic deformation of the aluminium. Therefore, it is necessary to redefine the yield criterion for CARE (and maybe for ARALL and GLARE also) using $\sigma_{0.05}$. This criterion is more realistic for CARE (fig 2.3) and will also be more relevant for ARALL and GLARE.

For Ultra High Modulus (UHM) Carbon fibres, where ($\sigma_{0.2}$- $\sigma_{0.0}$) would be extreme, a yield criterion is meaningless; the material can not yield because of the extremely low failure strain of the fibres. The CARE UHM behaviour will be an elastic behaviour until failure at approximately 0.45 % elastic strain.

2.5 Blunt notch properties

2.5.1 Introduction

The tensile strength of ARALL is dominated by the tensile strength of the applied fibre. The blunt notch properties are also highly dependent on this fibre strength. Therefore, it must be expected that ARALL with both T800 and IM600 Carbon fibres, as well as R-Glass fibres, will have the absolute highest blunt notch strength properties.

In ref. 2, it was found that GLARE can show static delamination during static failure resulting in an even higher blunt notch or residual strength. This is also observed for CARE with high strength carbon fibres. Due to the higher strength of the carbon fibres, the blunt notch strength is even higher than for GLARE.

2.5.2 Test specimens and test program

Ref. 2 provides evidence that the K_t value itself is not a suitable parameter to characterize the overall ARALL blunt notch behaviour for any of the applied fibres: aramid, R-Glass or carbon fibres. Therefore, notch test specimens for ARALL are examined for:

- different specimen width, to characterize the size effect of ARALL and
- different notch geometries (at constant width), to describe the notch geometry effect (fig 2.4).

The notch removes a certain fixed percentage of the specimen width: usually 25 or 50 % is used. The following notch shapes were chosen: a circular hole, a slot with variable notch root radius, and a saw cut as the most severe damage. The K_t values of these specimens can be calculated and found in the tables. For a constant specimen width and a fixed notch width, the shape of the notch will indicate the notch effect of the material.

The availability of most of the materials made it necessary to adopt small W=40 mm specimens. In some cases, W = 100 mm specimens were also used (T300 and T800 carbon fibre both in UD and crossed laminates). Different notches were applied, indicated in the tables with slot length and notch root radius. An example is ' slot 10 mm ρ 2 ' which means a slot of 10 mm length with a notch root radius of 2 mm. This W=40 mm specimen has a K_t value of 3.32 (see fig. 2.4).

Survey of the blunt notch test program

aluminium alloy	fibre used in CARE	notch results	
		W (mm)	results in table
2024 - T3	HM 35 TENAX UD	40	2.5
	HTA TENAX UD	40	2.6
7075 - T6	IM600 TENAX UD	40	2.7
2024 - T3	T 300 TORAY UD crossed crossed	 100 40 100	 2.8 2.9 2.9
	T 800 TORAY UD UD crossed crossed	 40 100 40 100	 2.10 2.10 2.11 2.11
	FT700 TONEN UD 1° batch 2° batch	 40 40	 2.12 2.13

2.5.3 Results and discussion

The results of the blunt notch tests can be found in tables 2.5 to 2.13. Most of the results are shown in fig. 2.5 and 2.6.

<u>fibre failure strain</u>

The limited failure strain of the carbon fibre, when used in ARALL, was thought to be a disadvantage compared to both the aramid and R-Glass fibre.

New developments in carbon fibre technology led to the intermediate modulus fibres. These combined a relatively high modulus with high strength resulting in fibres with a high strain of about 2.0 %. This strain, for example, is in the same order as the failure strain of the aramid fibre (2.3 %).

As far as static strength properties are concerned, the absolute strength of ARALL is dependent on the failure strength of the fibre and not on its strain. The results of the blunt notch tests indicate that notch strength properties of CARE in general are as good as, or sometimes even better than the blunt notch strength properties of aramid ARALL or GLARE. In a relative comparison, this can be seen from the ratio of the blunt notch and the tensile strength: σ_{net}/σ_u (blunt notch ratio). For aramid ARALL, W = 40 mm specimens have a ratio of 0.62 (ARALL based on 2024-T3). For GLARE UD material, this ratio is about 0.70.

The CARE results show a blunt notch ratio of 0.60 to 0.70. for W = 40 mm specimens with 2024-T3. W = 100 mm specimens give slightly lower ratios for UD laminates (0.51 to 0.63 for CARE T800 an between 0.56 and 0.70 for CARE T300). The same is found for both aramid ARALL and GLARE. The crossed versions with T300 and T800 give satisfactory results for W = 100 mm specimens; ratios between 0.55 and 0.69.

FT 700 Carbon fibre,with approximately 0.5% failure strain and a stiffness of 700 GPa, is a remarkable fibre with respect to blunt notch strength. The CARE UHM material with this fibre, has no possibility of plastic deformation of the aluminium because it fails even before the aluminium starts yielding. On the other hand, this material has a very high blunt notch ratio for W = 40 mm specimens around 0.70 to 0.80! The strength of this fibre is around 3300 MPa and, compared with IM 600, not very high. The limited failure strain, however, appears not to affect the CARE static tensile strength behaviour.

In general, it should be mentioned, that a lower fibre failure strain will limit, to some extent, the stress carrying capabilities of the aluminium due to limited strain hardening. This effect, however, is small for 2024-T3 and will even be smaller for 7075-T6 which has less strain hardening capabilities.

static delamination

In ref. 9, static delamination was shown to be of considerable importance for the blunt notch strength of GLARE. Static delamination was also found during tensile strength testing of CARE. Blunt notch ratios of 0.8 - 0.9 were found in ref. 9. The prepreg thickness of those specimens was 0.32 - 0.34 mm which facilitates static delamination (ref. 10, 11). In the present investigation, prepreg thicknesses were in the order of 0.2 - 0.25 mm and static delamination was not always found.

2.6 Conclusions

- The tensile strength of ARALL is directly related to the strength of the applied fibre and the aluminium alloy. The strength and modulus of ARALL can accurately be calculated with the rule of mixtures using the virgin fibre strength and modulus.

- The variety in mechanical properties of different carbon fibres allows easy tailoring of mechanical properties of CARE.

- The high stiffness of ARALL during plastic deformation of the aluminium in general, and of CARE in particular, makes the definition of a new yield limit necessary. It is recommended to use $\sigma_{0.05}$ for all ARALL materials.

- The notch strength and the residual strength of CARE are directly related to the fibre strength. Static delamination has been found to have a beneficial effect on strength properties. Fibre failure strain has been found to have little influence on strength.

CHAPTER 3

FATIGUE RESULTS

3.1 Introduction

ARALL was developed as a fatigue insensitive material. In the presence of fatigue cracks in the aluminium, the fibres in ARALL (fig 1.1) can still carry a significant part of the load over the crack, thus, reducing the stress intensity at the crack tip. This leads to reduced crack growth rates in the metal and sometimes even to crack arrest. The efficiency of the crack bridging fibres strongly depends on the fibre stiffness in combination with the amount of prepreg delamination. Therefore for low crack growth rates, fibre stiffness should be high and delamination should be limited.
A good way of comparing different types of ARALL is to do a Constant-Amplitude (CA) fatigue test. Both crack growth rate and delamination areas can be observed and compared. For aramid ARALL and GLARE, CA fatigue tests were done with an R = 0.05, 6 - 120 MPa load.
This specific load proved not to be severe enough for several CARE materials because the load did not cause any fatigue damage due to the efficient crack bridging of the very stiff carbon fibres. Therefore, higher loads, up to 400 MPa, were used during Constant-Amplitude fatigue testing, discussed in chapter 3.2. Also some flight simulation fatigue tests (FALSTAFF and TWIST) were performed, which are discussed in chapter 3.3.

3.2 Results of Constant-Amplitude fatigue

In the last few years, a lot of Constant-Amplitude fatigue test data were generated for both ARALL and GLARE. The load applied in most cases was an R = 0.05 load with Smax = 120 MPa, which is considered to be a realistic load for a fuselage in ARALL or GLARE.
A survey of the fatigue test program can be found on the next pages.

Survey of the fatigue test program

carbon fibres with aluminium 2024 - T3 alloy	Fatigue tests		
	Constant Amplitude	Flight Simulation	result figure
HM 35 TENAX	6 - 120 MPa 10 - 200 13 - 250 15 - 300		3.3&3.4 3.4 . .
HTA TENAX	6 - 120		3.3
IM600 TENAX	6 - 120 120 +/- 60 with cycles in compression 50 +/- 130	TWIST: Smf = 120 MPa FALSTAFF: Smax = 250 MPa	5.1 3.2 3.9 3.10
T 300 TORAY	6 - 120 - in lab. air - with glass prepreg isolation 8 - 150 9 - 180 10 - 200 10 - 200 - in lab. air in subst. ocean water coated / uncoated - PEI coated t = 10 μm t = 20 μm - R-Glass prepreg isolated 13 - 250		3.5 3.5 4.5 4.2 4.4 3.5
T 800 TORAY	6 - 120 8 - 150 9 - 180 10 - 200 13 - 250 15 - 300		all in table 3.6
FT700 TONEN	6 - 120 MPa 10 - 200 13 - 250 15 - 300 20 - 400		3.3&3.7 3.7 3.7&3.8 3.7

Survey of the fatigue test program (continued)

Aramid ARALL and GLARE 2 with 2024-T3	Fatigue tests		
	Constant Amplitude	Flight Simulation	result figure
HM Aramid	6 - 120 Mpa		3.3
		TWIST: Smf = 120 MPa	3.9
R-Glass	6 - 120 MPa		3.3
		TWIST: Smf= 120/150 MPa	3.9
		FALSTAFF Smax= 250 Mpa	3.10

All fatigue tests were done on UD CARE 2/1 lay-ups.

Due to the possible fibre failure of the aramid fibres under this specific load cycle, where, in the as-cured condition, the aramid fibres are loaded alternating in tension and compression, GLARE is considered to be a better alternative for fuselage application. (ref. 11) Fibre failure never occurred in fatigue tests on GLARE specimens.

The efficiency of crack bridging strongly depends on the stiffness of the crack bridging prepreg. For that reason, aramid fibres are better than R-Glass fibres because of their 40 % higher stiffness. Carbon fibres, on the other hand, are much stiffer than both Aramid and R-Glass fibres. In the range from 250 to 700 GPa or more, carbon fibres are two to five times stiffer than aramid, and three to eight times more stiff than glass fibres. It can be expected that better fatigue results will be achieved with CARE.

Fibre Failure

At this time, it is hardly possible to explain the results from 1978 that led to the use of the Aramid fibre in ARALL. In fig. 3.1 (ref. 14), the sudden increase in crack growth of the CARE T300 material under flight simulation condition, with severe compression cycles, was explained by the occurrence of fibre failure (which at this point can not be verified). The result for the same material under constant-amplitude loading was extremely good. It was then concluded that because of the limited failure strain of the carbon fibres, the behaviour under tension/ compression cycles was inadequate.

Roebroeks (ref.11) investigated the aramid fibre failure phenomenon using a very severe fatigue load:
Blocks of 10 cycles, consisting of 9 cycles with S_{max} = 180 MPa and S_{min} = 60 MPa, followed by 1 cycle with the same S_{max} but a severe compression cycle of S_{min} = -80 MPa (see fig. 3.2).
It can be deduced from the exponential crack growth rate that aramid ARALL suffers from fibre failure. Etching off the aluminium layers also revealed the broken fibres. Neither GLARE nor CARE IM 600 (based on 2024-T3 alloy) give fibre failure under this fatigue load. The aluminium layers of several specimens were etched off, but apart from some small delamination areas at the location of the crack, no broken fibres were found.
The results show an increase in fatigue life for GLARE and even more so for CARE IM600. For the latter material, the thickness factor is also shown in this figure. All CARE IM600 materials tested here, consisted of two layers of 0.3 mm aluminium alloy and one carbon prepreg layer of different thicknesses. It is shown in this figure, that even a very thin carbon prepreg layer (0.1 mm) is capable of carrying high fatigue loads, both in tension and compression.

Fibre Modulus

As mentioned before, the fibre stiffness is a very important factor in the fatigue behaviour of ARALL. Fig. 3.3 shows the CA fatigue behaviour for 6 - 120 MPa, (R=0.05) for ARALL with different fibres. Apart from the fact that the aramid fibre shows fibre failure (the aramid fibre is stiffer than the R-Glass fibre), the figure shows that the stiffer the fibre, the better the fatigue properties. This is also true for the three different carbon fibres in CARE with increasing fibre modulus: CARE HTA, HM35 and, in the extreme case, CARE FT700, with an excellent fatigue life, barely a crack growing after 1.5 million cycles.

CA fatigue tests for different carbon fibres

In fig. 3.4 to 3.6, the CA fatigue tests for CARE HM 35, T300 and T800 are given respectively. Fatigue loads from S_{max} = 120 MPa up to 300 MPa have been applied, resulting in excellent fatigue lives for the material in the as-cured condition. Specimens of W = 100 mm have been used with a starter notch of 3 mm.

CA fatigue results of the first batch of CARE FT 700 are shown in fig. 3.7. Loads up to 400 MPa have been applied and it should be emphasized that loads of this magnitude

are in the order of 60 - 70 % of the tensile strength of this material! For both aramid ARALL and GLARE fatigue loads in the order of 10 - 15 % are realistic (fig. 3.8). Also, for the other CARE materials high loads of about 30 - 45 % of the tensile strength can be applied, resulting in fairly good fatigue lives.
It was mentioned before that the first batch of CARE FT700 material was of inferior quality compared to the second batch. In fig 3.9, the results of this second batch are compared with the first results and it is again demonstrated that the CA fatigue properties of this material are very good. The difference in batches shows that the prepreg quality is also extremely important. Thus, it is believed that a properly manufactured prepreg will improve the properties of CARE FT700 even more.

3.3 Results of Flight Simulation

The Constant-Amplitude fatigue test is a relatively simple test to perform. It is a quick and reliable test for the comparison of different grades of ARALL. The relevance of this fatigue load for the aircraft itself, depends on the intended use of the material for the fuselage. Past results show that the load frequency has a significant influence on the test outcome.
For the application of the material in, e.g. aircraft wings, a different kind of fatigue loading should be applied. For transport aircraft, a TWIST flight simulation can be applied; for fighter aircraft, a FALSTAFF flight simulation fatigue program is appropriate.

Fig. 3.10 shows the results of TWIST for aramid ARALL and CARE IM600, both with a mean stress in flight of S_{mf} = 120 MPa, with a truncation level of 1.3. As-cured ARALL 2 shows fibre failure. The post-stretched material (0.2%) does not. CARE IM600 material, with a prepreg layer of only 0.1 mm (2/1 lay-up 0.3 mm aluminium 2024-T3), performed extremely well. The specimens used for these tests were W = 160 mm with a 3 mm starter notch.
A test on GLARE 2 (5/4 lay-up, t= 2.5 mm, W = 100 mm specimen), showed a better behaviour than CARE IM 600. Due to the extremely favourable ratio of the prepreg thickness to the aluminium alloy thickness (0.67 for GLARE 2, to 0.17 for the CARE IM 600 specimen), the fatigue properties of the GLARE 2 specimen were better.

The result for CARE IM 600 (3/2 lay-up 0.3 mm aluminium 2024-T3) for FALSTAFF with a maximum stress of σ_{max} = 250 MPa is show in fig. 3.11. The specimen width was W=300 mm (3 mm starter notch), for both GLARE and CARE.
In the same figure, the result for GLARE 2 is shown (same

geometry and lay-up) and the influence of fibre modulus is again illustrated. In fig. 3.11, a result from ref. 5 is also shown:
ARALL 7H37 0.4%, a 7/6 lay-up 0.4% post-stretched based on 7075-T6 alloy of 0.3 mm sheet thickness. The latter test geometry was different, as shown.

3.4 Conclusions

- The fibre stiffness is an important parameter for the fatigue properties of ARALL. The higher the fibre stiffness, the better the fatigue properties

- Neither GLARE nor CARE has shown fibre failure under constant-amplitude fatigue or flight simulation fatigue.

