THE EFFECTS OF AGEING ON COMPOSITE MAIN ROTOR BLADES

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Abstract

The effects of ageing on composite materials is well known, with a variety of techniques in use to determine degradation factors, which engineers use in the design of components. At GKN Westland Helicopters over the past 15 years numerous research programmes have been conducted to determine the true effect of ageing on coupons and components. Coupons and components were aged in a variety of natural and artificial environments before being subjected to structural tests and the determination of moisture absorption. Results showed that accelerated ageing at 45°C and 84% relative humidity (RH) replicated the effects of natural ageing with both coupons and components. The effects of ageing were most detrimental on static matrix dominated properties, with the least effect on fatigue properties. Components did not degrade to the same extent as coupons. It was shown that it may be possible to determine the effect of ageing on components by testing at an elevated temperature above the maximum in-service operating temperature. This would reduce the time and cost to certify a primary structure.

Introduction

Polymeric composite structures have been used in the aerospace industry for over 35 years, but it is only in the last fifteen years that these materials have experienced rapid growth in their use for primary structures. The improved specific properties of these materials over conventional aerospace alloys has meant that the helicopter industry in particular has taken advantage of polymeric composites to develop high performance rotor blades. At GKN Westland Helicopters a Ministry of Defence sponsored programme was initiated in the late 1970's to develop composite main and tail rotor blades (Refs 1,2,3). The Sea King main rotor blade was designed as a true retrofit for the metallic blade. It used a D shaped spar manufactured from predominantly unidirectional carbon and glass fibre reinforced epoxy pre-pregs, with woven glass epoxy skins over a Nomex honeycomb for the trailing edge (Figure 1). Erosion resistance was achieved by the use of titanium erosion shields bonded to the leading edge of the blade. This blade provided lower life cycle costs, longer fatigue life and better damage tolerance, without any substantial change in dynamic performance.

Later, work on the British Experimental Rotor Programme conducted by GKN Westland Helicopters and DRA, Farnborough would see the advantages of composite materials exploited to provide rotor blades with varying aerodynamic profiles and swept tips. These were used on a Lynx Aircraft in 1986 to attain the absolute helicopter world speed record; a scaled up version of this technology now provides the lift for the GKN Westland/Agusta EH101 medium lift helicopter.

Epoxy composites however, have a disadvantage which the designers and airworthiness authorities must take into account in substantiating composite structures. These materials generally have an affinity to absorb atmospheric moisture with the consequent degradation of the strength in matrix dependant properties (Refs 4, 5), particularly at elevated temperatures. This is because the moisture lowers the resin glass transition temperature (Tg), which has the effect of reducing the maximum allowable operating temperature for a component. An allowance for this reduction in strength during the life of the component must be made during the design process.

Therefore in 1978, GKN Westland Helicopters embarked upon a programme of work, sponsored by the Ministry of Defence, to assess the degradation of Fibredux 913 epoxy reinforced composites, which were to be used in the manufacture of composite rotor blades. This work was to be undertaken using a variety of natural environments.

Environmental Ageing Programme

Coupon Specimens

To assess the effect of hygrothermal ageing on composite materials, laboratory environmental exposure tests were conducted on coupons at 35°C and 95-100% relative humidity. This technique was satisfactory for making comparisons between materials but it would not generally be acceptable for assessing the rate at which deterioration of the material occurs in natural environments. It was therefore decided to take advantage of the facilities at the Joint Tropical Trials Research Establishment, Australia (JTTRE later changed to the Joint Tropical Science Unit, JTSU) to conduct environmental exposure to hot/dry and hot/wet conditions. As a control, the GKN Westland Helicopters site in Yeovil, England would be used as a temperate zone.

Coupon specimens were exposed in both stressed and non stressed states due to the operational and related inspection requirements of the simulated components. When an aircraft is parked the rotor blades effectively act as a cantilever beam and it had been calculated that the stress in the component under these conditions may exceed that due to centrifugal load in flight. As the accumulated flight time of an aircraft, and hence its components, is substantially lower than the total parked time, the effect of ambient conditions on a statically stressed composite, forms an essential consideration in the airworthiness clearance of these components. To limit solar heating and actinic matrix degradation during the exposure tests, all coupons were given a paint finish comparable to that used on the components. This involved: wiping the surface with an approved solvent to remove dust and grease; applying one coat of epoxy filler to DTD 5555 and one coat of dark green polyurethane paint to DTD 5580. The paint finish was inspected and rinsed regularly at 3 month intervals during the exposure trials and repaired if it became scratched or chipped.

All the coupons were attached to racks for the exposure period at an angle of 10° to the horizontal (to facilitate water run off) and facing the equator. The stressed specimens were exposed with the laminate parallel to the horizontal and a load of ten percent of the failure load for an unaged control specimen, was applied. The specimen configurations to be tested were 0° tension, 0° flexural (both static and fatigue), interlaminar shear and ± 45° angle ply tension. Four specimens for each exposure period were used except for fatigue where sixteen specimens were employed.

The coupon specimens at the hot/wet site (Innisfail, Australia) and the temperate site (Yeovil, England) were withdrawn at the following intervals for test :

- 6 months
- 12 months + 6 months stepped
- 36 months
- 60 months
- 120 months

All specimen exposure was initiated at the same time except for the 6 month stepped coupons which were delayed 6 months in order to investigate seasonal variations. The specimens at the hot/dry site at Cloncurry, Australia were removed after 12 months, 36 months, 60 months and 120 months.

Painted and unpainted traveller specimens (1, 2 and 5 mm thick) were exposed alongside the test specimens to monitor moisture absorption .

