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Cyclic Fatigue Testing of Adhesive Joints Environmental Effects

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ABSTRACT

This report examines the combined effect of cyclic loading and environment (i.e. elevated temperature and heat/humidity) on the residual strength of adhesively bonded joints. Double-lap shear, tapered-strap and scarf joint configurations are considered. Residual strength/endurance limit data generated within the programme and obtained from industry have been assessed to determine any synergistic effects that may occur between cyclic loading and environmental agents (i.e. temperature and moisture).

Test data, supplied to the programme by Aerospatiale (courtesy of British Aerospace, Sowerby), from the ABHTA *"Adhesives Bonding for High Temperature Applications"* Brite-Euram Project BE-5104 have been analysed to determine the endurance limit of hot/wet conditioned double-lap joints. This work involved the combined effect of cyclic loading and temperature of moisture pre-conditioned bonded composite and metallic joints bonded with either epoxy FM 350NA or bismaleimide HP655 adhesives. A systematic approach can be used to determine intermediate residual strength or endurance limits, and to estimate knock-down factors for the individual actions or the combined effects of the degrading agents.

The work conducted on tapered-strap and scarf joints attempts to quantify knock-down (or correction) factors for the individual and combined actions of cyclic loading and hot/wet conditioning on joint strength. The results demonstrate that the complexity of determining design parameters to account for the combined effect of two or more degrading factors and there is a need to generate full **S-N** curves for design purposes rather than rely on a specific set of conditions to represent worst case scenarios.

The report was prepared as part of the research undertaken at NPL for the Department of Trade and Industry funded project on "Performance of Adhesive Joints - Combined Loading and Hostile Environments".

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1. INTRODUCTION

Adhesive joints are expected to retain a significant proportion of their load bearing capacity for the entire duration of the service life of the bonded structure. However, service conditions can often involve exposure to combinations of static or cyclic fatigue load and hostile environments. Fatigue damage can be particularly harmful to the structural integrity of bonded joints, shortening the life expectancy of bonded joints by considerable margins, and is known to occur at relatively low stress levels, particularly in the presence of hostile environments.

Designing of adhesive joints for real-life conditions has always proved problematic due to numerous factors that need to be considered:

- Environmental conditions (temperature, humidity)
- Magnitude, nature and frequency of applied loads
- Adhesive and adherend properties
- Joint geometry

Being able to determine reliable knock-down factors to account for the individual effects and interactions of key degrading agents, such as elevated temperature, exposure to hot/wet environments and cyclic loading, would bolster confidence in the use of adhesive technology in aggressive environments.

This report examines general principles that could be used to assess the degree and rate of material degradation due to prolonged exposure to combinations of cyclic stress, elevated temperature and moisture attack. The approach adopted is universal, applying equally to the determination of residual strength or endurance limits. The data examined in this report has either been generated within the programme or obtained from an industrial source.

Durability data, supplied from the ABHTA "*Adhesives Bonding for High Temperature Applications*" Brite-Euram Project BE-5104, have been analysed to determine the endurance limit of hot/wet conditioned double-lap joints. The industrial data supplied by Aerospatiale (courtesy of British Aerospace, Sowerby) is propriety and it is therefore not possible to provide detailed information on surface treatments and processing variables. However, the data is sufficient to demonstrate test data manipulation for life assessment. The half-life strength has been determined as a function of test temperature for both dry and hot/wet conditioned composite and titanium alloy joints.

The research discussed in this report forms part of the Engineering Industries Directorate of the United Kingdom Department of Trade and Industry project on "Performance of Adhesive Joints - Combined Cyclic Loading and Hostile Environments", which aims to develop and validate test methods and environmental conditioning procedures that can be used to measure parameters required for long-term performance predictions. This project is one of three technical projects forming the programme on "Performance of Adhesive Joints - A Programme in Support of Test Methods".

Throughout this report, statements of particular importance or relevance are highlighted in bold type.

2. COMBINED TEMPERATURE AND CYCLIC LOADING

This section presents the results of tensile fatigue tests conducted on double-lap joint specimens, examining the fatigue life (i.e. applied stress, **S**, against number, **Nf**, of cycles to failure) of hot / wet pre-conditioned adhesive joints to cyclic loading under a wide range of temperatures. Test data was supplied to the programme by Aerospatiale (courtesy of British Aerospace, Sowerby), from the ABHTA *"Adhesives Bonding for High Temperature Applications"* Brite-Euram Project BE-5104. Fatigue data was generated using the double-lap shear test configuration shown in Figure 1. The rapid shear fatigue test was used in the Brite-Euram project to define an endurance limit, which is a relationship between stress and mean service life of the bonded joint.