- For the best fatigue results, in both constant-amplitude and flight simulation, CARE materials should be used. Very high fatigue stresses can be applied to the material in the as-cured condition resulting in excellent fatigue lives.

CHAPTER 4

GALVANIC CORROSION

4.1 Introduction

The use of aluminium and carbon in contact with each-other, is often thought of as a major, unsolvable galvanic corrosion problem. The gradual introduction of carbon fibre reinforced materials into the aircraft structure, however, put this specific problem before many aircraft designers. The difficulty was in connecting the innovative parts to the conventional aluminium structure. The potential for galvanic corrosion problems was introduced by using carbon fibres together with aluminium sheets. It may be that this problem was not properly taken care of in all cases (by means of any kind of isolation). Maybe for reasons of ignorance but more likely for reasons of serious doubt whether galvanic corrosion really was a major problem, e.g. when the environment was not supposed to be present in the interface area. Monitoring the potential problem area by proper inspection in closely spaced intervals would, in that case, be the right way of dealing with the problem, preventing it from becoming dangerous during service.

It is impossible to predict if CARE will cause serious galvanic corrosion problems in service. If it is desired to take measures to prevent galvanic corrosion during service, two ways of doing this are described in this chapter.
Isolating the aluminium from the carbon fibre could be the solution since both aluminium and carbon fibres are excellent conductors. When both materials are electrically connected in a corrosive environment, galvanic corrosion may occur; thus, the aluminium will corrode more quickly. This problem was investigated by Kleinendorst (ref. 3).

Going into details on the galvanic corrosion theory is beyond the scope of this report. Thus, only a suggestion is made as to how to prevent galvanic corrosion. The mechanical properties of CARE with the isolation layers against galvanic corrosion are shown and evaluated.

4.2 Isolation

Two possible ways of isolating the carbon fibres from the aluminium are proposed here (see fig 4.1):

1 **coating the aluminium surface with PolyEtherImide (PEI): a thermoplastic coating.**

This is presently done in the b2-laboratory. The isolation obtained in this way between carbon and aluminium is good. Care should be taken when making notches in the material. In this way it was discovered that, in some cases, carbon and aluminium again make contact in the edge area.

2 **isolating the carbon prepreg with a glass prepreg on both sides.**

This was also done satisfactorily. It would be sufficient to use an extremely thin glass fibre prepreg, for example.
Though only present for isolation purposes, the glass prepreg contributes to the laminate strength but also reduces the stiffness of the laminate.

It should be noted that in the ARALL concept the prepreg is always protected from the environment by the outer aluminium layers. Potential problem areas therefore are sheet edges, notch edges, scratches, fatigue and incidental damage. It will be important to protect not only the interface between carbon and aluminium, which still is of primary importance, but also to protect the outer surfaces, as is being done by using the normal protection methods: primers, sealants and paints. Possibly the PEI coating could fit in here as well.

4.3 Fatigue Results

Fatigue results for CARE with galvanic corrosion protection measures.

It is likely that an isolating layer between the aluminium and the carbon prepreg will have some influence on the mechanical behaviour of the CARE material. This influence however, should be small. To investigate the mechanical behaviour, tests have been done on CARE material with a PEI isolation and with additional R-Glass prepreg layers. The results of galvanic corrosion testing were very satisfactory (ref. 3).
This chapter deals with the influence of the isolation on

the fatigue behaviour. At the same time, it was assumed that a sufficiently thin isolating PEI layer would not seriously affect the strength of the material, but would only increase the thickness. An R-Glass prepreg, with its fibres in the same direction as the carbon fibres, will certainly have an effect on the mechanical properties: due to the thickness of the R-Glass prepreg, the stiffness will be reduced and the strength will be lower. These reductions will occur for two reasons:

- carbon fibres can be stronger than R-Glass fibres (in the case of T800 or IM600 fibres (not used here))
- at the moment of carbon fibre failure, the R-Glass fibres will not have been fully loaded, while it is expected that the laminate will fail immediately at the moment of carbon fibre failure.

material and isolation

In this investigation, carbon fibre T300 was used, assuming that differences in corrosion behaviour between different carbon fibres are negligible. Aluminium 2024 - T3 in bare sheet of 0.3 mm was used. The aluminium was pretreated by degreasing, pickling and chromic acid anodizing (CAA).

Both isolation methods are shown in fig 4.1. The thermoplastic coating was applied on the aluminium layers by means of a dipping process (ref. 13). The layer thickness was approximately 0.02 mm and the thermoplastic used was PolyEtherImide (PEI). The specimens used for these CA fatigue tests were smaller than the ones used previously in chapter 3 because the PEI coating machine was limited in size.

Glass isolation was achieved by two layers of R-Glass prepreg of 0.1 mm each, at either side of the carbon fibre prepreg. The epoxy systems were compatible and the laminates were made in one autoclave run.

The fatigue results

Fig. 4.2 shows the results for CARE T300 uncoated, and PEI-coated with two different coating thicknesses. As was expected, the uncoated material behaves best. The coating layer does not provide sufficient stiffness for effective crack bridging. Therefore, the shear deformation of the PEI layer (fig 4.3) is larger with increasing coating thickness. Thus, the efficiency of the crack bridging by the prepreg layer will be reduced and crack growth rates will increase. As seen in fig. 4.2, the thicker PEI layer shows higher crack growth rates. The difference between the uncoated material and the material with the thin 10 μm coating layer is small.

Fig. 4.4 shows the results for CARE T300 with R-Glass isolation. Two different CA fatigue loads were applied; R=0.05, 6 - 120 MPa and 10 - 200 MPa. In both cases, the isolated material behaved somewhat better. This can be explained by the fact that the R-Glass prepregs carry a significant part of the load, compared to a PEI coating. Although the load on the specimen was chosen in accordance with the laminate thickness, the ratio of prepreg layers over laminate thickness was significantly higher for the R-Glass isolated material; this is favourable for fatigue. The isolation material, in the case of the R-Glass prepreg, is at the same time heavier and more expensive.

Fig. 4.5 shows the results of fatigue at low frequency (one cycles in 40 seconds), in isolated (PEI coated) and non-isolated (coupled) conditions. It was expected from earlier investigations that a low frequency gives higher crack growth rates. The corrosive environment now has more time to affect the material.
The figure shows that the tests in laboratory air were slightly better than the tests done in a corrosive environment (being substitute ocean water).
The application of a coating influenced the fatigue behaviour more profoundly than the corrosive environment. The increase in crack growth rate is considerable due to the mechanism explained previously in figure 4.3.

4.4 Conclusions

- The Galvanic corrosion problem of CARE can be dealt with by isolating the carbon prepreg layer from the aluminium layers. (ref. 3)

- The mechanical properties of isolated CARE material will be different from the non-isolated CARE material:

  - The fatigue properties of isolated CARE material are influenced by the isolation:
    - With a PEI coating, an increase in crack growth must be anticipated for increasing PEI coating thickness.
    - With an R-Glass prepreg isolation, good fatigue results can be expected. However, the CARE material will be heavier.

- Low frequency testing reveals that the application of a PEI coating with low shear modulus has more influence on the fatigue behaviour than the corrosive environment: the coating layer reduces the crack bridging efficiency due to its low shear stiffness. Therefore, crack growth rates will increase.

CHAPTER 5

TITANIUM ARALL

5.1 Introduction

All ARALL materials, thus far, are materials for aircraft applications. ARALL laminates are bonded with epoxy systems cured at 120 °C. The laminates can be used at temperatures up to 80 °C. In this report, 180 °C cure epoxy systems are also used. These systems can be used at temperatures up to 180 °C for longer periods. For epoxy systems, this temperature is the limit. For elevated temperatures from 150 °C up to 400 °C, only thermoplastic adhesives like Poly-Imide (PI) and Poly-Ether-Ether-Ketone (PEEK)can be used.
Another limiting factor for elevated temperatures is the aluminium alloy. The heat treatment of the commonly used alloys like 2024-T3 and 7075-T6 will be deteriorated when used at these temperatures. Therefore, titanium alloys will be necessary in this particular ARALL material. Possible applications of this material will be in space vehicles or space structures and those elevated temperature aircraft structures near engines or subjected to aerodynamic heating.

A preliminary investigation has been carried out to explore the merits of this kind of material (ref. 6, 7). The main subject of this investigation was:
- The selection of a suitable pretreatment of the titanium alloy, and
- the choice of a thermoplastic adhesive system together with its bonding features.

Here, the results of some tensile and fatigue tests will be shown in order to give an idea of the possibilities for this kind of ARALL material.

Two different titanium alloys have been used: commercially pure titanium and Ti-6Al-4V. Sheet gages were 0.1, 0.3, 0.6 and 0.8 mm. Al materials were 2/1 lay-up. The pretreatment existed of a short version of the Chromic Acid Fluoric Anodize (CAA) method developed by Boeing.

5.2 Results

Static properties

Titanium alloys are characterized by a high modulus of elasticity, high yield and tensile strength as well as good corrosion properties, even at high temperatures. These favourable properties will contribute to the Titanium ARALL properties and are shown in table 5.1.
The yield strength for commercially pure titanium (code is cpT) is not very high and the addition of R-Glass fibre will not change this strength. The addition of carbon fibres, however, results in a much higher yield strength. The yield strength of Titanium- 6Al-4V (used in material codes is T_4^6) is extremely high.
One of the major advantages of titanium over aluminium is the higher Young's modulus. Therefore, it is almost necessary to use carbon fibres instead of Glass fibres in order not to lower the Titanium ARALL modulus. The strain to failure is dictated by the failure strain of the applied fibres.

Blunt notch properties

From the results shown in table 5.2, it is interesting to see that the Titanium ARALL material has such good blunt notch behaviour. The ratio of the net stress and the tensile strength is very high compared to aluminium ARALL. High notch strength is obtained and, therefore this material looks very promising from the structural point of view.

Fatigue results

In figure 5.1, CA fatigue (8 - 150 Mpa) tests are shown using commercially pure titanium and 2024 - T3 aluminium alloy, with IM 600 carbon fibre, 180 °C cure prepreg (ref. 6).
Tests are done both at room temperature and at 180 °C.
Due to the limited size of the test equipment the specimens (fig 5.1) were smaller (W = 75) than the ones described earlier.
The outcome shows better results for the elevated temperature tests for both materials. This can be explained with the residual stress system in the as-cured condition and at the cure temperature of 180 °C. In the latter case, the residual tensile stress in the metal layer is zero. At room temperature, the stress is a considerable tensile stress and, therefore, unfavourable for fatigue.
For the cpT material one specimen was post-stretched 0.4 % and had a compressive stress in the metal layers at

180 °C. The fatigue result for this specimen was better.

Figure 5.2 shows the CA fatigue test results (8 - 150 MPa and 15 - 300 Mpa) for another material using extremely thin 0.1 mm sheets of Ti-6Al-4V alloy using a PEEK / AS4 prepreg with the ICI trade name APC-2 (ref. 7).
The first CA fatigue test (8 - 150 Mpa), at room temperature, revealed a fatigue insensitive behaviour. This same specimen was then tested at an elevated temperature of 250 °C. After some initial crack growth, the crack growth rate leveled off to a very low growth level. A second specimen was tested at room temperature with a CA fatigue load of 15 - 300 Mpa. The crack growth was considerable.

5.3 Conclusions

- Titanium sheets can be used in the ARALL concept leading to a material:
  - with high strength, high modulus and good blunt notch properties, and
  - with good fatigue properties both at room temperature and elevated temperatures.

- PEEK can be used as an adhesive for titanium alloys allowing the material to be used in combination with carbon fibres, at temperatures of at least 250 °C

CHAPTER 6

GENERAL CONCLUSIONS

ARALL is a family of structural materials. In this report it is shown that by using carbon fibre prepregs and/or titanium alloy sheets, totally different ARALL laminates are generated.

The use of carbon fibres can offer high tensile and notch strength dependent on the applied carbon fibre. Carbon fibres always offer a higher material stiffness than aramid ARALL or GLARE. Material optimization with respect to strength and modulus is possible within a wide range of values (tailoring).

Due to the high stiffness of the carbon fibre layer, crack bridging is very efficient. Both constant-amplitude and flight simulation fatigue properties are extremely good.

The potential problem of galvanic corrosion, if really present, can be dealt with by means of isolation of the carbon fibre prepreg from the aluminium sheets. Both the investigated R-Glass prepreg isolation and the applied PEI coating serve well as isolators, without interfering too much with mechanical properties.

By applying titanium (alloy) sheets and carbon fibre thermoplastic prepregs, elevated temperature use of titanium ARALL, up to 250 °C is possible. The material has good tensile and notch properties combined with high Young's modulus. Good fatigue properties are found at both room and elevated temperature.

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Table 2.1 Carbon fibre properties. Comparison with aramid and R-Glass fibres. All values as provided in the industrial brochures.

Fibre Name	Tensile properties Modulus (GPa)	 Strength (MPa)	 Failure Strain %	density kg/dm^3
HM 35 TENAX	358	2350	0.6	1.79
HTA TENAX	238	3400	1.4	1.77
IM600 TENAX	295	5400	1.7	1.79
T 300 TORAY	230	3530	1.5	1.77
T 800 TORAY	294	5590	1.9	1.81
FT700 TONEN	700	3300	0.5	2.16
HM Aramid	121	2800	2.0	1.45
R-Glass	86	3500	5.0	2.54

Table 2.2 Carbon fibre properties. Comparison with aramid and R-Glass fibres. Values as provided in data sheets with specific lot information.

Fibre Name	Tensile properties Modulus (GPa)	 Strength (MPa)	 Failure Strain %
HM 35 TENAX	358	2890	0.8
HTA TENAX	239.3	4181	1.64
IM600 TENAX	288	5855	2.03
FT700 TONEN	705	3360	0.48
HM Aramid	125	3000-3150	2.3
R-Glass	88.8	4500-5000	5.2

Tabel 2.3:
prepreg: ARALL carbon fibre / adhesive information

prepreg with Fibre	% Vf	adhesive system	thick-ness mm
HM	58	AF	0.22
HTA	58	AF	0.22
T300	60	DLS 1095	0.20
IM600	60	Fd 924C	0.105 0.21 0.315
T800	60	Fd 924C	0.20
FT700	55	AF	0.23
Aramid	50	AF	0.20
R-Glass	60	DLS 1095	0.25

Fd 924C = Ciba-Geigy Fibredux 924C / T_{cure} = 180 °C
DLS 1095 = Ciba-Geigy experimental prepreg / T_{cure} = 120 °C
AF = 3M AF 163 - 2 / T_{cure} = 120 °C

Tabel 2.4: Tensile properties.
aluminium sheets: 0.3 mm 2024-T3.
all UD laminates 2/1 lay-up;
crossed laminates 3/2 lay-up

ARALL with fibre	thick-ness mm	Tensile properties # strength (MPa) calc.	result	ratio	modulus (GPa) calc.	result	ratio
HM	0.82	716	800	0.90	108.4	105	1.03
HTA	0.82	921	984	0.94	89.9		
T300 UD	0.80	806	747	1.08	89.7	85.2	1.09
crossed	1.30	581	585	0.99	71.1	71.3	1.00
IM600	0.705	804	896	0.90	87.6		
	0.81	1187	1218	0.97	99.3		
	0.915	1454	1395	1.04	108.1		
T800 UD	0.80	1117	1030	1.08	100.0	100.0	1.00
crossed	1.30	773	728	1.06	76.9	75.1	1.02
FT 700 1°	0.83	675	575	1.17	149.5	175	0.85
* 2°			675	1.00		170	0.88
Aramid	0.80	674	700	0.96	69.6		
R-Glas	0.85	1127	1100	1.02	66.5		

The ratio is the 'calculation' devided by the 'result'.

* 1° and 2° refer to the first and the second batch respectively.