Exposure

Exposure of the specimens took place in the open, under a canopy, at the temperate site and at the hot/wet site in positions where they were protected from direct sunlight and the direct effects of rain. This was necessary in order to prevent any weight loss associated with actinic degradation and to ensure that the moisture absorption was related to the effects of airborne moisture only.

3 painted and 3 plain specimens of all material types and 1, 2 and 5 mm thicknesses were assessed as follows. The initial weight of each specimen was determined by GKN Westland Helicopters after drying to constant weight. Failure to dry out the travellers would have prevented the true moisture absorption within the specimens from being known. The specimens, including the controls, were weighed by JTTRE before exposure and thereafter at weekly intervals. (There was preference for having the specimens weighed at the same time of day between 0900 and 1000 hours). The frequency of weighing was lengthened to monthly intervals at the discretion of JTTRE when the specimens showed signs of reaching equilibrium in terms of moisture absorption. When necessary, the specimens were weighed after unusual weather conditions. At the conclusion of the test, the specimens were weighed and returned to the UK where they were re-weighed before force drying in a vacuum-oven and their dry weight finally determined after cooling.

The climatic conditions during the natural ageing period at the exposure sites can be found in:

a) Table 1 for the hot/wet site at Innisfail

b) Table 2 for the hot/dry site at Cloncurry

c) Table 3 for the temperate site at Yeovil.

Laboratory Controls The specimens were stored in sealed polythene bags in the laboratory. An initial surge in moisture absorption of the painted and unpainted 1 mm and 2 mm specimens of both materials was recorded, but this reduced considerably after approximately 300 days and any increase after that was slight. The maximum moisture absorption was similar for both thicknesses in the same material and can be approximated at 0.5% for GFRP and 0.6% for CFRP.

The 5 mm specimens however continued to absorb moisture at a slower, but more uniform rate, throughout almost the entire exposure period. The maximum moisture absorption for each material was 0.32% for GFRP and 0.50% for CFRP.

This test showed that painting GFRP and CFRP specimens had little or no effect on the rate of moisture absorption. The unpainted specimens did not suffer any noticeable degradation of the surface resin.

Temperate Site The moisture absorption in the painted specimens was similar to the laboratory controls, only at a higher rate. The 1 mm and 2 mm specimens, which were subject to more exaggerated fluctuations due to the seasons have also tended to level out, but at a point approximately 50% higher than the equivalent laboratory controls. The maximum moisture absorption achieved by the painted 1 and 2 mm GFRP specimens was 0.76% and 0.62% respectively. For the painted CFRP the figures were 0.93% and 0.87% respectively. The 5.0 mm painted specimens followed a similar pattern to the equivalent laboratory control, but at a faster rate. Maximum moisture absorption for the GFRP and CFRP specimens was 0.76% and 1.12% respectively.

Actinic degradation of the unpainted specimens became noticeable after approximately 200 days exposure by the slower rate of moisture absorption in comparison to the painted specimens. Subsequently the specimens actually started losing weight, and after 3 years exposure the surface degradation, especially on the GFRP specimens, was easily visible to the naked eye. The surface of the GFRP specimens took on a furry appearance and it was clear then that cleaning prior to weighing had been reducing the material in the specimens. This accounted for the marked difference in weight loss which had occurred between the specimens that had been weighed regularly and those that had not.

It should be noted that unlike the hot/wet specimens, which were stored under a large car port, the temperate site specimens were stored under a much smaller structure and were therefore, at certain times of the day, subjected to direct weather conditions.

Hot/Wet Site The rate of moisture absorption of specimens exposed at the hot/wet site was approximately 50% faster than that for the equivalent specimens exposed at the Temperature site. The total absorption of moisture was also approximately 50% higher than the temperate site specimens. For both painted and unpainted 1, 2 and 5 mm GFRP specimens these were shown as 1.1%, 0.88% and 1.12% respectively, and for the CFRP specimens the maximum figures were 1.28%, 1.26% and 1.12% respectively. Unlike the temperate site specimens, the painted and unpainted specimens retained fairly equal amounts of moisture throughout the exposure period. There was little or no actinic degradation of the surface matrix material of the unpainted specimens as a result of the better cover.

Specimen Test Results

The effect of environmental ageing on static test specimens varied with test type and material as well the type of conditioning to which the specimen had been subjected.

0° Tension GFRP specimens which had been conditioned in the temperate environment exhibited a similar pattern to that of the laboratory controls.

There was initially a small reduction in strength over the first year but a plateau was then achieved where strengths were consistent at approximately 90% of the original control. Specimens from the hot/dry site behaved in a similar manner but the plateau was 93% of the strength of the control.

Specimens from the hot/wet site however, gave a steady decline in strength, and those tested after ten years exposure had a strength which was approximately 75% of the control. This reduction in strength with ageing had also been noticed on all the other research programmes with E glass reinforcement. Since 0° tensile is a fibre dominated property, this large reduction was not predicted. As a result of this a further separate programme of work was conducted investigating this phenomena. The results of this programme are explained later.

CFRP specimens which were exposed in Yeovil produced strengths within 10% of the control and, in fact, 80% of results are higher. There is less consistency in the results obtained from the JTTRE specimens, but 58% of the hot/wet and all the hot/dry specimens exhibited strengths in excess of the control.

Flexural Strength The GFRP laboratory controls consistently produced low strengths, but the reason for this was not fully understood.

However, the specimens aged under temperate conditions were uniform over the whole period, within experimental tolerance, giving strength approximately 93% of the original control.

The flexural specimens exposed for ten years under hot/wet conditions, whether in the unstressed or stressed condition showed similar strengths: unstressed 71%, and stressed 75% of the control strength. These retentions in strength were considerably lower than predicted, but were consistent with the 0° tensile properties observed.

The hot/dry specimens reduced to approximately 94% of the strength of the control after one year, but have maintained this strength over the ten years exposure.