2.1 EXPERIMENTAL DETAIL

Both carbon fibre-reinforced composite and titanium adherend joints were tested at sub-zero, ambient and elevated temperatures. The results from tests conducted on two adhesive systems (epoxy FM 350NA and bismaleimide HP655) are considered in this section. Test data was extracted directly from histogram plots and fatigue curves. It was not possible to obtain the raw data for the fatigue tests.

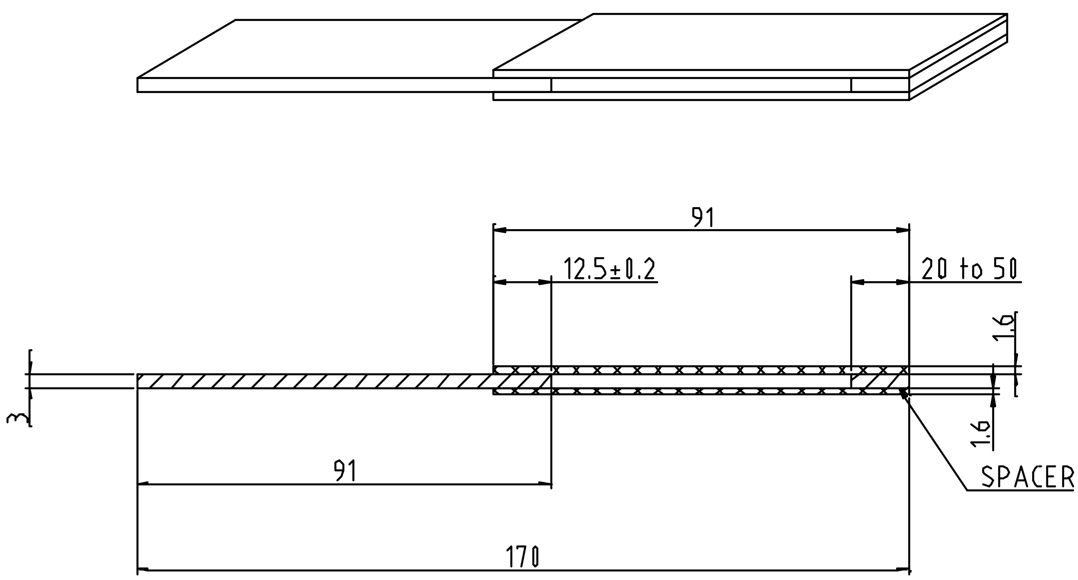

Figure 1 Schematic of fatigue specimen.

The fatigue testing was carried out according to Aerospatiale Inspection General Instruction IGC 04.26.390A, using a sinusoidal tension-tension cyclic loading (2 mm / min) with loads between 39% and 54 % of the failure stress being applied, with 12 specimens needed per curve. There was no evidence of the test frequency having an effect on the endurance limit over the range 1 to 10 Hz. The number of test specimens in the test matrix were reduced using Taguchi methods.

The two adherends considered in the test programme are given below.

- Ti-6Al-4V (titanium) alloy; and
- F6552 / T650-35 carbon fibre-reinforced bismaleimide composite.

The bonded joints were pre-conditioned at 70 ^{o}C and 95% relative humidity (RH) for 750 hours followed by fatigue testing at -55 ^{o}C, 20 ^{o}C (or 37.5 ^{o}C) and 130 ^{o}C. Static shear strength values for the double-lap shear joints are shown in Table 1.

Table 1 Static Shear Test Values (MPa) at 20 ^{o}C

Adherend	FM 350NA	HP655
Titanium	54.0	33
Composite	19.6	20

The glass-transition temperature **Tg** for FM 350NA and HP655 is 183 ^{o}C and 231 ^{o}C, respectively. Dynamic mechanical thermal analysis (DMTA) measurements on hot / wet conditioned FM 350NA adhesive indicated a small reduction in **Tg** of approximately 6 ^{o}C for a moisture uptake of 1.54 wt%. Specimens were conditioned for 168 hours at 70 ^{o}C and 85% RH. The water diffusion coefficient for FM 350NA is relatively low, 4.8 x 10^{-13} m^2s^{-1}at 70 °C.

2.2 EXPERIMENTAL RESULTS

The fatigue stress failure forecast for dry and hot / wet conditioned adhesive joints are presented in Tables 2 to 5. **S-N** curves for unconditioned and hot / wet conditioned titanium / FM 350 NA and titanium / HP655 joints are shown in Figures 2 to 5.