Table 2.5:

HM 35 TENAX Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	average	σ_{net}/σ_u
round 4 mm	2.74	494 526 564	528	0.66
round 10 mm	2.43	494 488 519	501	0.63
slot 10 mm, root radius 2 mm	3.32	468 444 435	449	0.56
sawcut 10 mm		475 475 521	491	0.61

CARE HM 35 σ_u = 800 MPa t = 0.82 mm
E = 105 GPa
ε_u = 0.6 %

Table 2.6:

HTA TENAX Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 10 mm	2.43	691	0.70
round 4 mm	2.74	701	0.71
slot 10 mm ρ 2	3.32	601	0.61
slot 20 mm ρ 2	3.57	583	0.59
sawcut		623	0.63

CARE HTA σ_u = 984 MPa t = 0.82 mm
E = 105 GPa
ε_u = 1.0 %

Table 2.7:

IM600 TENAX Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate with aluminium 7075 - T6 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 4 mm	2.74	754	0.64
slot 10 mm ρ 2	3.32	844	0.72
slot 20 mm ρ 2	3.57	637	0.54
sawcut		619	0.53

CARE IM 600		
	σ_u = 1176 MPa	t = 0.88 mm
	E = 92 GPa	
	ε_u = 1.5 %	

Table 2.8:

T 300 Carbon fibre UD laminate W = 100 mm

Blunt notch test results for CARE laminate with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 25 mm	2.74	520	0.70
slot 25 mm ρ 5	3.32	484	0.65
slot 25 mm ρ 2	4.74	479	0.64
sawcut 25 mm		415	0.56

CARE T 300		
	σ_u = 747 MPa	t = 0.80 mm
	E = 85 GPa	
	ε_u = 1.25 %	

Table 2.9:

T 300 Carbon fibre crossed laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 10 mm	2.74	402	0.69
slot 10 mm ρ 2	3.32	386	0.66
slot 10 mm ρ 0.8	4.74	393	0.67
sawcut 10 mm		389	0.66

T 300 Carbon fibre crossed laminate W = 100 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 3/2 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 25 mm	2.74	364	0.62
slot 25 mm ρ 5	3.32	363	0.62
slot 25 mm ρ 2	4.74	367	0.63
sawcut 25 mm		334	0.57

CARE T 300 crossed σ_u = 585 MPa t = 1.3 mm
E = 71.4 GPa
ε_u = 1.2 %

Table 2.10:

T800 Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	Kt	net stress	σ_{net}/σ_u
round 10 mm	2.43	728	0.71
slot 10 mm ρ 2	3.32	707	0.69
slot 10 mm ρ 0.8	4.74	675	0.66
sawcut 10 mm		648	0.63

T800 Carbon fibre UD laminate W = 100 mm

Blunt notch test results for CARE laminate with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	Kt	net stress	σ_{net}/σ_u
round 25 mm	2.74	648	0.63
slot 25 mm ρ 5	3.32	640	0.62
slot 25 mm ρ 2	4.74	579	0.56
awcut 25 mm		530	0.51

CARE T 800 UD	σ_u = 1030 MPa E = 100 GPa ε_u = 1.45 %	t = 0.80 mm

Table 2.11:

T800 Carbon fibre crossed laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	Kt	net stress	σ_{net}/σ_u
round 10 mm	2.74	584	0.80
slot 10 mm ρ 2	3.32	520	0.71
slot 10 mm ρ 0.8	4.74	508	0.70
sawcut 10 mm		494	0.68

T 800 Carbon fibre crossed laminate W = 100 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 3/2 lay-up)

notch geometry	Kt	net stress	σ_{net}/σ_u
round 25 mm	2.74	505	0.69
slot 25 mm ρ 5	3.32	469	0.64
slot 25 mm ρ 2	4.74	456	0.63
sawcut 25 mm		406	0.56

CARE T 800 crossed	σ_u = 728 MPa E = 75.1 GPa ε_u = 1.4 %	t = 1.3 mm

Table 2.12:

FT700 Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	average	σ_{net}/σ_u
round 4 mm	2.74	382 457 337	392	0.68
round 10 mm	2.43	392 421 430	415	0.72
slot 10 mm ρ 2	3.32	404 437 437	426	0.74
sawcut 10 mm		428 434 437	433	0.75

CARE FT700 1° batch σ_u = 575 MPa t = 0.83 mm
E = 175 GPa
ε_u = 0.32 %

Table 2.13:

FT700 Carbon fibre UD laminate W = 40 mm

Blunt notch test results for CARE laminate
with aluminium 2024 - T3 (0.3 mm 2/1 lay-up)

notch geometry	K_t	net stress	σ_{net}/σ_u
round 4 mm	2.74	530.4	0.79
round 10 mm	2.43	474.6	0.70
slot 10 mm ρ 2	3.32	482.3	0.71
sawcut		501.0	0.74

CARE FT700 2° batch σ_u = 675 MPa t = 0.83 mm
E = 170 GPa
ε_u = 0.49%

Table 5.1: Tensile properties of Titanium and Titanium ARALL

			tensile properties			
material	thick-ness mm	density kg/m^3	yield strength MPa	tensile strenght MPa	Modulus GPa	strain % to failure
cpT	0.31	4.51	258	345	95	19
cpTS32	0.86	3.79	291	991	83	5
cpTC32	0.84	3.57	452	1033	127	2
Ti-6Al-4V	0.82	4.42	956	1029	111	10
T_4^6C82	1.94	4.01	951	1022	114	2
T_4^6C32	0.88	3.55	1205	1452	125	2

cpT - commercially pure titanium
cpTS32 - Tit. ARALL with S-Glass prepreg / 0.3 mm cpT layers
cpTC32 - Tit. ARALL with Carbon IM600 prepreg / 0.3 mm cpT layers
Ti-6Al-4V - Titanium alloy (T_4^6)
T_4^6C82 - Tit. ARALL with Carbon IM600 prepreg / 0.8 mm T_4^6 layers
T_4^6C32 - Tit. ARALL with Carbon IM600 prepreg / 0.3 mm T_4^6 layers

All Titanium ARALL laminates are 2/1 lay-up

Table 5.2
Results of blunt notch tests
Test coupons: Width 40 mm
Length 200 mm
circular notch diameter 10 mm

material	net stress MPa	σ_{net}/σ_u
cpTS32	890	0.90
cpTC32	880	0.87
T_4^6C32	1241	0.86

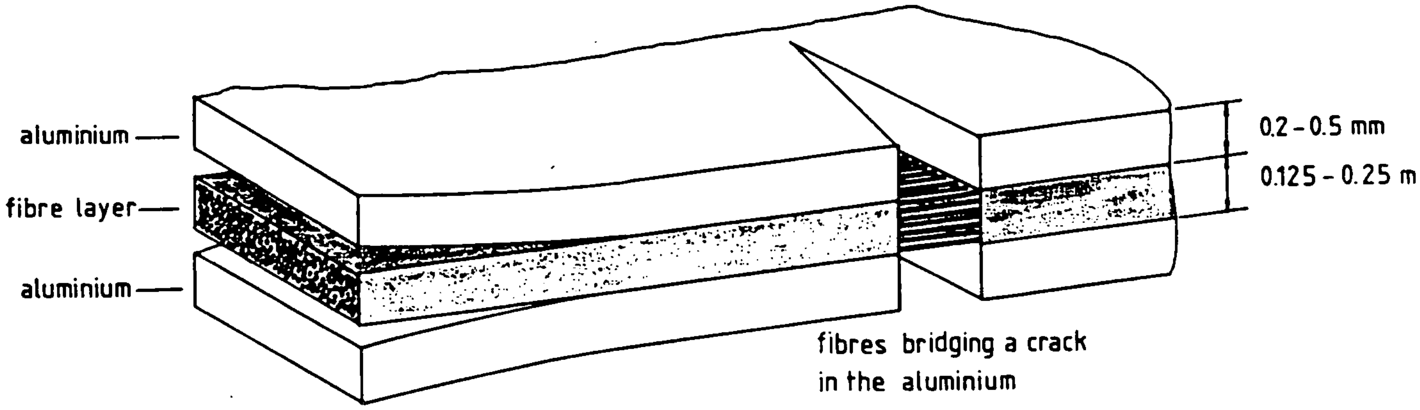


fig. 1.1 ARALL: a fibre reinforced metal laminate.

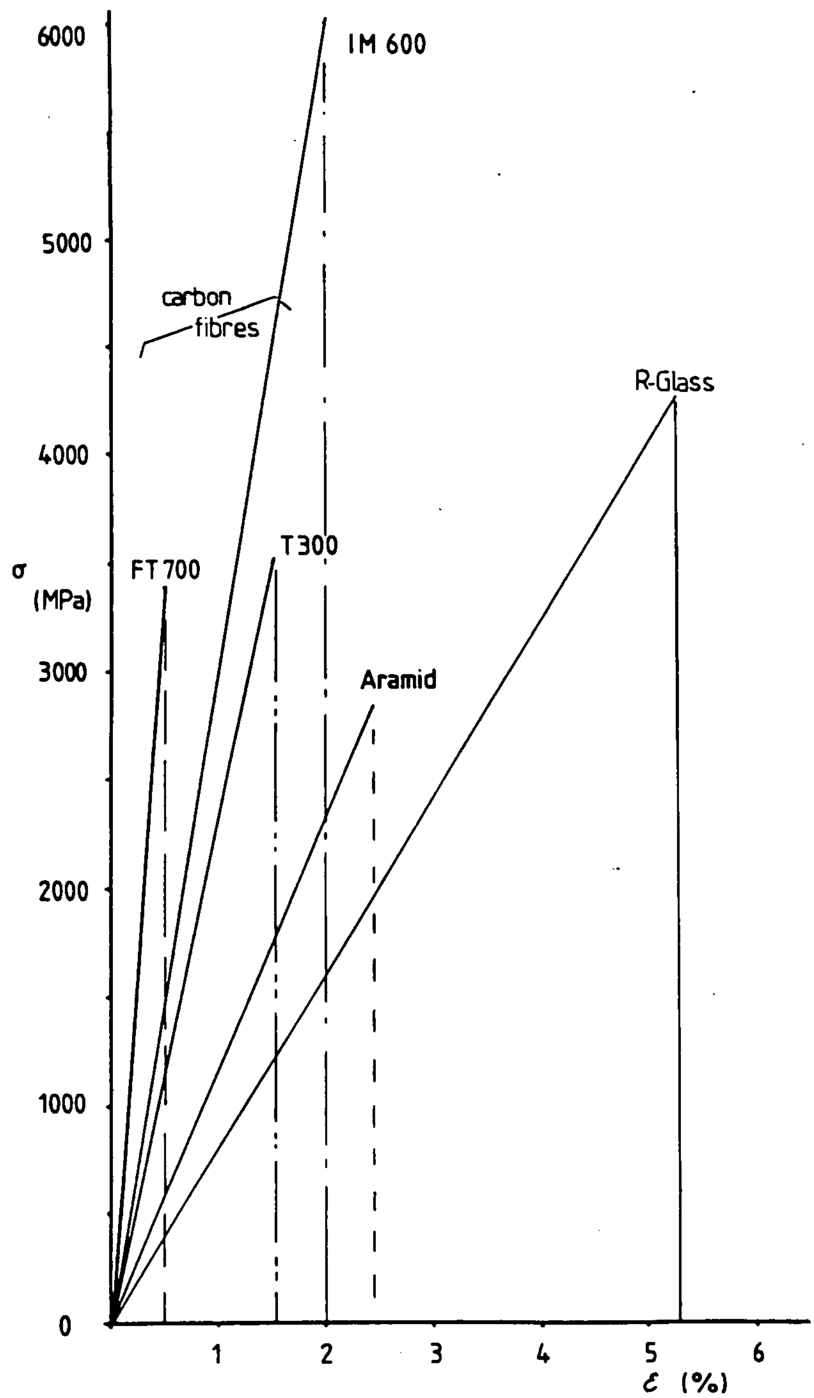


fig. 2.1 Stress - strain curves for various fibres.

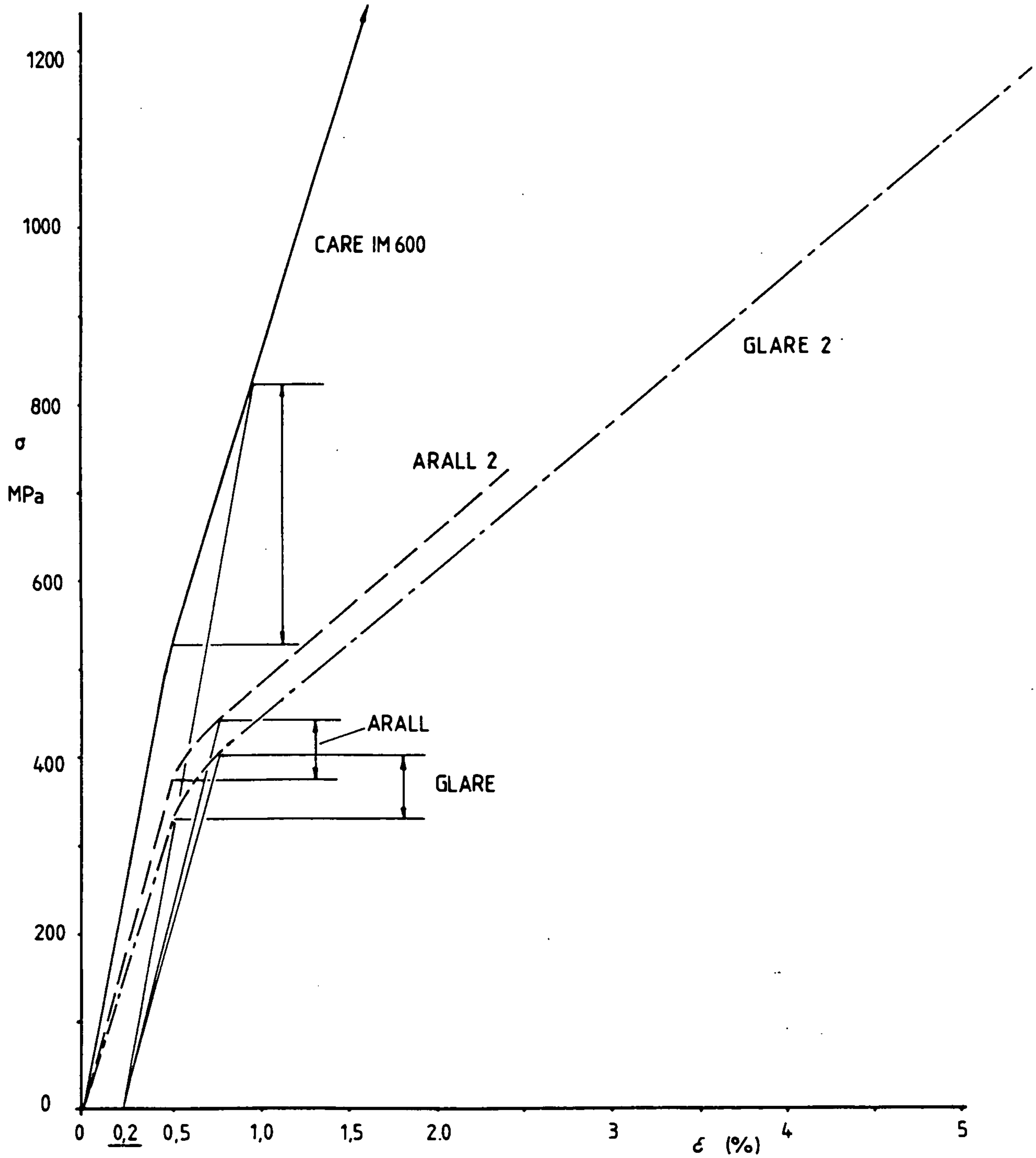


fig. 2.2 The difference between $\sigma_{0.0}$ and $\sigma_{0.2}$ for different ARALL laminates.