For CFRP, the laboratory control specimens consistently produced low results as was found with the GFRP ones.

The unstressed specimens, at both temperate and hot/wet sites showed a gradual depreciation in strength with ageing: the strength after ten years being 84% of the control.

The unstressed specimens exposed to hot/dry conditions produced uniform results over the ten year period (95% of control strength).

There was no definite trend in the results obtained for specimens exposed in the stressed condition, but those exposed to a temperate climate for ten years have shown a 4 percent increase in strength over the controls.

Because of the inconsistency of the results obtained from stressed specimens, it was difficult to obtain a definite comparison between the effects of exposure in the stressed and unstressed conditions. The basic evidence indicates that a stressed specimen is no more affected than one exposed in the unstressed state.

Interlaminar Shear Strength For GFRP there was a small reduction in strength over the first year (97%). The strength reduced slightly more after three years exposure but was then maintained over the full ten year period (92% of control strength).

The specimen exposed to hot/dry conditions maintained the strength over the full ten year period (99% of control).

The temperate CFRP specimens and the stressed hot/wet specimens showed a gradual reduction in strength with time of exposure: the specimens exposed for ten years having a strength 92% of the control.

There were no unstressed specimens available from the hot/wet site for testing after ten years exposure. The specimens tested up to five years exposure showed that the strength was maintained for six months but reduced to 88% of the control strength at the end of the first year. The strength gradually increased with age and after five years exposure had retained 94% of the control strength.

There was a slight increase in strength with hot/dry exposure, the specimens tested after ten years exposure were 7% stronger than the control.

±45 degree tension GFRP specimens showed uniform strengths over all the exposure sites and periods of exposure. The maximum reduction in strength was equal to 92% of the control strength.

The one year laboratory controls for CFRP specimen produced very low strengths (80% of original control) but there was no obvious reason for this. The results after three years were also relatively low (86%) compared to those obtained from other exposure periods.

There did not appear to be any real trend in these results although the hot/dry specimens did give fairly uniform results over the whole exposure period (94% of control strength).

For specimens exposed to temperate and hot/wet conditions there was a fairly large scatter band ranging from 82% to 100% of the control strength, with an overall average of 90%.

Fatigue tests The fatigue properties of specimens exposed to temperate, hot/wet and hot/dry conditions for periods up to ten years were not adversely affected by the conditioning. In some cases, there appeared to be a slight improvement in fatigue properties due to moisture softening of the matrix which inhibited crack growth.

Reduction in 0° tensile strength of GFRP

It was postulated that the reduction in the 0° tension (and flexural) strength of uni-direction glass reinforced epoxy may have been the result of a chemical attack upon the glass fibres. The Fibredux 913 epoxy resin system used by GKN Helicopters for the construction contained a dicyandiamide (Dicy) hardener. As with most epoxy systems, not all of the hardener may be reacted during the curing process, this therefore leaves small pockets of Dicy. Previous research (Refs 6,7,8) had shown that the Dicy will dissolve in absorbed moisture to form an alkaline solution which is able to attack the glass fibres and the greater the residual Dicy content the higher the moisture absorption will be.

Work was conducted at GKN Westland Helicopters, funded by the Ministry of Defence (Ref 9), to determine whether this phenomena was unique to the Fibredux 913 E-glass system or if other glass fibres and resin systems were affected. Eight different materials were evaluated to form a matrix, investigating 3 different Dicy contents; 3 different glass reinforcements and 2 different glass coatings (sizes) and resins. The materials were cured at 120°C with and without a dwell at 90°C (the dwell is used by GKN Westland Helicopters to prevent an exotherm occurring during the cure of thick laminates in rotor blades). The environmental ageing was carried out using two sets of specimens, one aged at 45°C and 84% RH and the other at room temperature and 84% RH. This was to determine if degradation would be greater in high temperature climates due to the increased solubility of the unreacted Dicy in the absorbed moisture.

It was found from the research that all the uni-directional glass fibres (E, R and S2) were affected by residual Dicy after ageing. A level of 1% by weight of unreacted Dicy in the cured matrix was enough to degrade the 0° tensile strength by 30% at room temperature and 42% at 70°C (Figure 2), when the composite had been aged at 45°C and 84% RH. However, the reduction in strength was less when aged at room temperature even though the moisture absorption was greater (1.1% by weight as opposed to 0.95%). The strength in this instance had been degraded 10% less than the equivalent case at 45°C.

The 25% reduction in strength for 0° tension and flexural at the hot/wet site was comparable to that seen in the laboratory, taking into account the temperatures observed during the 10 year natural ageing period.

The research conducted at GKN Westland Helicopters and DRA, Farnborough showed that natural ageing can be simulated by accelerated ageing at 45°C and 84% RH but the temperature can in some instances increase degradation. The results of the natural ageing environments showed that it is no longer valid to use a single degradation factor when designing with composite materials, as the value varies with the material and the mode of applying the load. Generally, fibre dominated and fatigue properties are affected little by hygrothermal ageing but resin dominated properties, such as compression, interlaminar shear and angle ply tension may be reduced by up to 30% (50% at elevated temperatures) when aged at 84% RH.

Rotor Blade Specimens

In conjunction with the programme of work to age coupons in natural environments, outboard Sea King blade specimens were exposed on rigs at Innisfail hot/wet site for the periods of time listed below. Two types of specimen were exposed:

a) Outboard specimens: these were exposed as a centrally supported cantilever beam to which a dead load of 54 lbs was applied at the free end (Figure 3). These specimens were for use as a fatigue test.

b) Root end specimens: these were exposed as a single cantilever beam to which a load 410 lbs was applied at the free end.