Table 2 Stress Failure Forecast for Titanium/FM 350 NA

Temperature	Number of Cycles		
	5 x 10^3	**10^5**	**10^7**
<u>-55 ^{o}C/218 K</u>			
dry	38.0	25.7	21.0
wet	32.6	22.7	18.0
<u>37.5 ^{o}C/293 K</u>			
dry	28.2	21.6	18.4
wet	23.5	18.0	15.5
<u>130 ^{o}C/403 K</u>			
dry	19.5	16.3	16.1
wet	14.1	13.1	12.4

Table 3 Stress Failure Forecast for Composite/FM 350 NA

Temperature	Number of Cycles		
	5 x 10^3	10^5	10^6
-55 °C/218 K			
dry	13.7	11.3	10.6
wet	11.6	10.0	8.9
20 °C/293 K			
dry	13.1	9.6	8.2
wet	8.8	7.2	6.7
130 °C/403 K			
dry	7.3	5.3	4.6
wet	5.3	4.4	4.1

Table 4 Stress Failure Forecast for Titanium/HP655

Temperature	Number of Cycles		
	5 x 10^3	10^5	10^7
-55 °C/218 K			
dry	21.6	14.9	10.6
wet	15.7	11.5	6.9
37.5 °C/293 K			
dry	19.8	15.3	12.4
wet	14.4	12.4	11.0
130 °C/403 K			
dry	17.6	16.1	15.7
wet	12.2	12.5	12.2

Table 5 Stress Failure Forecast for Composite/HP655

Temperature	Number of Cycles		
	5 x 10^3	10^5	10^6
-55 °C/218 K			
dry	15.4	13.5	12.5
wet	13.0	12.2	11.9
20 °C/293 K			
dry	14.9	11.6	10.5
wet	12.9	9.4	7.5
130 °C/403 K			
dry	14.4	9.7	8.5
wet	11.9	8.2	6.6

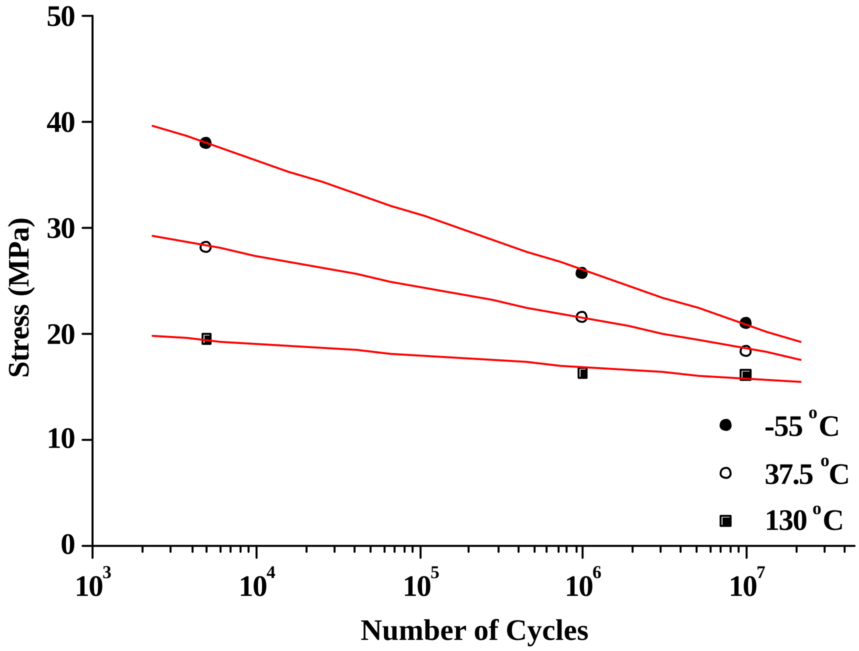

Figure 2 **S-N** data for unconditioned (dry) titanium / FM 350NA joints.