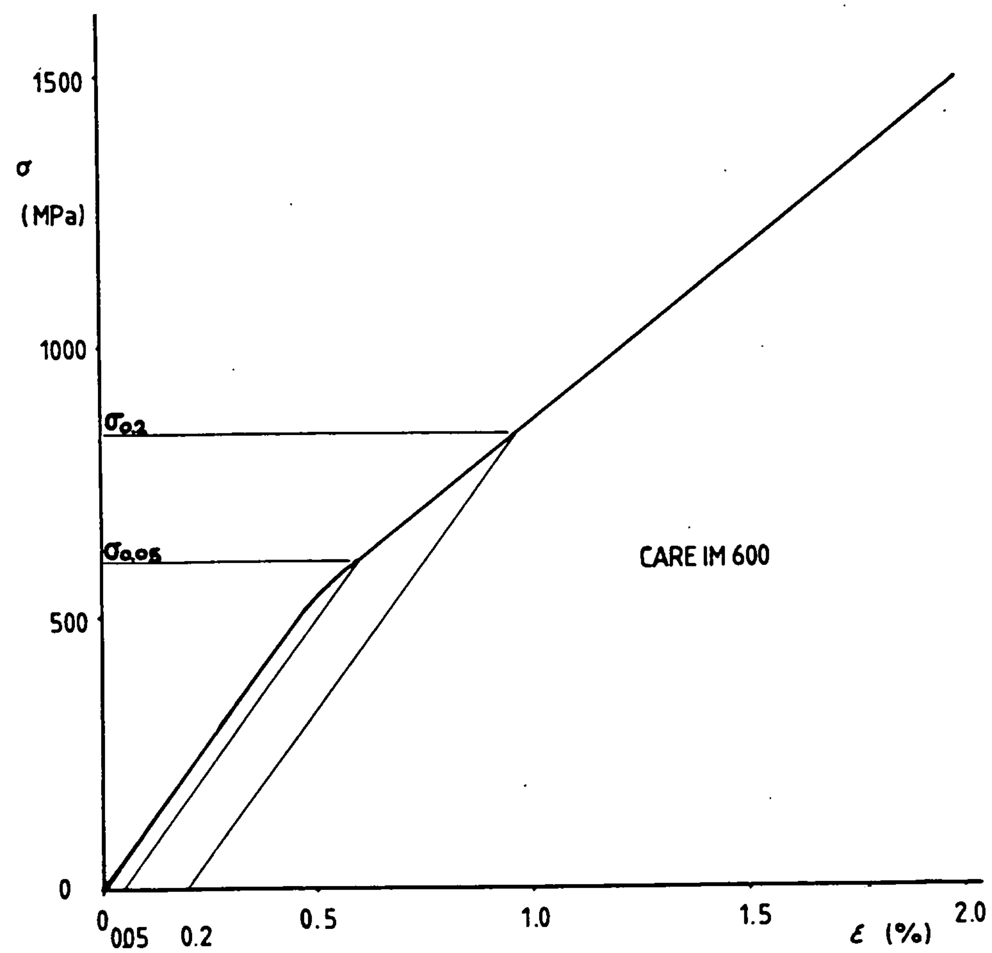
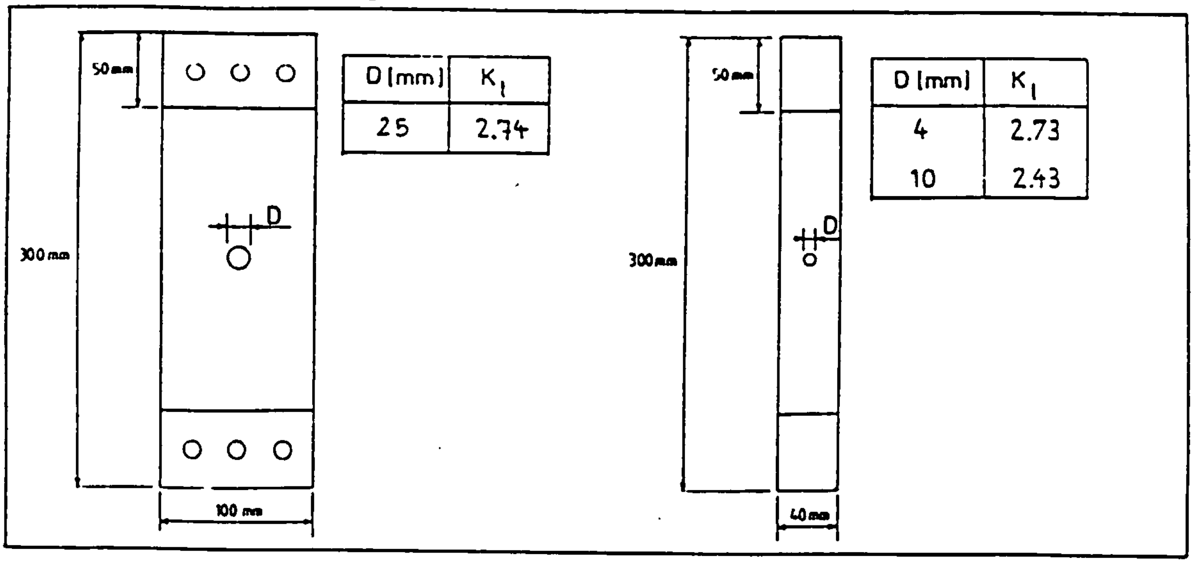
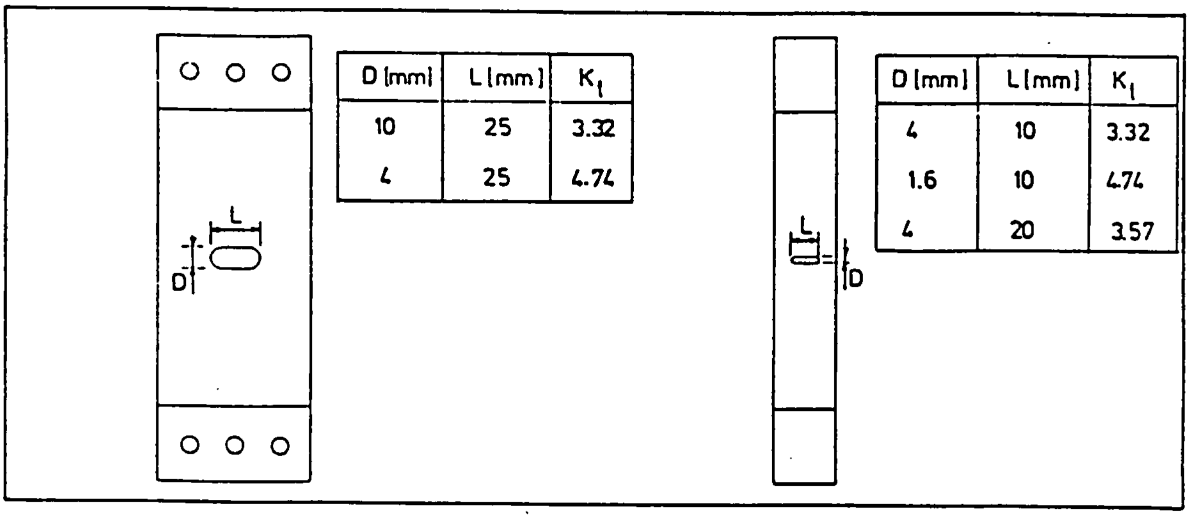


fig. 2.3 The difference between $\sigma_{0.05}$ and $\sigma_{0.2}$ for CARE IM 600.

circular holes



slotted holes



saw cuts

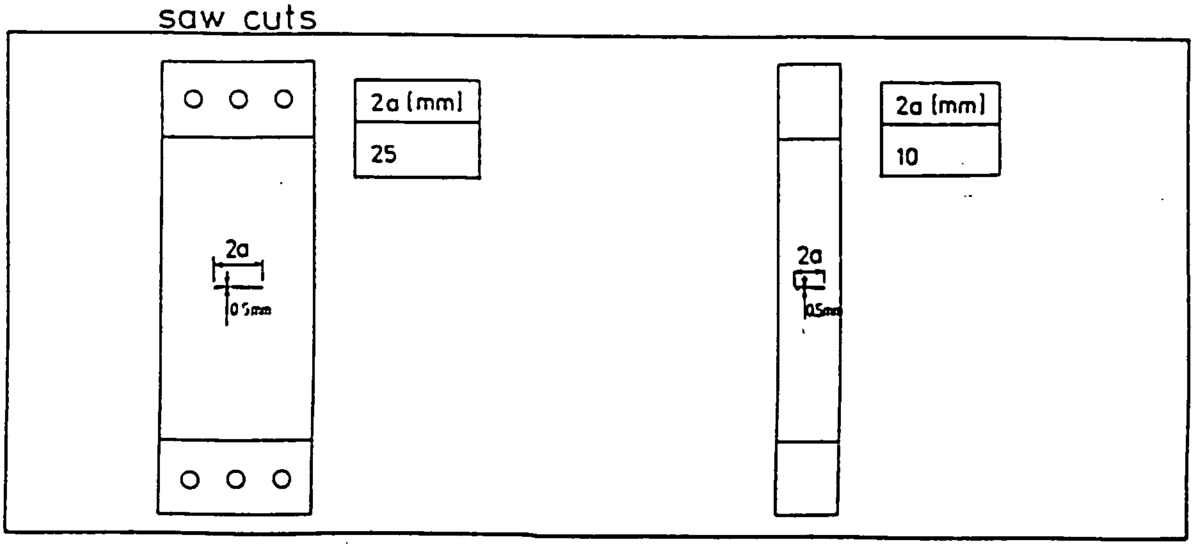


fig. 2.4 Blunt notch specimen geometries.

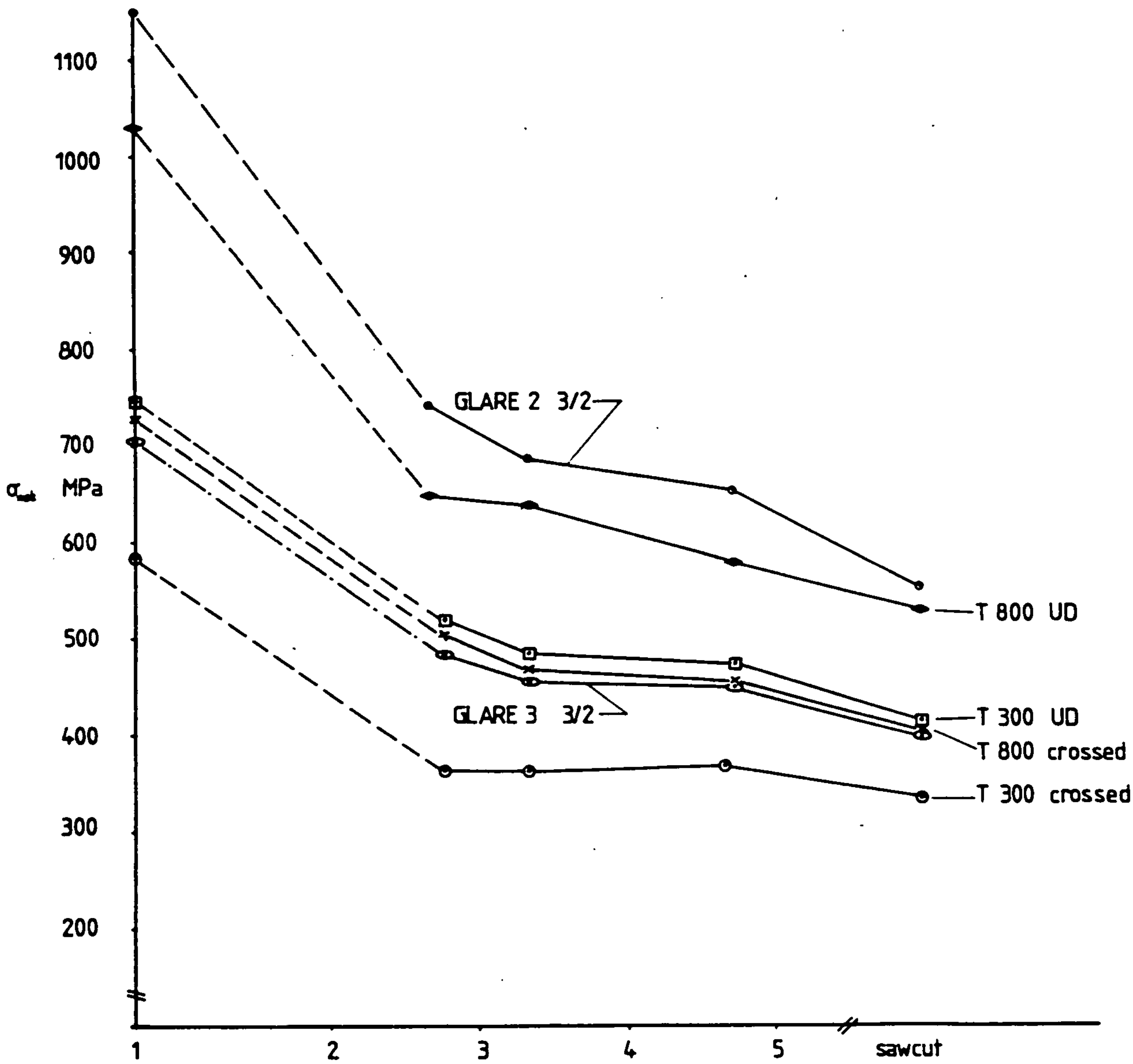


fig. 2.5 Results of blunt notch testing (W=100 mm 3/2 lay-up).

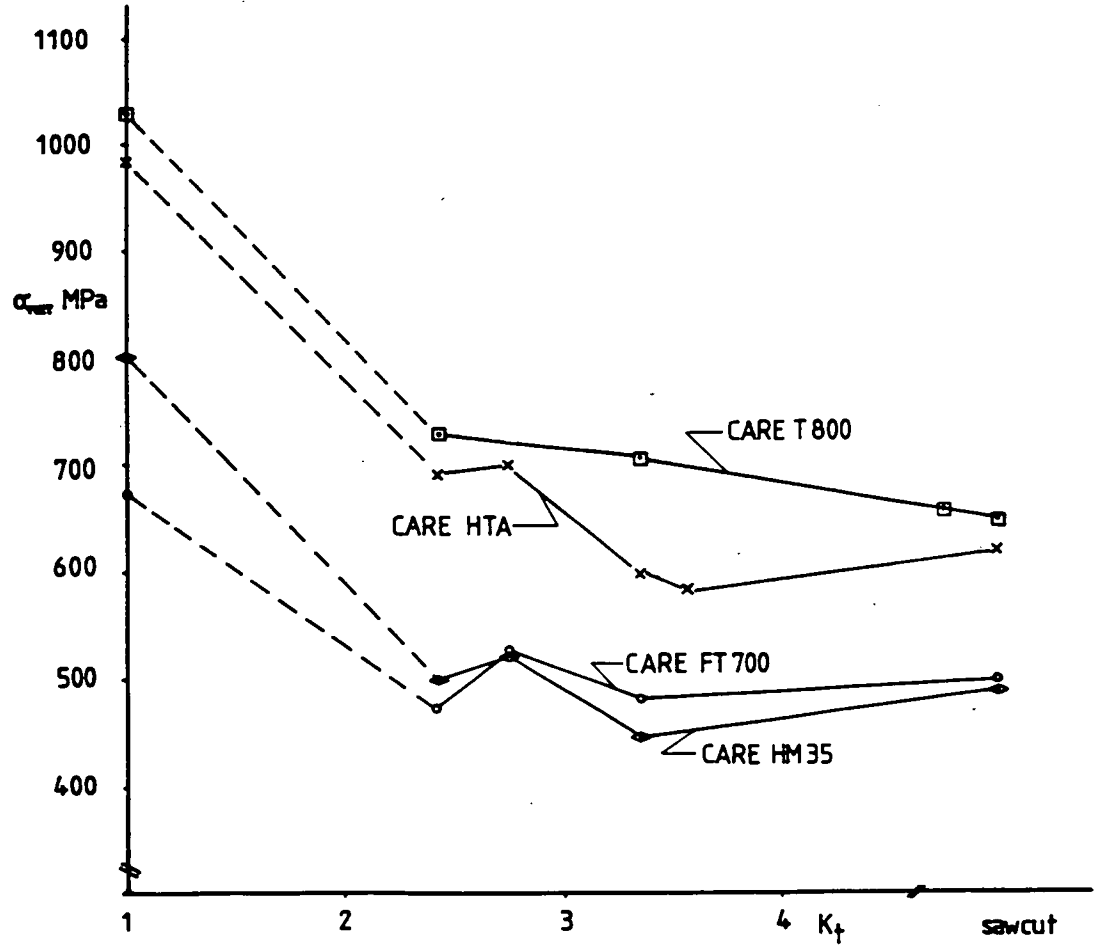


fig. 2.6 Results of blunt notch testing (W=40 mm 2/1lay-up).