Blade sections exposed:

Blade	Exposure	Condition	Removal	Test
WAH 20	4 Years	Natural	Apr 86	A,B,C
WAH18	6 Years	Natural	Jun 87	A,B,C
WAH 19	8 Years	Natural	Mar 90	A
WAH 21	10 Years	Natural	May 91	A
WAH 17	10 Years	Natural	May 91	A
AAM 9878	1 Year	45°C / 84%RH	Apr 87	A,D
WAL 28	5 Years	45°C / 84%RH	Apr 91	A,D
AAR 3739	10 Years	45°C / 84%RH	Jun 96	A,D
WAH 13	Datum			E,F
WAH 12	5 Years	Natural	May 86	E,F
WAH 15	10 Years	Natural	Jun 91	E,F
WAH 14	3 Years	45°C / 84%RH	May 86	E, F
WAH 16	4 Years	45°C / 84%RH	May 87	E,F

A - Outboard Fatigue
B - Trailing Edge Static
C - Trailing Edge Fatigue
D - Root End Static
E - Moisture Profile Slicing (DRA, Farnborough)
F - Interlaminar Shear and Flexural Tests

As with the coupon specimens the blades were exposed with their longitudinal axis parallel to the north/south line. All blade specimens were examined at regular intervals to monitor degradation and rinsed with distilled water. The extent of the damage identified increased with ageing time. July 1987 showed the blades with moderate dirt accumulation with some paint erosion was continuing at a slow rate. No new defects had occurred in the next 12 months. March 1991 was the last detailed inspection before removal of the final 10 year exposure blades. This identified the following features on the remaining blades.

WAH 17 and 21: 50-70% of upper surface had experienced complete paint loss with 60% algae cover. On the lower surface of the blade, bands 150-200 mm wide of algae ran along the length of the blade leading edge.

WAH 15: 60-70% of the upper surface had suffered complete paint loss with glass fibres prominent on the front centre of the blade aft of the erosion shield. The caulking between the erosion shield and trailing edge skin had swollen and cracked due to exposure to the elements. The lower surface of the blade was covered by heavy algae growth.

The actinic degradation described in the blades above far exceeds that which would ever occur in service. Routine maintenance and flight would ensure algae build up would not occur and paint repairs would be conducted when and where necessary.

Artificial Ageing

Additional blade specimens were put into an environment chamber at GKN Westland Helicopters and aged artificially. The conditions used for artificially ageing were those set by Collings (Ref 10) and also adopted by MIL-HDBK-17B and used in the United States (Ref 11). Collings showed after a survey of world climate data that the mean worst relative humidity level found globally was 84% RH. Generally it is the environmental humidity level that determines how much moisture can be absorbed by composites. This level is referred to as the equilibrium moisture content. To accelerate the rate at which moisture is absorbed the temperature can be increased. Collings *et al* (Ref 12) determined that if Fickian diffusion is to be obeyed the maximum temperature for the accelerated ageing of Fibredux 913 is 45°C. (Higher temperature cure systems can be aged at higher temperatures and still maintain Fickian diffusion).

Therefore the environment chamber at GKN Westland Helicopters was operated at 45°C and 84% RH.

The analysis of moisture absorption in the rotor blades conducted by DRA Farnborough correlation between the naturally aged and those aged artificially. Blades WAH 14 which and WAH 12, which had been aged for 3 years artificially and 5 years naturally respectively, had absorbed on average 0.4% moisture at the root end (STN 2.98 inches) and 0.55% moisture at outboard end (STN 65.75 inches). The increase in moisture further outboard is a result of the reduced thickness of the spar sidewall (Figures 4 and 5).

Blades WAH 16 and WAH 15 were aged for 4 years artificially and 10 years naturally. Although some anomalies existed between the moisture absorptions of certain sections generally the moisture absorption in both blades was 0.6% by weight, (slightly greater for naturally aged than artificially). It was noted that sections removed from under the erosion shield contained significantly lower moisture levels. As expected the Titanium shield had acted as a barrier.

The mechanical testing of flexural and interlaminar shear specimens conducted on these blades after ageing and compared to unaged production quality tests (PQT) indicate that there was no significant degradation in the strength of the spar.

Testing of the aged blade outboard fatigue and root end static showed that both natural and artificial ageing had no significant effect when compared to the PQT results of unaged blades. Figure 6 presents the fatigue S-N curve for the plain section spar. The naturally aged spars lie slightly above the curve as opposed to the artificially aged, which are slightly below, but comparable with the PQT results.

The root end static results after 1 year and 5 years ageing at 45°C and 84% RH gave strengths for the blade which were either side of the PQT test mean and within the experimental scatter. All specimens failed in the same mode at the outboard bolt hole.

A further outboard fatigue specimen and static root end specimen are due to be tested in the last quarter of 1996 after ageing at 45°C and 84% RH. This will complete the ageing programme on the Sea King composite main rotor blade.

Simulating Hygrothermal Ageing by Use of Temperature

The use of natural or accelerated ageing for determining the effect of environment on the degradation of a component is both lengthy and time consuming. It would therefore be useful if a quicker but equally valid method could be used to simulate hygrothermal ageing. Collings *et al* (Ref 13) evaluated the use of glass transition temperatures and elevated temperature testing to simulate the effects of hygrothermal ageing. The work was conducted at GKN Westland Helicopters in conjunction with DRA Farnborough, using specimens cured from E-glass reinforced Fibredux 913.

All unaged specimens in this research were tested at; 20, 45, 70, 90 and 110 ± 3°C to investigate the effect of elevated temperatures on the strength and compare them to the effect of hygrothermal ageing on material strength when tested at 20 to 70°C. Specimens which had been subjected to hygrothermal conditioning at 45°C and 84% RH until equilibrium were evaluated at temperatures of: 20, 35, 45, 55 and 70 ± 3°C.