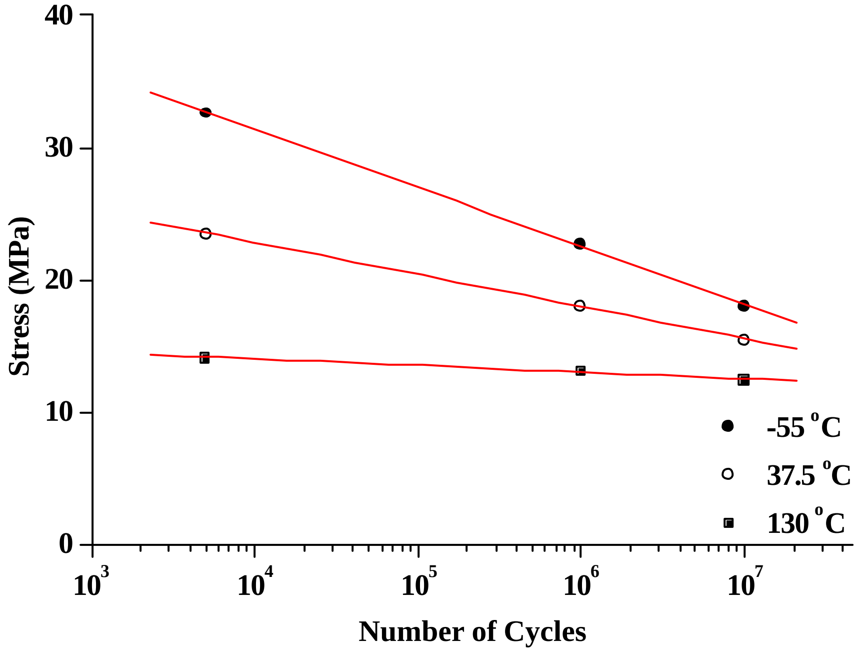

Figure 3 **S-N** data for hot / wet conditioned titanium / FM 350NA joints.

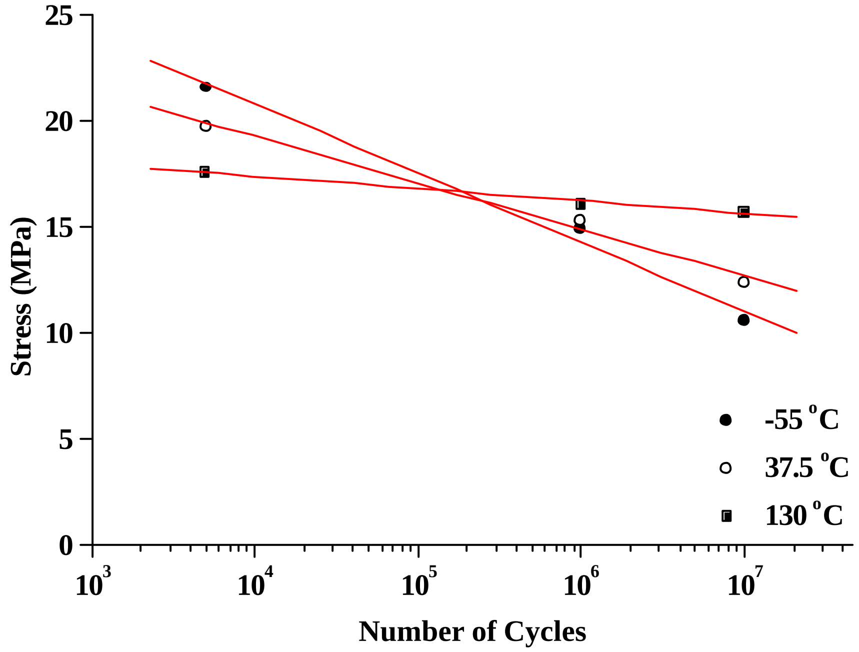

Figure 4 **S-N** data for unconditioned titanium / HP655 joints.