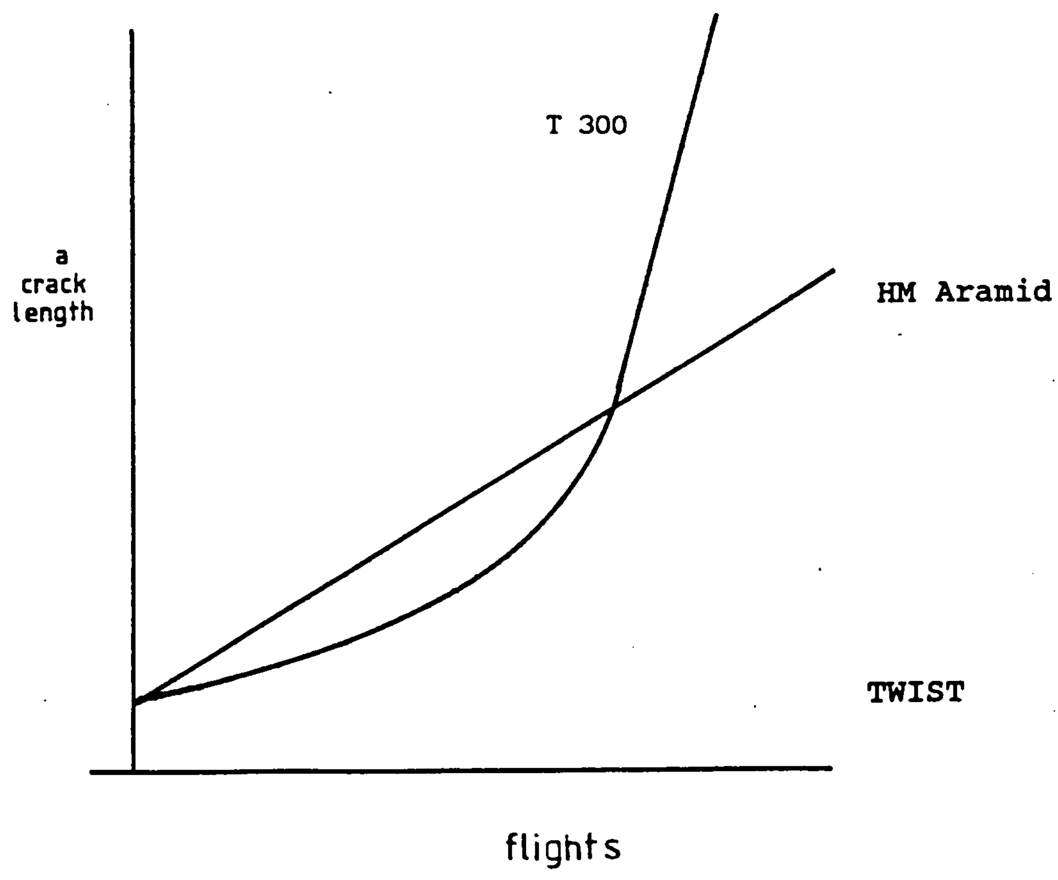


fig. 3.1 Earlier result of ARALL with carbon fibre T 300.

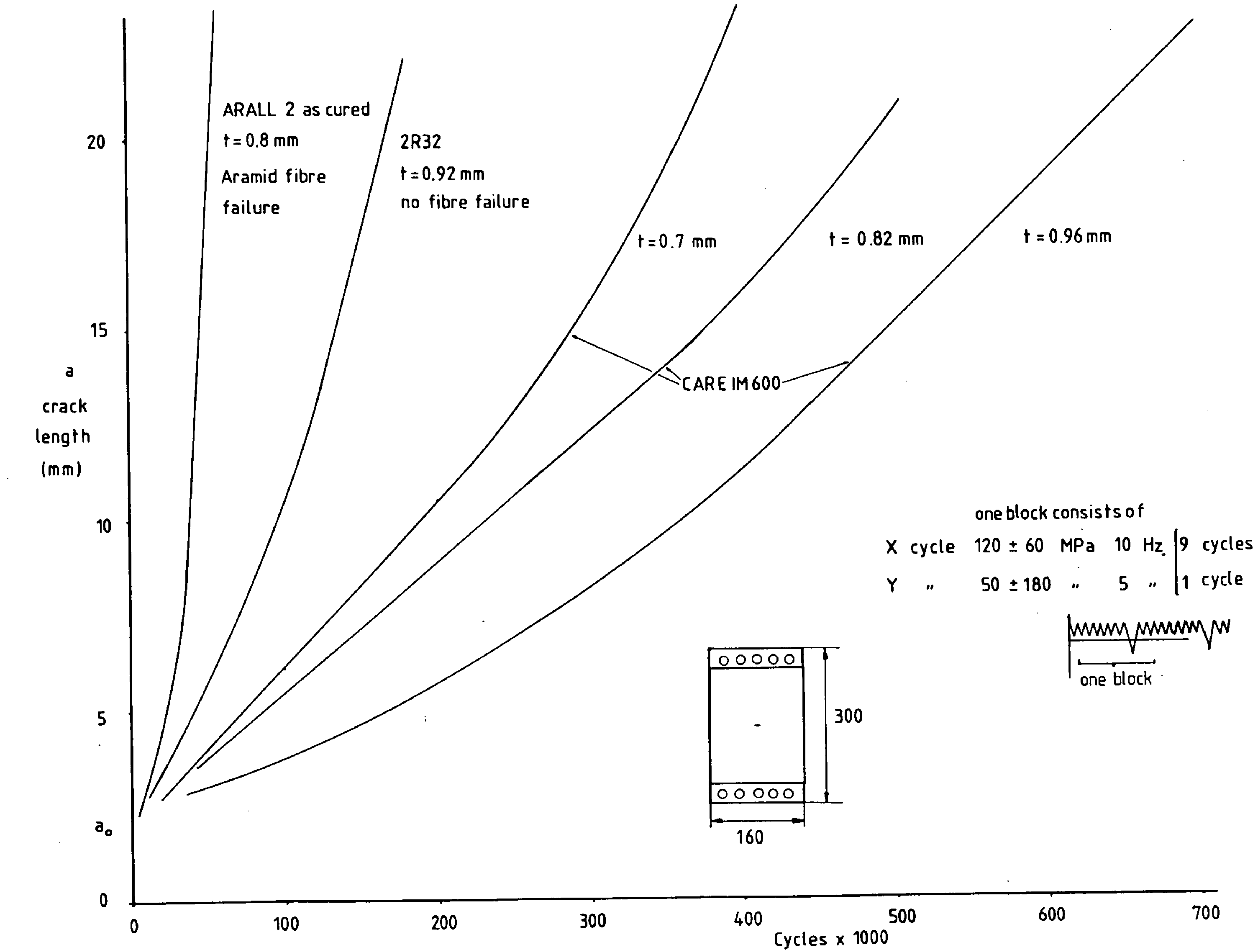


fig. 3.2 CA fatigue with peakloads: curves for different ARALL materials

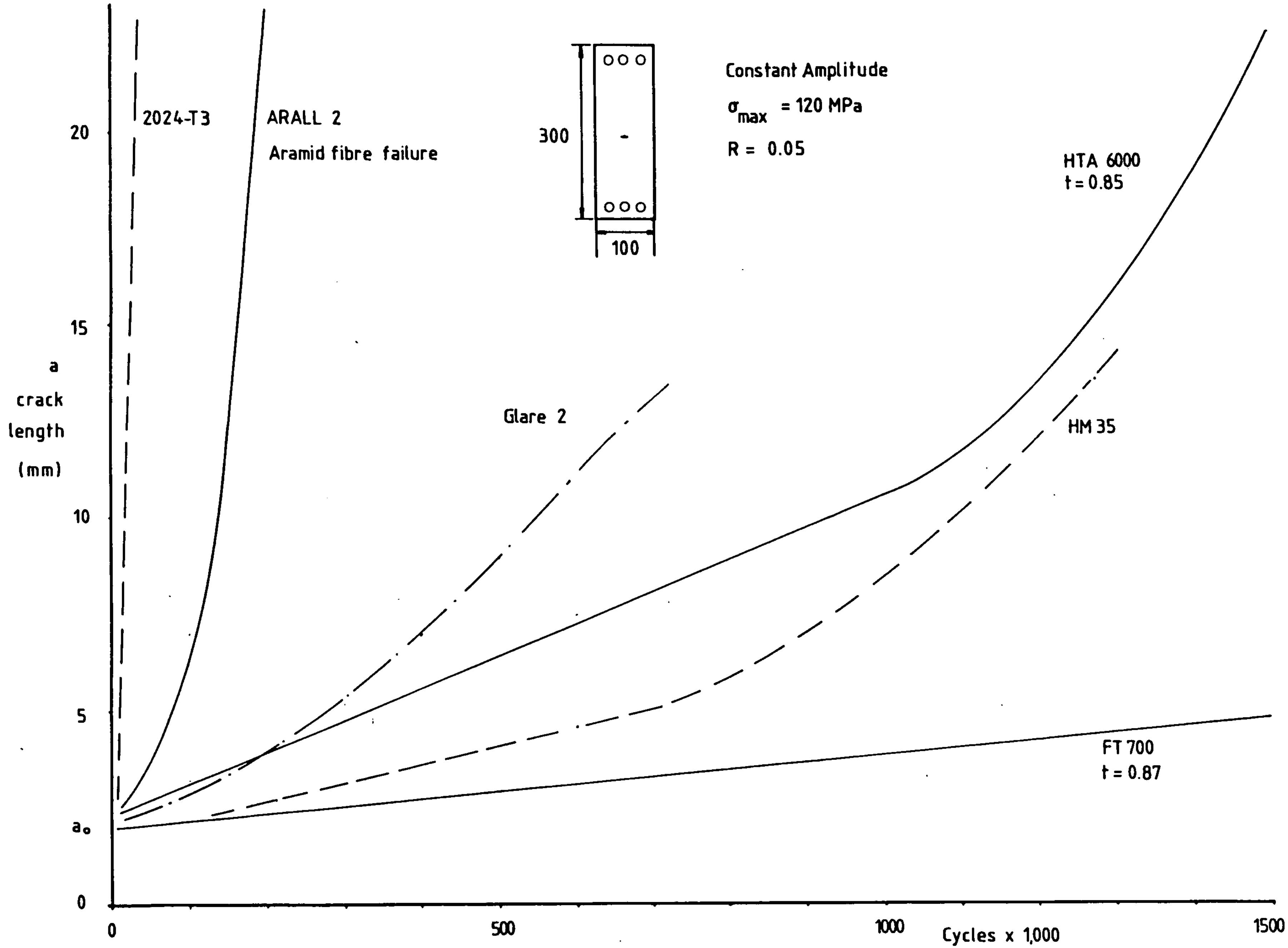


fig. 3.3 Constant amplitude fatigue curves for different ARALL materials

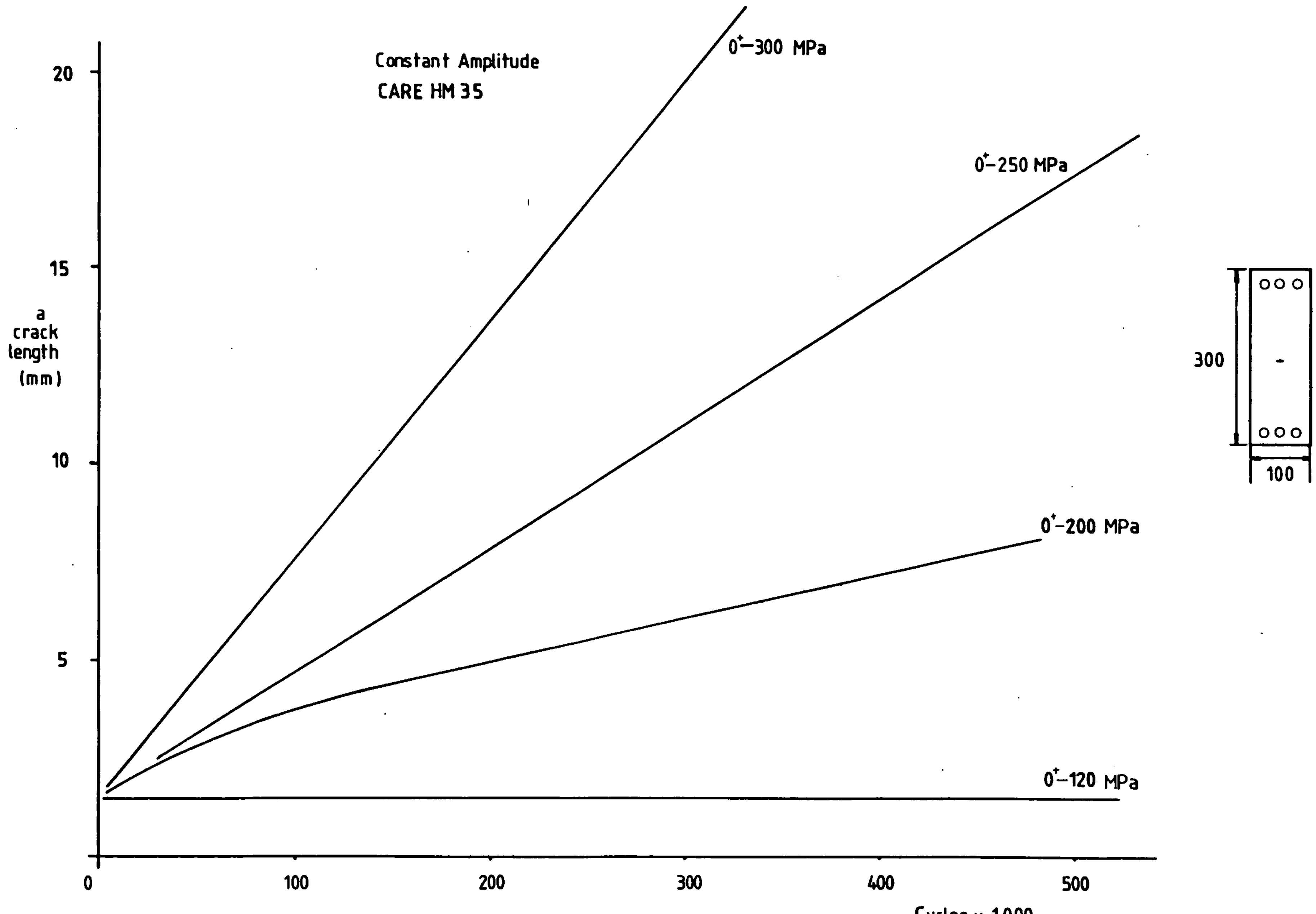


fig. 3.4 Constant amplitude fatigue curves for CARE HM 35; increasing applied fatigue stress.