Three different test methods were employed, using 3 specimens for each condition:

a) 0° compression

b) ±45° angle ply tensile

c) Interlaminar shear

The 913 GE5 (Gevetex) material when aged gave a 31°C reduction in Tg. It was postulated and shown that an increase on test temperature equivalent to the change in Tg due to ageing, could be used to represent the degradation due to moisture. Although this technique has its advantages its limitation must also be considered, if it is ever going to be used in the airworthiness certification of composite primary structures.

Advantages

1) Elevated temperature, at least for the lower temperature cure resin systems (120°C), is readily achievable and the time constraint associated with moisture conditioning is removed.

2) The modes of failure, for at least three matrix dependent properties, are truly represented. This is not necessarily the case when the degradation load factor approach, currently in favour for very thick structures is used, as testing at factored loads can overstress a component.

Limitations

1) The effects of real-time fibre surface degradation, such as that seen in some glass/resin combinations, for example the effect of moisture and residual Dicy on glass fibres, is not realized.

2) Shielded structure, such as that masked by metal components through bonded or bolted joints, will be represented as fully degraded. This would not be representative of in-service conditions.

3) In multi-thickness structures, some structure may assume a full degradation through-the-thickness which would not necessarily occur under service conditions. It is possible that temperature gradients through thick structures will exist to some degree, so by default some alleviation of the over-degradation may occur. Clearly a temperature survey of a structure would provide a good monitor of the level of degradation being applied throughout the structure, including through-the-thickness of a very thick structure. A similar type of degradation survey, by estimating moisture content when using moisture conditioning techniques, cannot be assessed so readily. For moisture assessment it is necessary to use either a traveller or to use mathematical modelling.

Chamis *et al* (Ref 14) described an algebraic expression which could be used to predict the effects of moisture and temperature on resin dominated properties of composite materials:

$$\frac{M_w}{M_d} \cong \left(\frac{T_s - T}{T_s - T_o}\right)$$

where: M_w is the wet matrix dominated mechanical property at the test temperature.
M_d is the dry matrix dominated mechanical property at room temperature
T_s is the aged Tg measured by DMTA and determined from the Log E' curve at 10Hz (°K).
T is the test temperature (°K)
T_o is 273K.

The Log E' Tg was used as this was determined to be the most representative of the mechanical performance of the material, as it is derived from the reduction in the modulus of the composite. This expression gave a close correlation between predicted strengths and experimentally measured data. However, a closer correlation may have been achieved if the Tg had been determined by the DMTA being run at 1Hz (aerospace norm) as this produced a slightly lower Tg value.

It could be concluded, therefore, that the resin dominated properties after hygrothermal ageing of angle ply tension, 0 degree compression and interlaminar shear strengths, may be predicted from knowledge of the unaged room temperature strength, and the Tg (determined from Log E') of the material after hygrothermal ageing to equilibrium. This could substantially reduce the time required to determine the effects of hygrothermal ageing on a material, as only a small thin specimen was required for DMTA and would, therefore, reach an equilibrium moisture concentration more quickly than the mechanical evaluation specimens.

The relationship, however, did not give an acceptable prediction for the fibre dominated 0 degree tensile strengths. The predictions were too high at room temperature aged and too low at 70°C aged. This was possibly due to the failure at room temperature when aged being dominated by degradation of the matrix/fibre interface rather than the matrix only. At 70°C aged, although the matrix and the matrix/fibre interface had degraded, the fibres were the dominant factor and could withstand the higher stresses.

Conclusions

The results of this long term ageing programme have shown that the effects of ageing are more complex than was originally envisaged and the external weather conditions will cause fluctuations in the absorbed moisture level.

The use of accelerated ageing at 45°C and 84% RH represented well the effects of hot/wet natural ageing on coupon specimens and main rotor blade components in a reduced period of time.

Matrix dominated properties, compression and interlaminar shear etc. are affected by moisture considerably more than fibre dominated properties. However the effect of other factors such as residual Dicy hardener attacking the glass fibres in hot/wet environments should not be overlooked. Hence the use of a single degradation factor for a material is unsafe and separate values should be used for individual properties

It has been shown that it is possible to predict with some accuracy, particularly for matrix dominated properties, the effect of ageing using elevated temperatures or aged glass transition temperatures.

Generally, for both hot/wet natural ageing and hygrothermal ageing at 45°C and 84% RH, coupon data gave a more pessimistic effect of the ageing on the mechanical properties than was seen on equivalently aged rotor blade components.

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Note. Most of the data reported in this paper has been documented in GKN Westland Helicopters internal reports or in DRA, Farnborough Technical Reports.

Table 1 Environmental Data for Innisfail, Australia - Hot/Wet Site

Year	Temperature (°C)			Mean Relative Humidity (%)	Time above 70% RH (%)	Rainfall	
	Max	Min	Mean			(mm)	Days
1981	35.3	11	22.9	85	81.2	4884	186
1982	36.3	7.8	22	87	83.2	3136.7	183
1983	37	7.3	22.8	85	79.4	2962.7	176
1984	40.8	6.3	22.6	84	78.8	2681	164
1985	36.4	8.5	27.9	86	79.3	3045.5	156
1986	35.4	9.6	23.5	83	71.1	3453.2	167
1987	37.4	12.3	24.7	83	78	2992.5	182
1988	38	12.3	24.2	83	79.8	3269	197
1989	34.9	10.6	23.5	82	77.8	3565	184
1990	37.6	9.7	23.6	80	73.6	3098.5	165
1991	37.2	11.8	23.4	80	74.7	3030	155
MEAN			23.7	83.5	77.9	3283	174