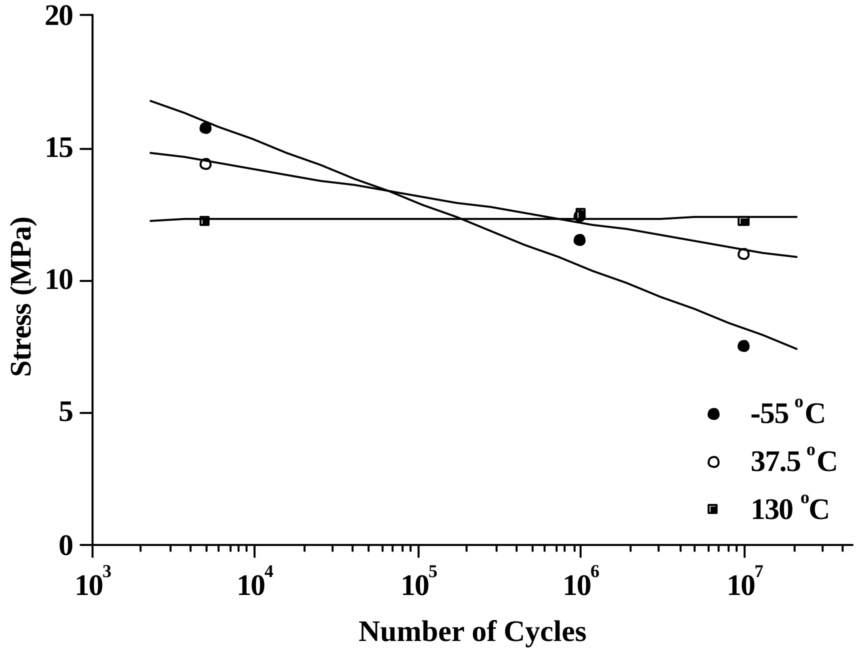

Figure 5 **S-N** data for hot / wet conditioned titanium / HP655 joints.

For inter-comparative purposes, fatigue strength data are normalised with respect to the ultimate static strength P_O of identically conditioned specimens measured at the fatigue test loading rate. The scatter associated with fatigue testing is generally large.

Normalised **S-N** curves can be approximated by a straight line fit as follows:

$$P_{MAX} / P_O = 1 - k \log Nf \quad (1)$$

where **k** is the slope and $\mathbf{P_{MAX}}$ is the maximum load applied to the specimen. The **k** values for all the fatigue data presented in Tables 2 to 5 are shown in Table 6.

Table 6 Estimated k Values for Fatigue Tests

System/Condition	Temperature (°C)		
	-55	20	130
Titanium/FM 350NA			
dry	0.091	0.075	0.047
wet	0.088	0.074	0.031
Titanium/HP655			
dry	0.099	0.078	0.030
wet	0.096	0.055	0.002
Composite/FM 350NA			
dry	0.078	0.104	0.103
wet	0.074	0.077	0.072
Composite/HP655			
dry	0.063	0.089	0.110
wet	0.033	0.110	0.115

Key Observations

- The ambient value of **k** ranges from 0.075 to 0.104 for unconditioned (i.e. dry) joint specimens, which is similar to the values obtained for cyclic fatigue tests on single-lap and tapered-lap joint specimens (see NPL Report CMMT(A) 191 [1]).

Titanium adherends

- **k** decreases with increasing test temperature for wet and dry joints.
- **k** is lower for wet joints.

Composite adherends

- **k** increases with increasing test temperature for dry joints.
- **k** is approximately constant with increasing temperature for wet joints.

The reduction in **k** with increasing temperature for the unconditioned bonded titanium/FM350NA joints parallels the reduction in bulk tensile properties for FM 350NA adhesive (see Table 7). This may be further evidence that changes in the tensile properties of the adhesive due to environmental factors are directly reflected in the static and fatigue performance of the bonded joints. This is understandable since high peel stresses at the ends of the overlap govern static and fatigue performance for this particular joint configuration (see NPL Reports CMMT(A) 191, 196 and 197 [1-3]).

Table 7 Bulk Tensile Properties and k Values for Unconditioned FM 350NA

System/Property	Temperature (°C)		
	-55	20	130
Titanium/FM 350NA **k**	0.091	0.075	0.047
Bulk FM 350NA **Tensile Modulus (GPa)** **Tensile Strength (MPa)**	7.54 94	6.32 76	3.99 54

2.3 DATA MANIPULATION

The results presented in the Section 2.2 show no distinct pattern. However, a pattern begins to emerge when the data is presented in terms of stress versus temperature for different endurance limits (i.e. **Nf**); as shown in Figure 6. The stress/temperature curves for dry and hot/wet conditioned titanium/FM 350NA joints are linear and virtually parallel with the rate of stress reduction with respect to temperature (i.e. slope) decreasing with increasing number of cycles (i.e. endurance limits).

Stress/temperature curves can be approximated by a straight line fit as follows:

$$P_{MAX} / P_O = 1 - k \log T \qquad (2)$$

where **k** is the slope, **T** is the temperature (K), $\mathbf{P_{MAX}}$ is the maximum (stress) applied to the specimen and $\mathbf{P_O}$ is the projected failure stress of the joint at absolute zero. The **k** and $\mathbf{P_O}$ values for the titanium/FM 350NA and composite/FM 350NA fatigue data is presented in Tables 8 and 9.