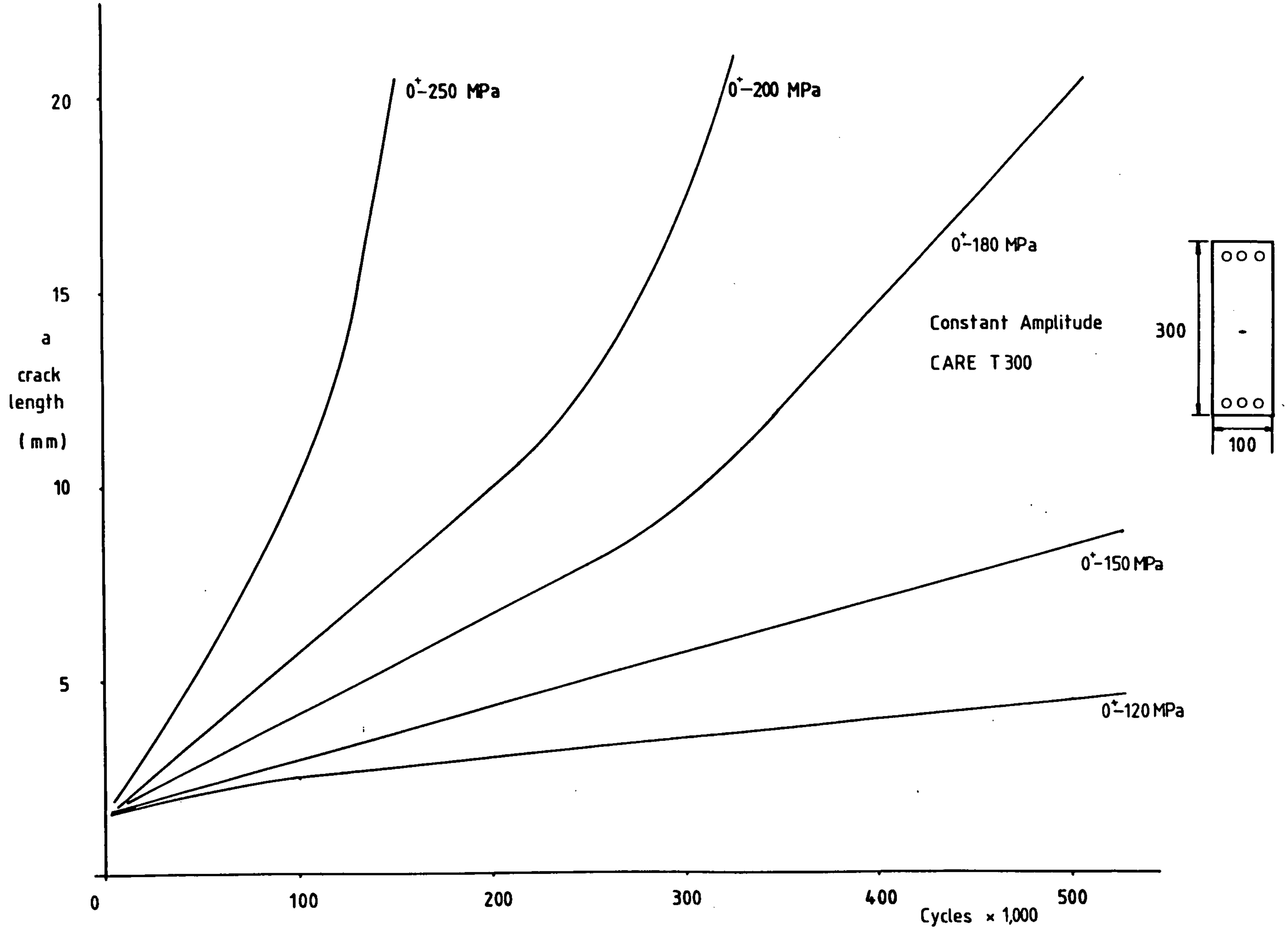


fig. 3.5 Constant amplitude fatigue curves for CARE T 300; increasing applied fatigue stress.

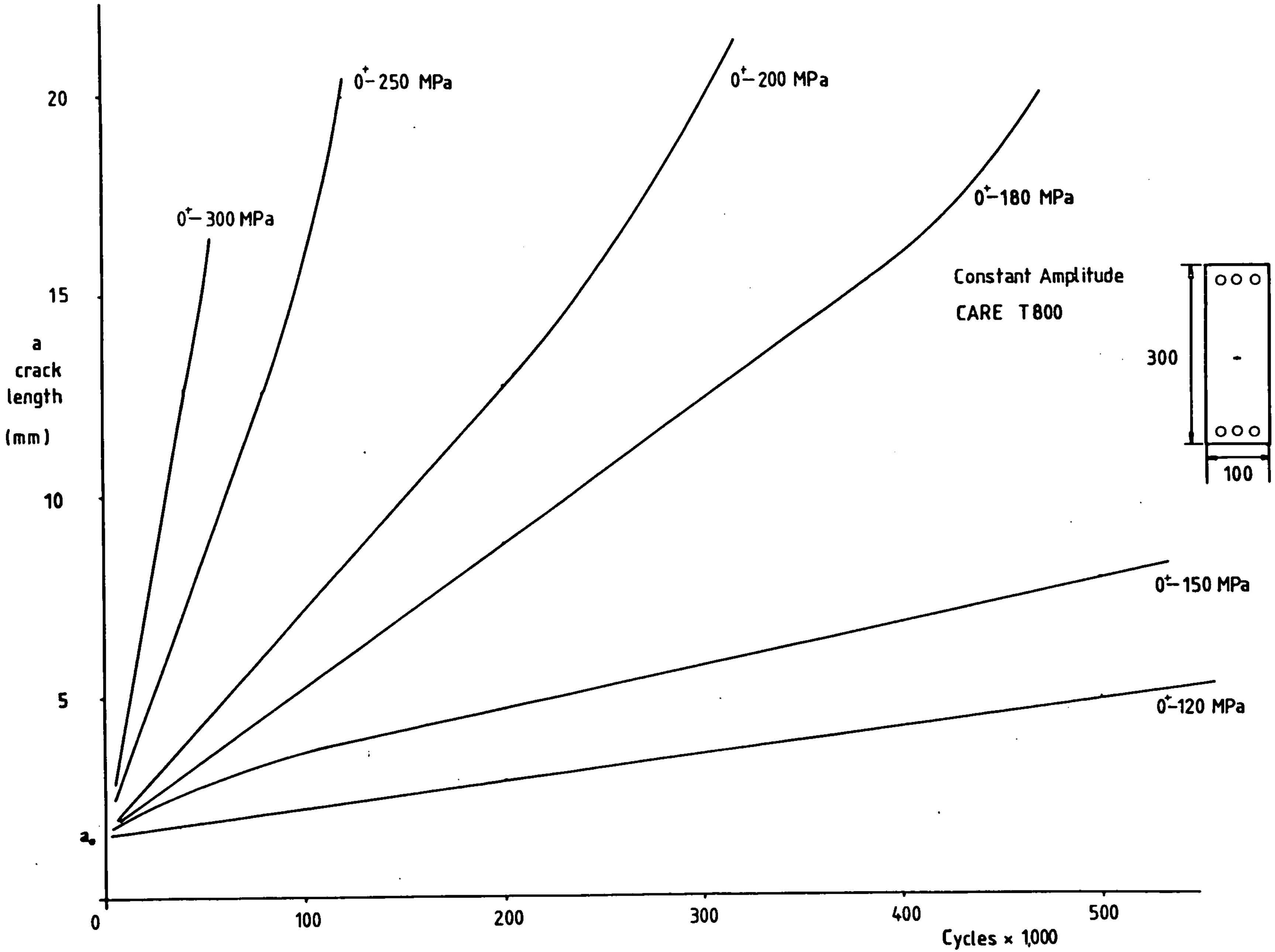


fig. 3.6 Constant amplitude fatigue curves for CARE T 800; increasing applied fatigue stress.

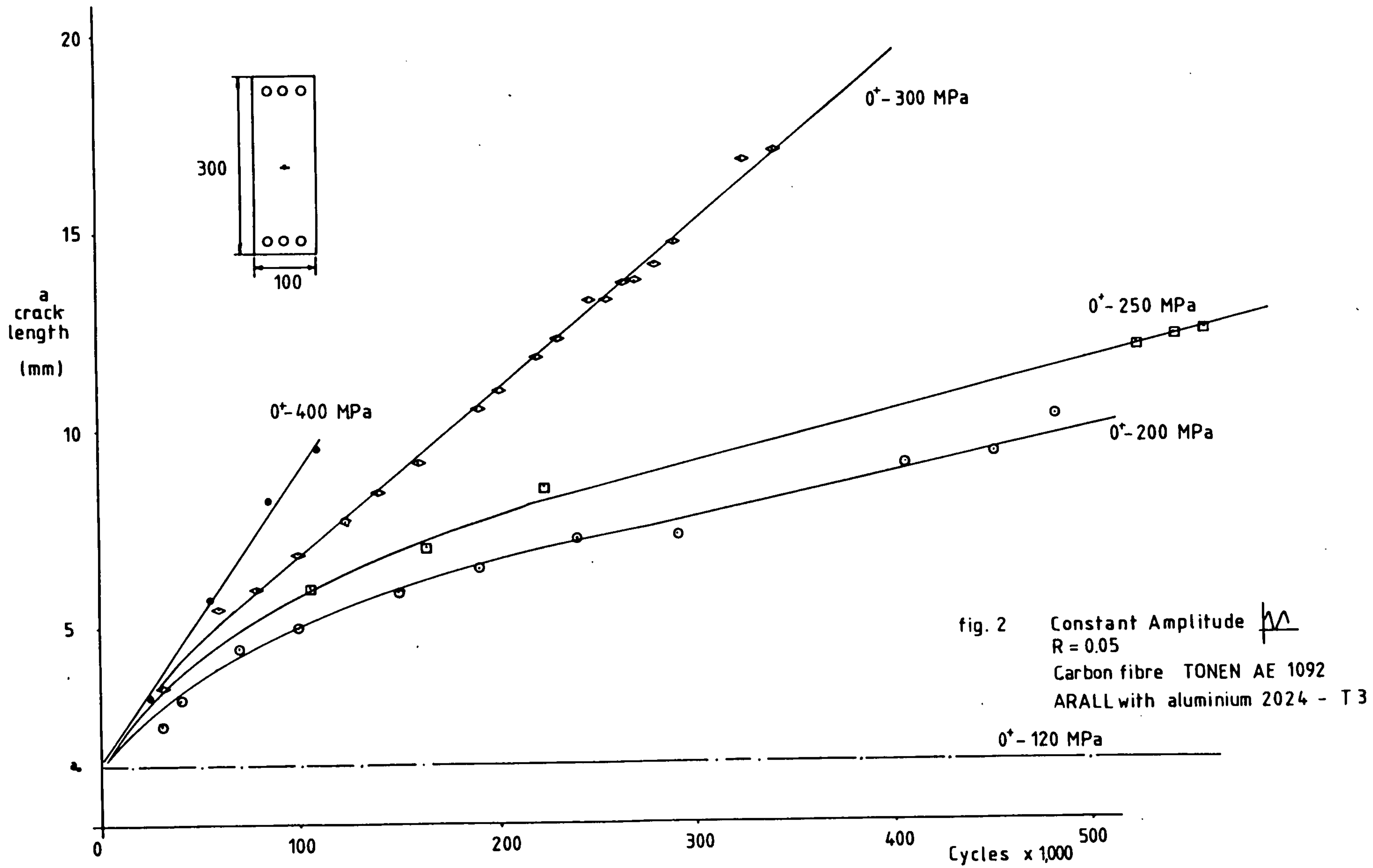


fig. 3.7 Constant amplitude fatigue curves for CARE FT 700; increasing applied fatigue stress,

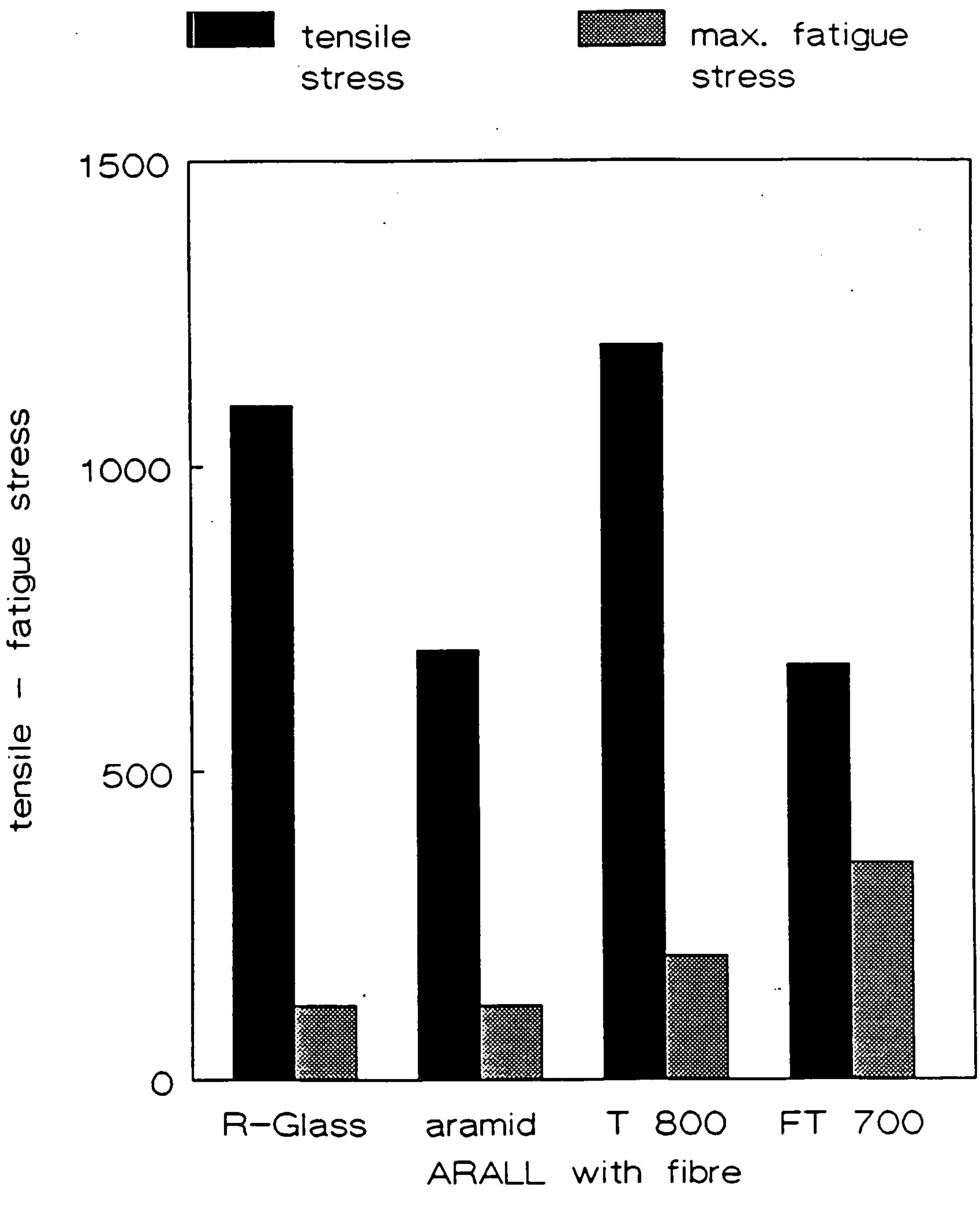


fig. 3.8 The material strength compared to the applied maximum stress during CA fatigue testing, for various ARALL laminates.