Table 2 Environmental Data for Cloncurry, Australia - Hot/Dry Site

Year	Temperature (°C)			Mean Relative Humidity (%)	Time above 70% RH (%)	Rainfall	
	Max	Min	Mean			(mm)	Days
1981	45	2	27	59	23.8	739.8	58
1982 *	44	5	26.4	67	21.8	350.8	4
1983 *	45	4.8	27.2	49	1.8	319	47
1984	43.8	0.8	25.4	48	17.2	668.5	57
1985	44.8	4.3	26.6	55	34.7	319	44
1986	44.5	4.4	27.1	37	5.4	198.3	36
1987	44.2	4.8	24.9	53	19.1	205.3	38
1988	38.8	6	26.2	49	10.4	218	29
1989	38.4	4.2	24.7	48	20.1	388	42
1990	44.2	2.9	25.5	49	23.3	212.8	36
1991 **	38.7	2.7	22.7	50	21	608	30
MEAN			25.8	51	19.4	395	41

* Incomplete data for these years therefore not included in mean results.
** Data from January to September only.

Table 3 Environmental Data for Yeovil, England - Temperate Site

Year	Temperature (°C)			Rainfall	
	Max	Min	Mean	(mm)	Days
1981	27	-9.3	9.9	728.9	168
1982	27.3	-16.1	10.4	789.6	188
1983	32.1	-7.4	10.6	582.3	169
1984	29.2	5.8	10.3	612.2	175
1985	29.4	-10.7	9.3	633.6	229
1986	30.4	-10	9.2	769.9	267
1987 ***	28.2	-5.9	11.5	494.9	141
1988	27.7	-6.6	102	667.9	183
1989	29.9	-6.9	11.1	741	157
1990	34.9	-5.5	11.1	614.3	176
MEAN			10.2	682.2	190

*** Incomplete records January, February and March data not available therefore not included in mean result.
Note. No humidity data was recorded at this site.