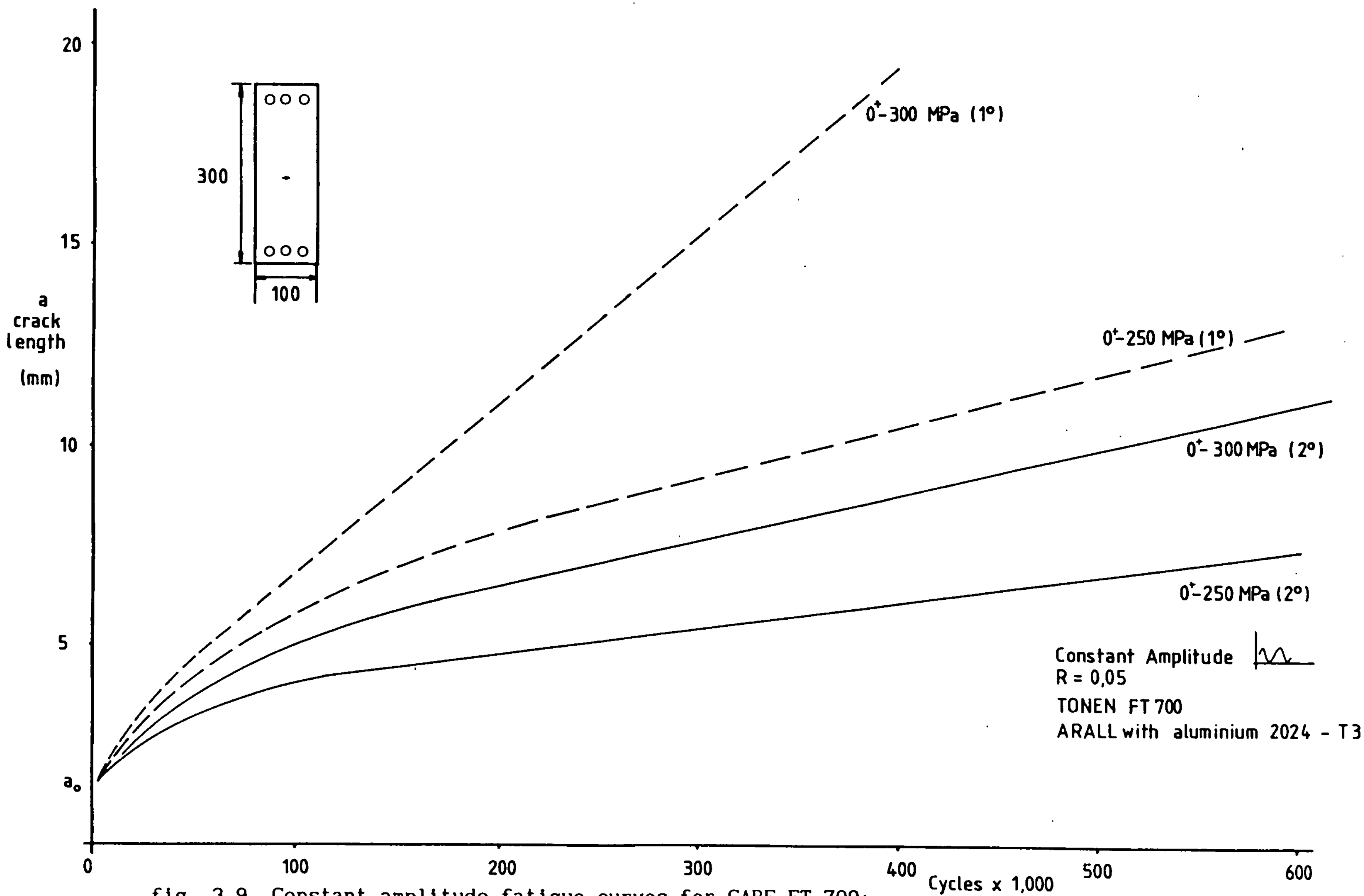


fig. 3.9 Constant amplitude fatigue curves for CARE FT 700; increasing applied fatigue stress, for two different batches of material.

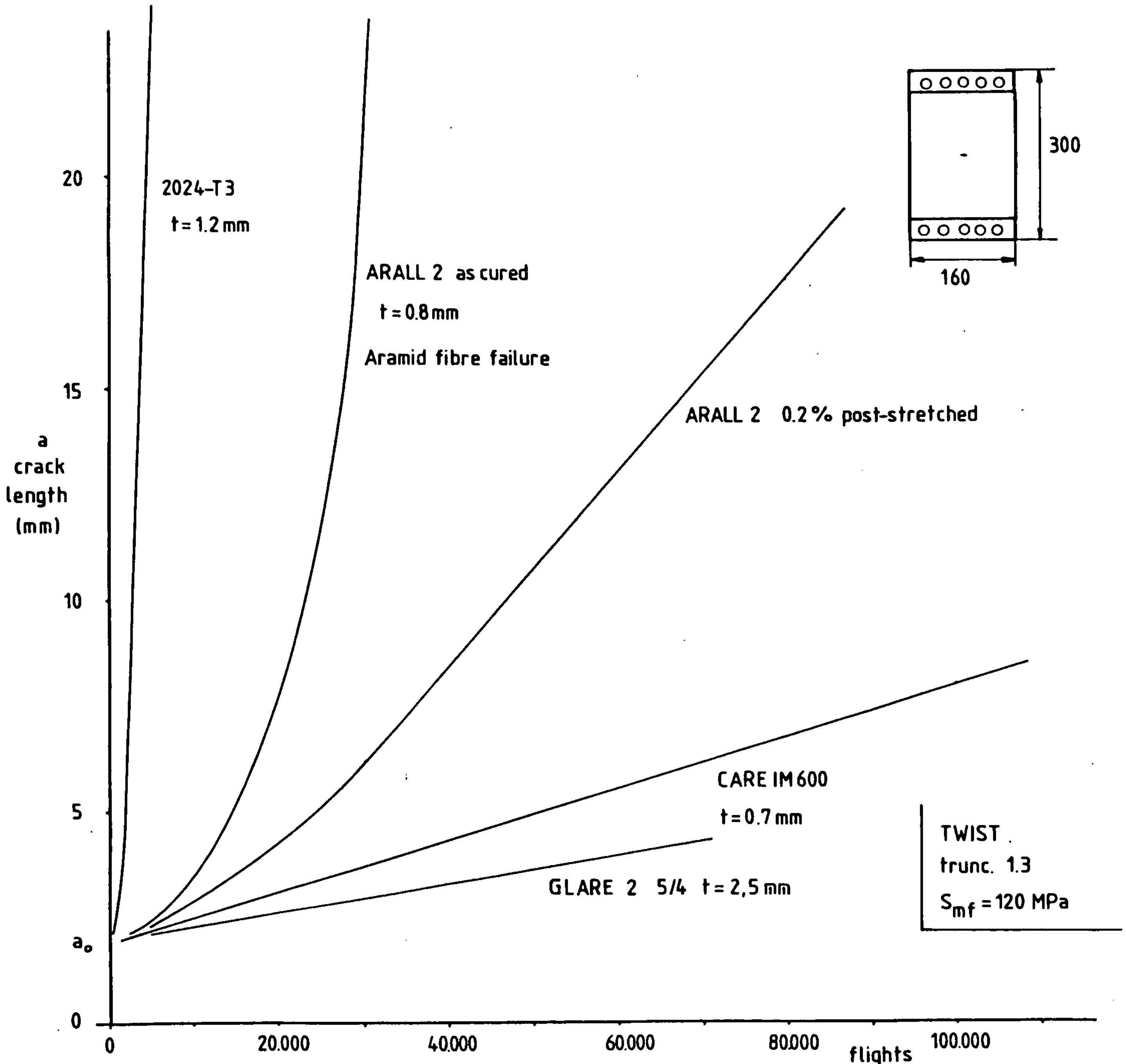


fig. 3.10 TWIST flight simulation fatigue curves for different

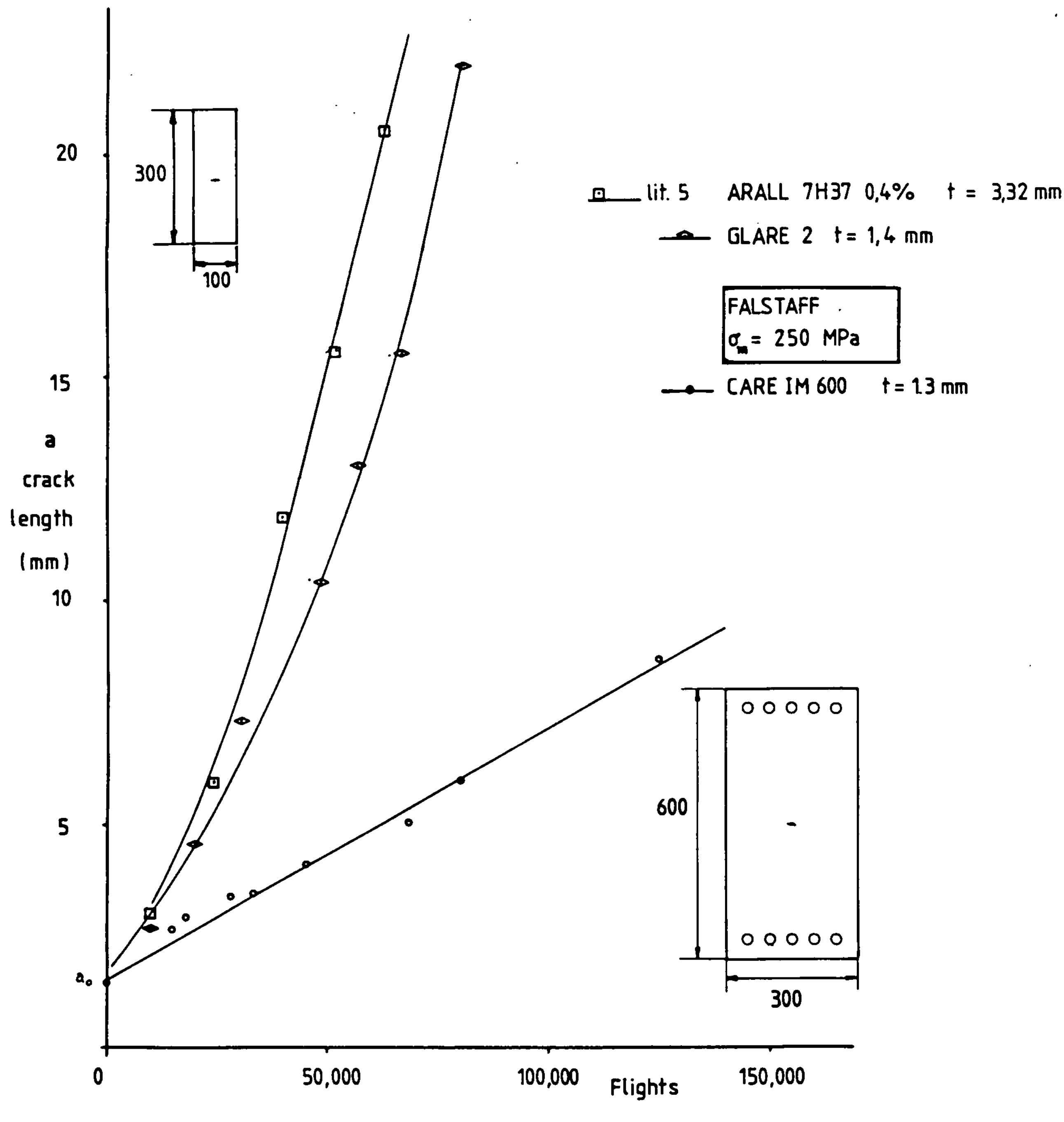


fig. 3.11 FALSTAFF flight simulation fatigue curves for different ARALL materials. σ_m = 250 MPa.

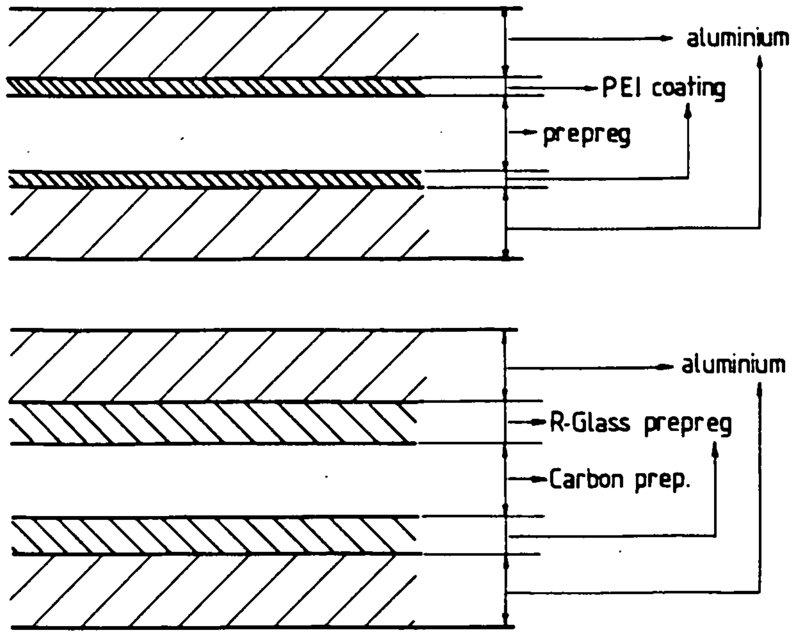


fig. 4.1 Isolation obtained by thin PEI coatings or by R-Glass prepregs.

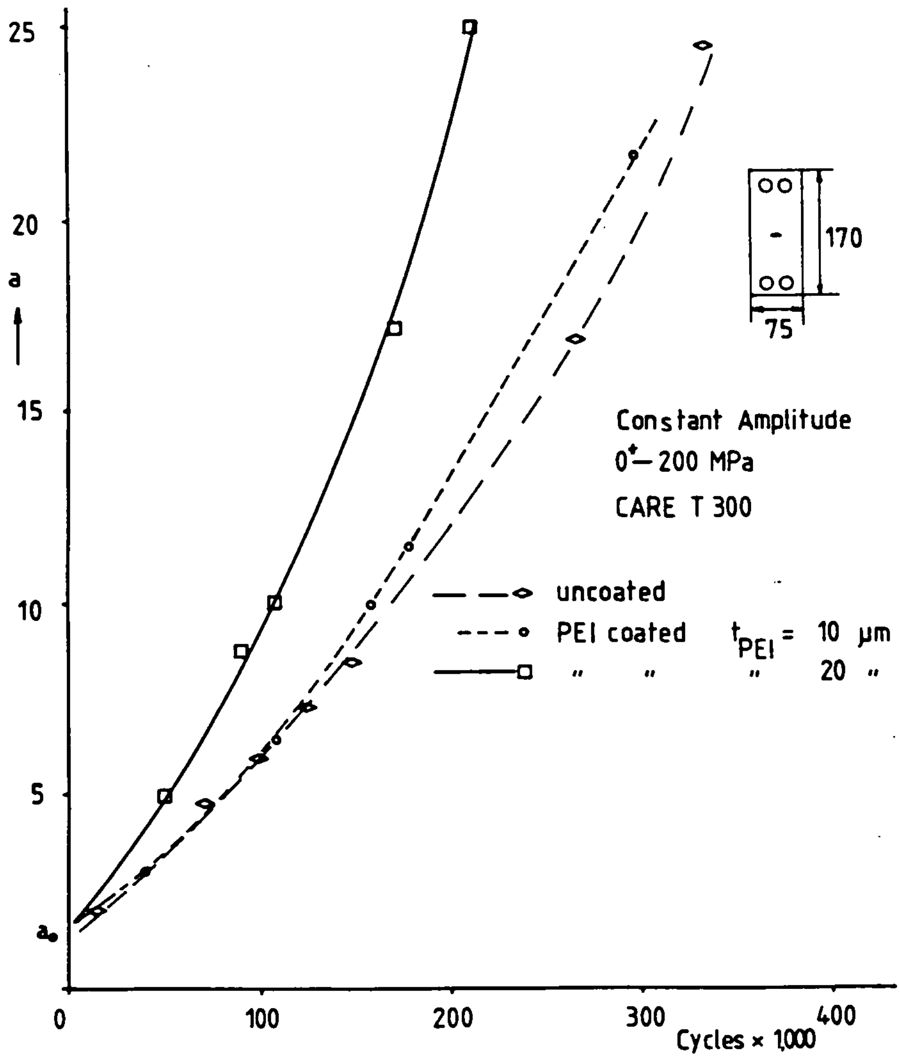


fig. 4.2 Constant-amplitude fatigue curves for CARE T 300; uncoated and with two different coating thicknesses.

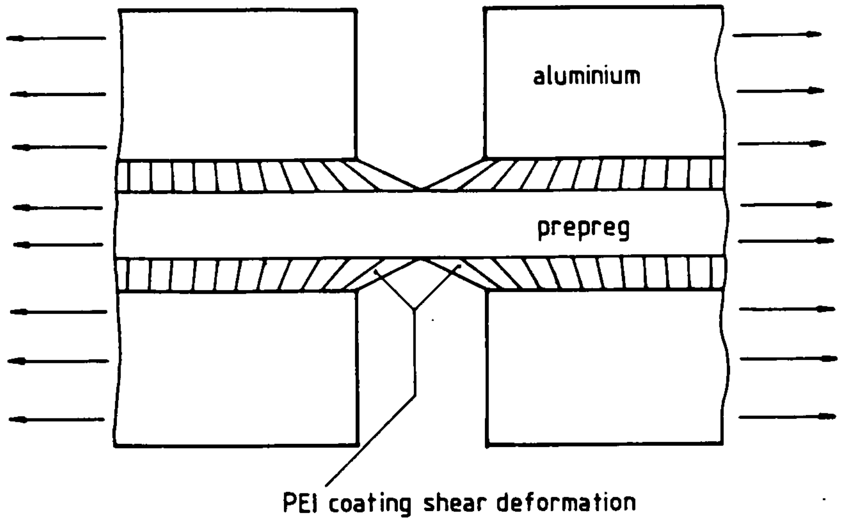


fig. 4.3 Shear deformation of the PEI coating layer at the location of the crack.

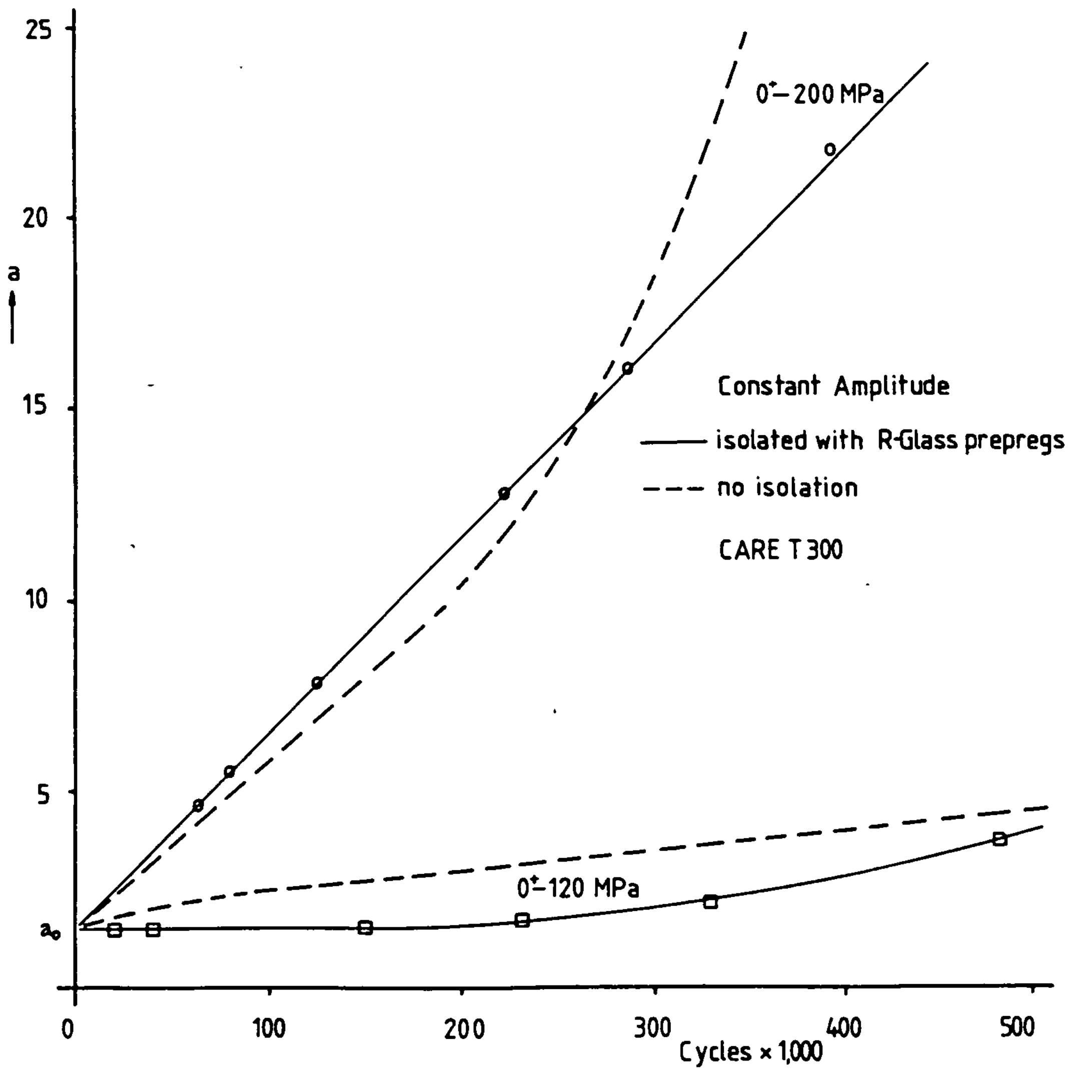


fig. 4.4 Constant-amplitude fatigue curves for CARE T 300; for two different stresses, with and without R-Glass prepreg isolation.

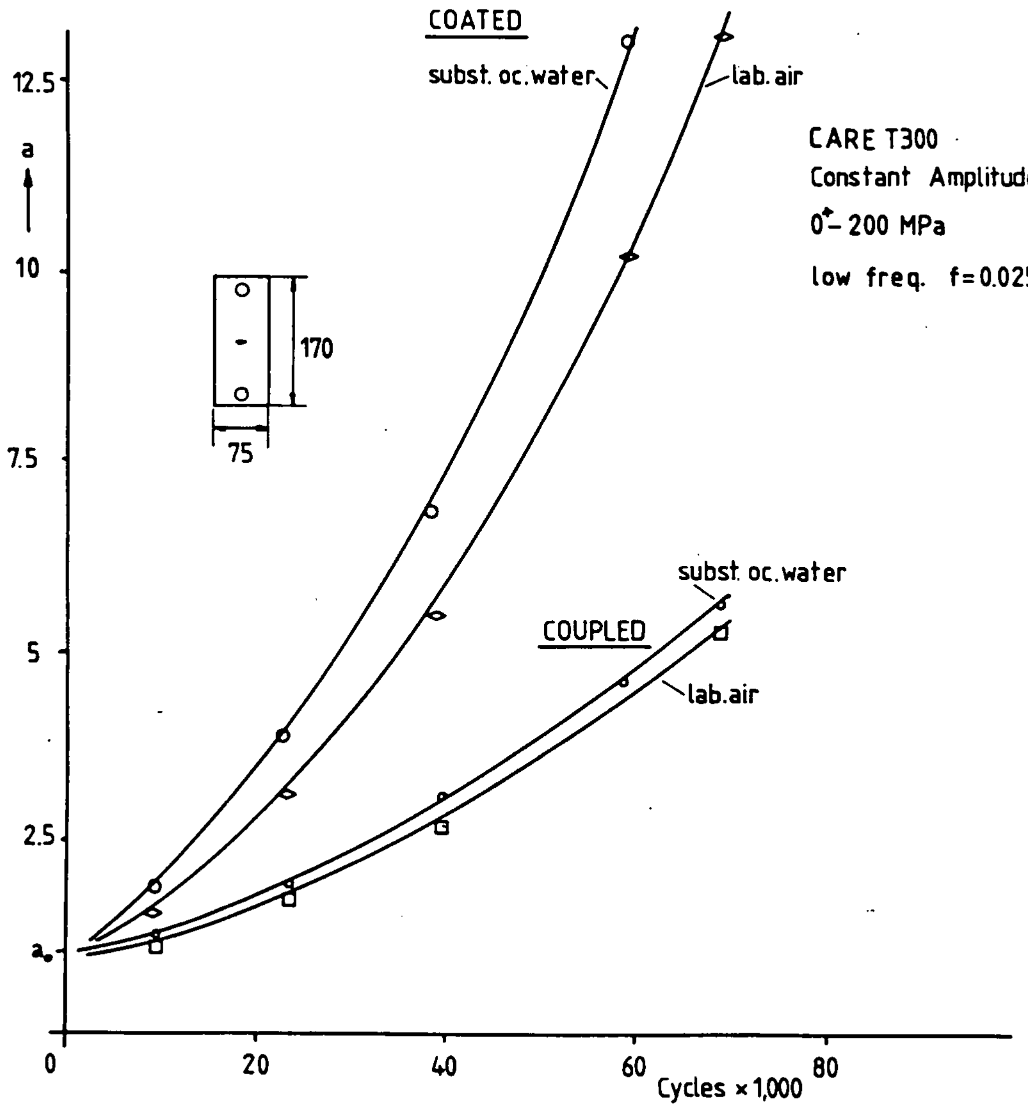


fig. 4.5 Constant-amplitude fatigue curves at low frequency, for CARE T 300, with or without PEI coating.

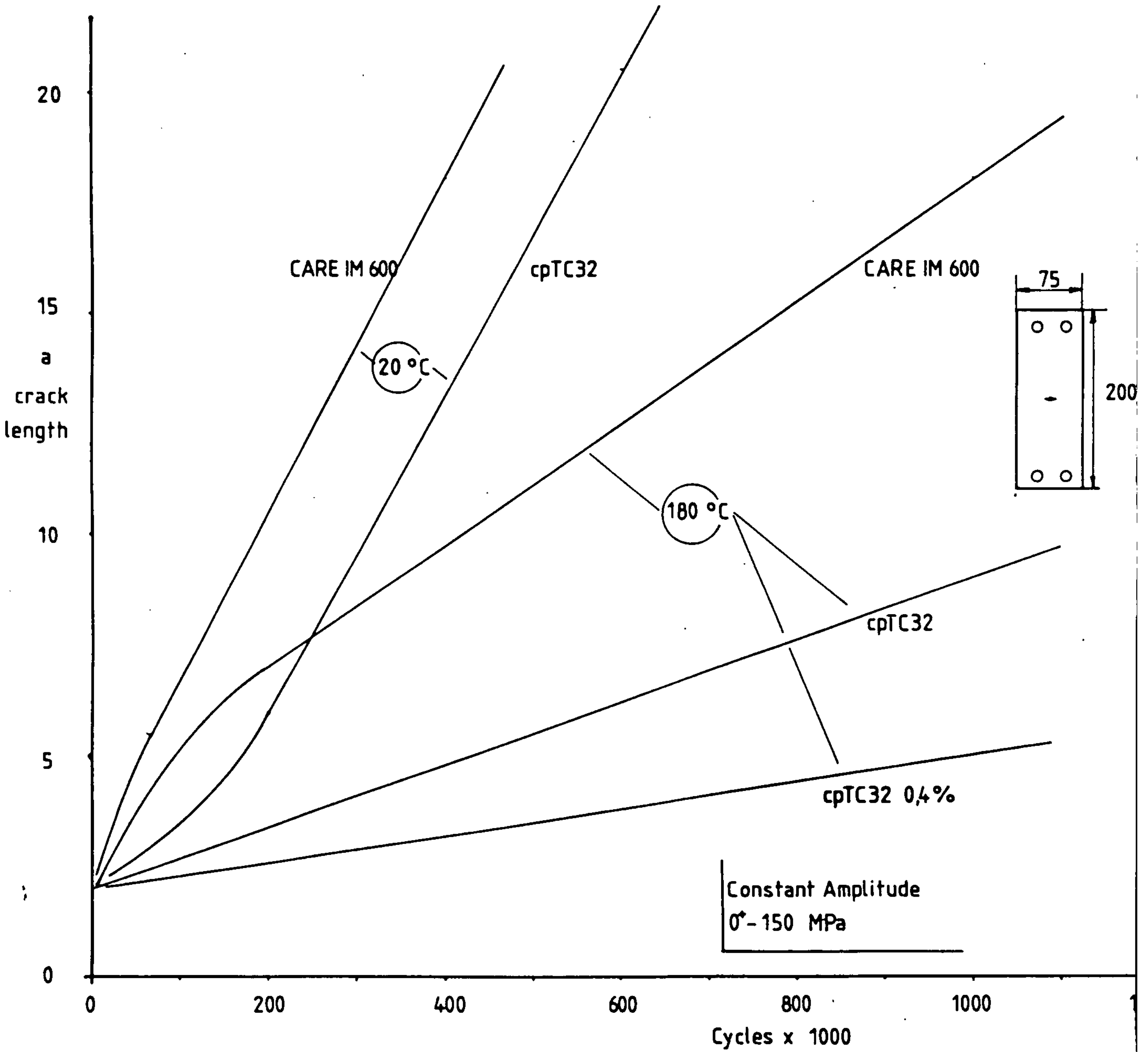


fig. 5.1 Constant-amplitude fatigue curves for ARALL with carbon fibre IM 600 and aluminium 2024-T3 or commercially pure titanium.

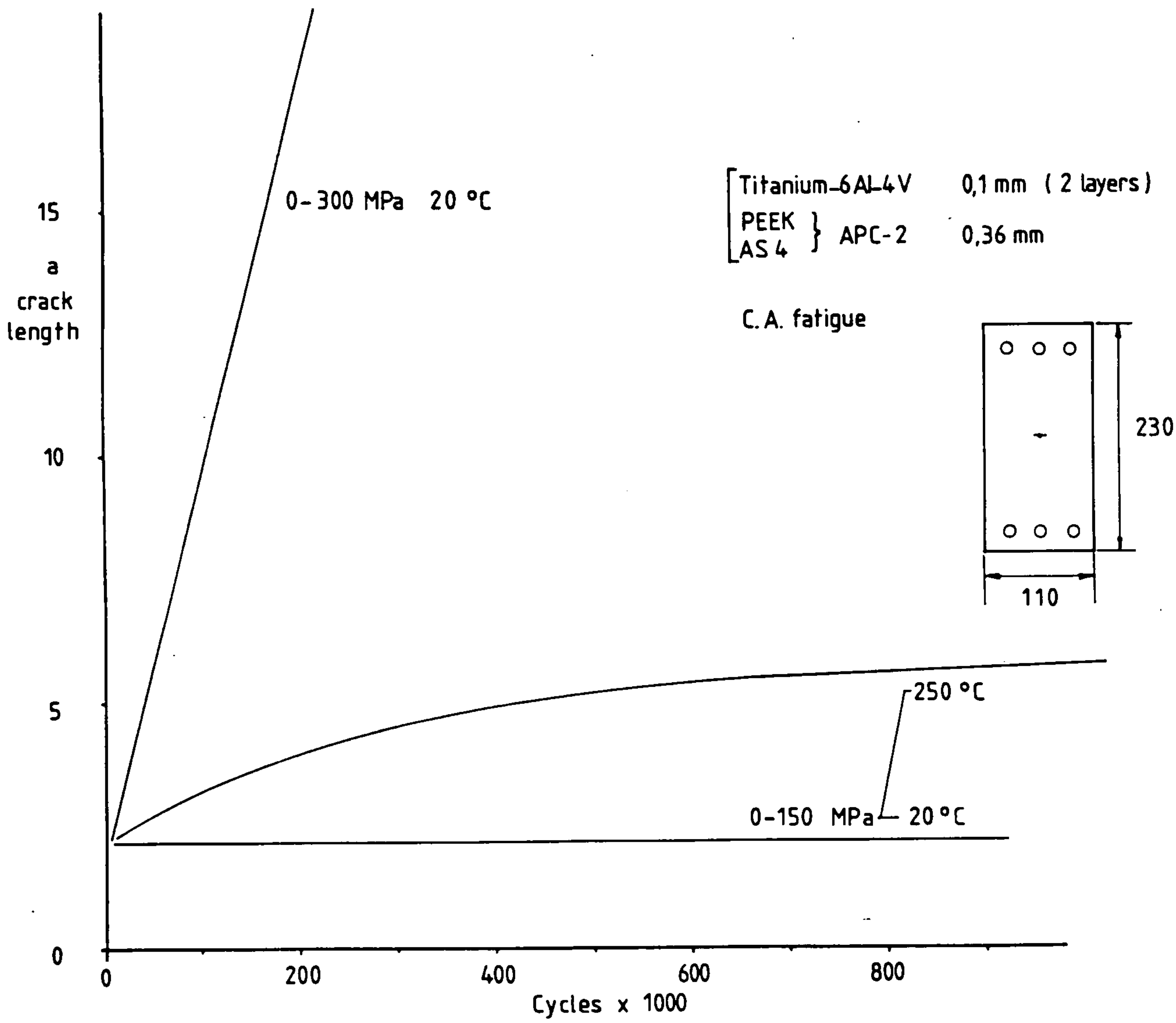


fig. 5.2 Constant-amplitude fatigue curves for ARALL with APC-2 and Ti-6Al-4V, both at room and at elevated temperature.

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