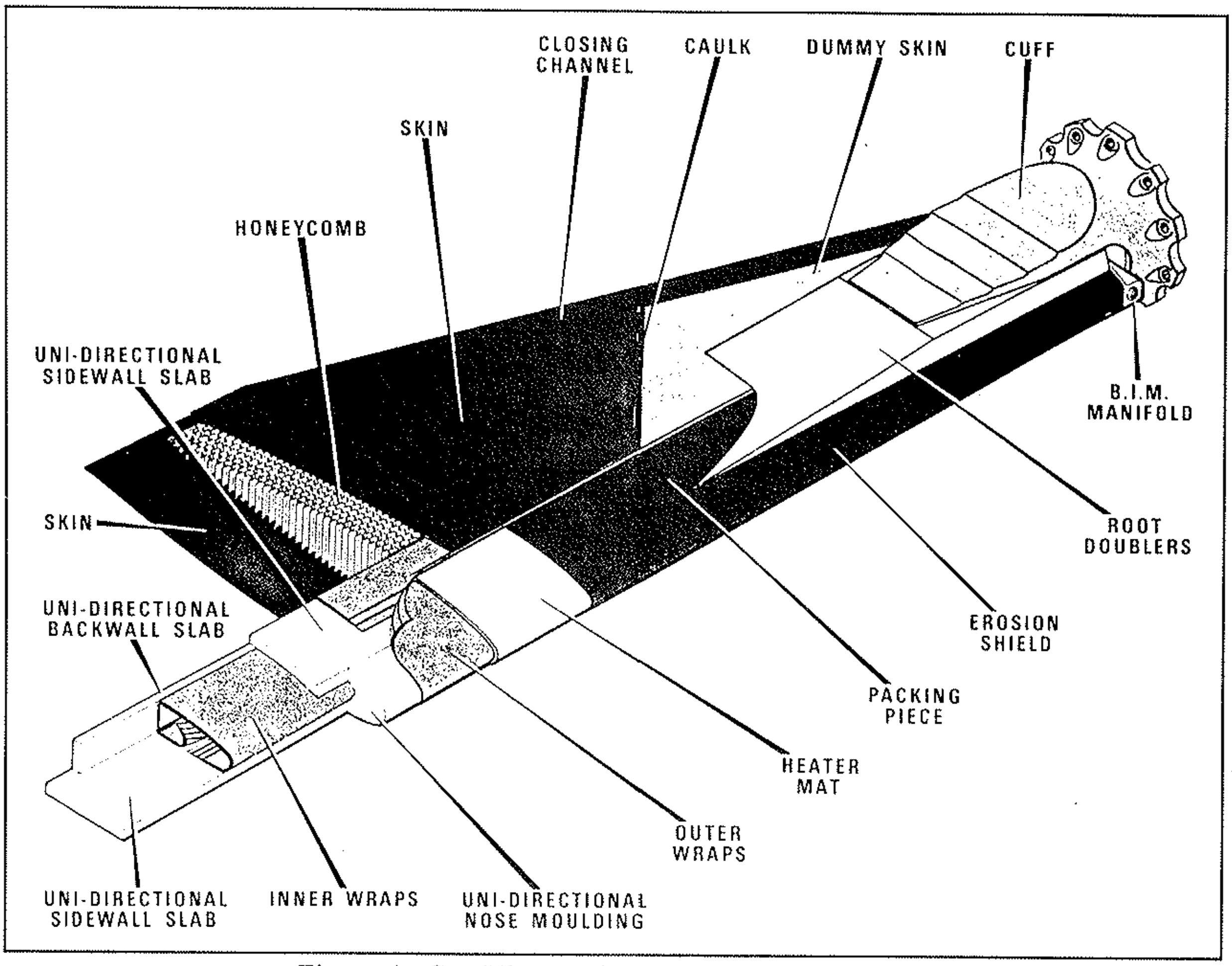

Figure 1 Sea King Main Rotor Blade Root End

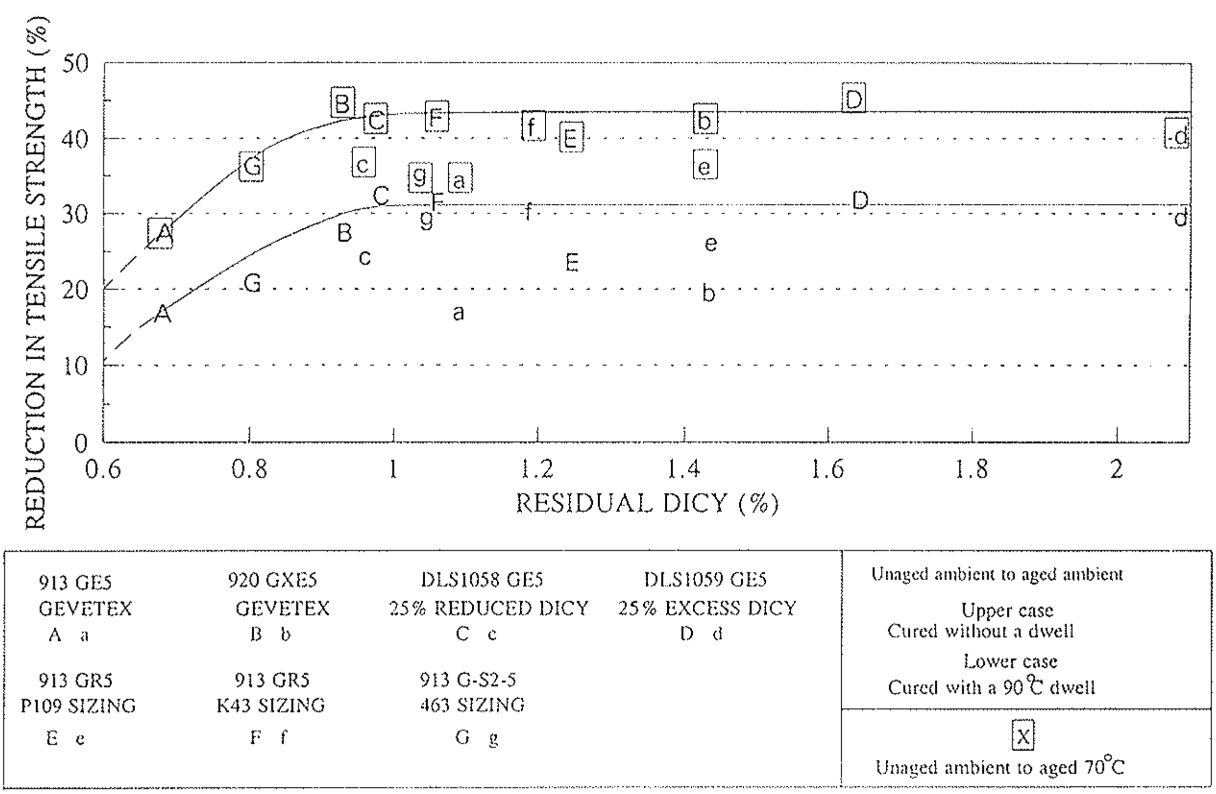

Figure 2 Effect of Residual Dicy on the 0 Degree Tensile Stength of GFRP

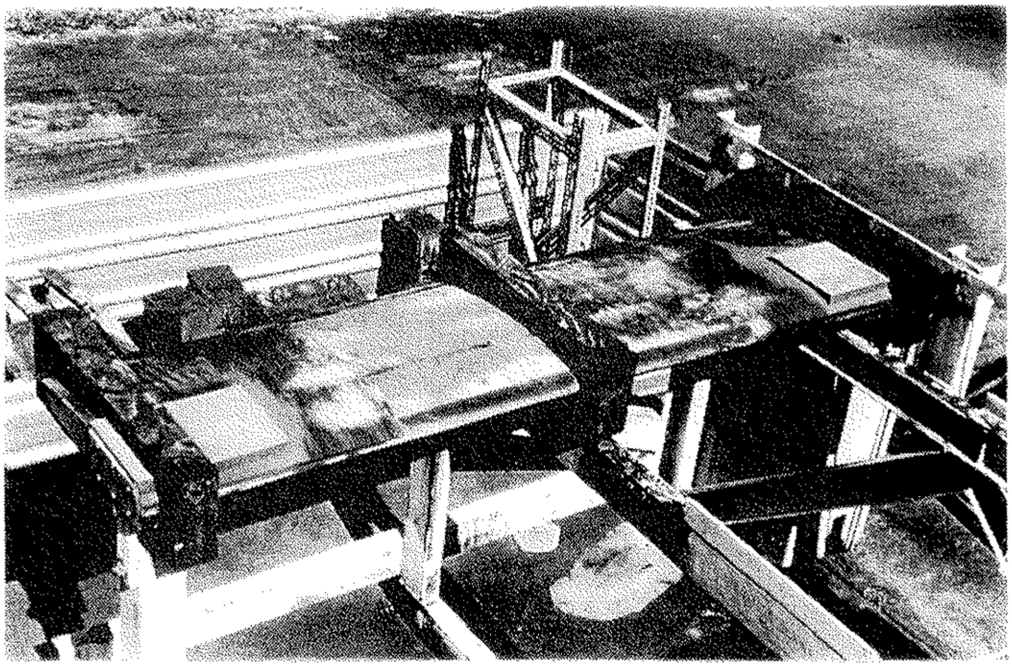

Figure 3 Outboard Sea King Blade on Exposure at Hot/Wet Site, Australia

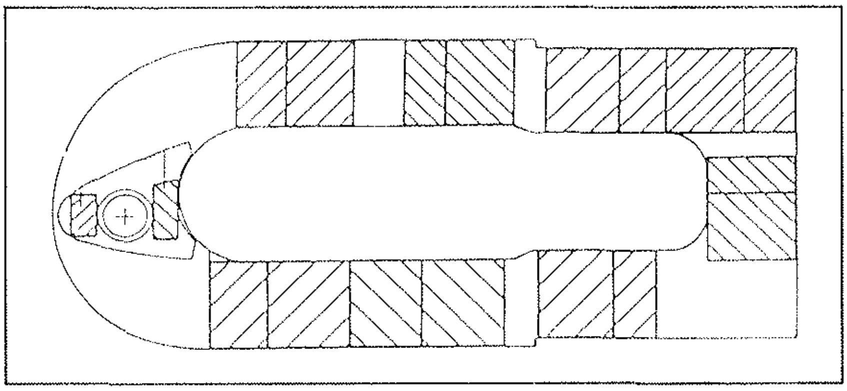

Figure 4 Root End Section of Sea King Spar

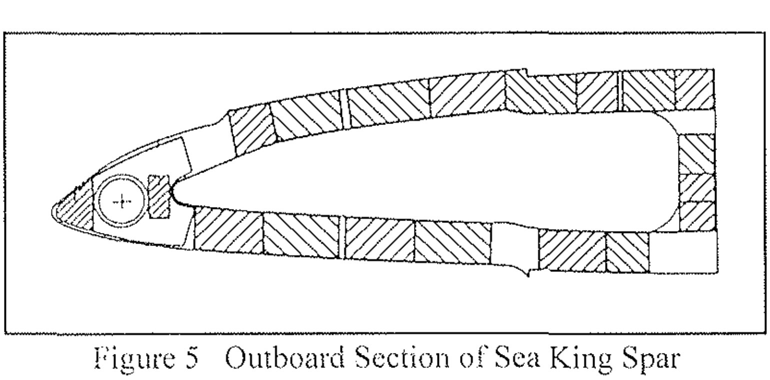

Figure 5 Outboard Section of Sea King Spar

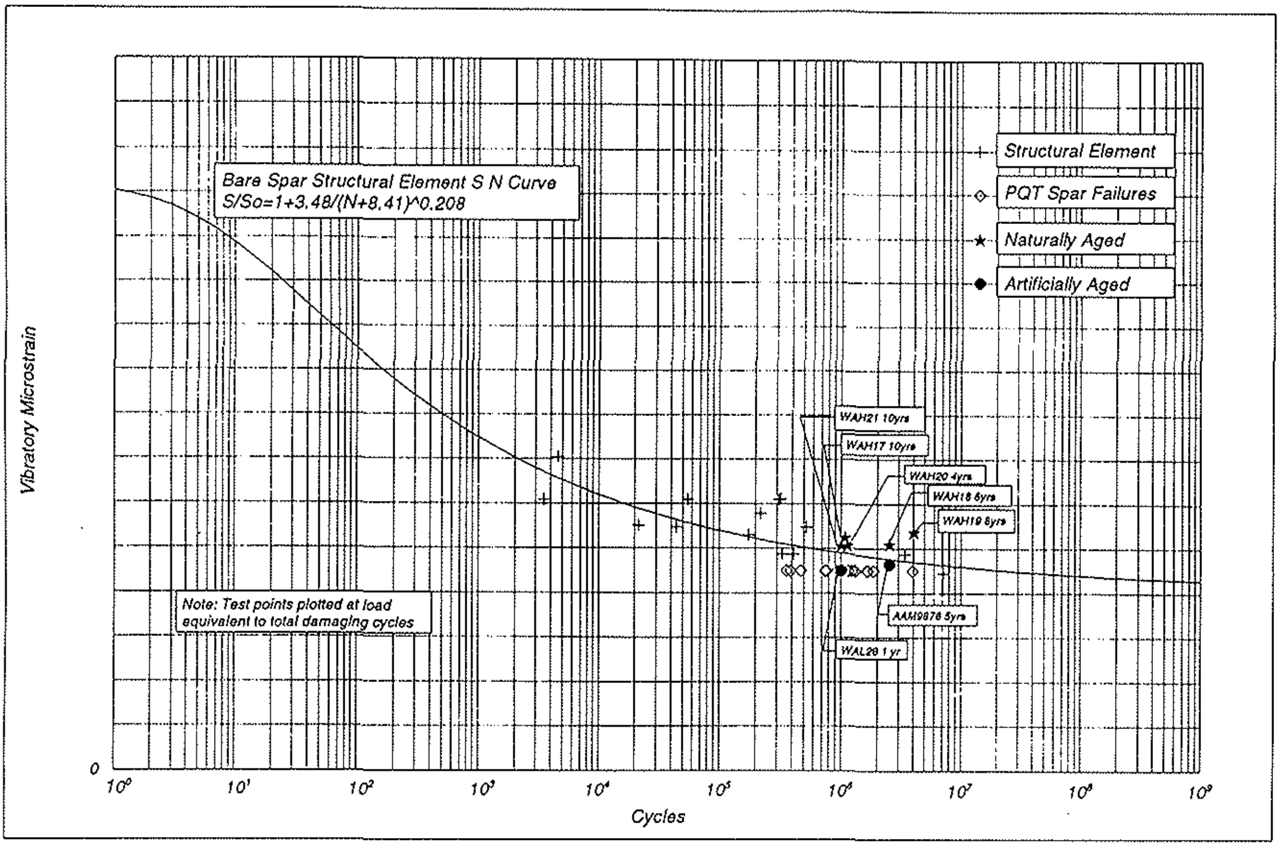

Figure 6 Comparison of Spar Fatigue Strength, Aged and Unaged