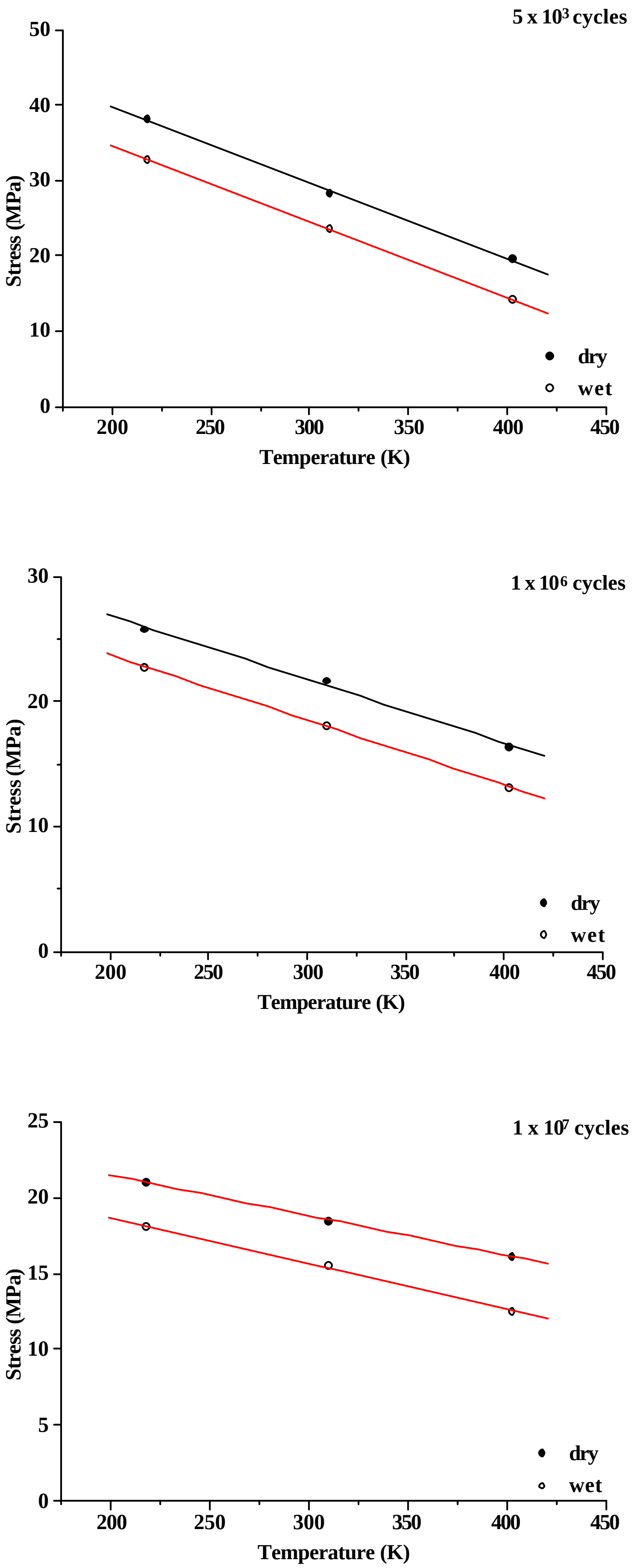

Figure 6 Stress versus temperature for titanium / FM 350NA joints.

Table 8 Estimated k and Po (MPa) Values for Stress-Temperature Data Titanium/FM 350NA Joints

System/Condition	Number of Cycles		
	5×10^3	**1×10^6**	**1×10^7**
Dry Titanium/FM 350NA			
k	0.100	0.051	0.027
P_O	59.62	36.98	24.72
Wet Titanium/FM 350NA			
k	0.100	0.052	0.030
P_O	54.45	34.05	24.70

Table 9 Estimated k and P_O (MPa) Values for Stress-Temperature Data Composite/FM 350NA Joints

System/Condition	Number of Cycles		
	5×10^3	**1×10^5**	**1×10^6**
Dry Composite/FM 350NA			
k	0.036	0.032	0.032
P_O	22.32	18.76	17.69
Wet Composite/FM 350NA			
k	0.033	0.030	0.026
P_O	18.89	16.32	14.42

The stress / temperature curves for dry and hot / wet conditioned composite / HP655 joints are also approximately linear and parallel. This particular trend is not evident from the fatigue data for the titanium / HP655 joints.

2.4 DISCUSSION

The analysis carried out on the Aerospatiale data indicates that intermediate residual strengths and endurance limits can be determined for bonded joints, and it is possible to account for the individual actions of hot/wet conditioning, cyclic loading and testing at elevated temperature. Knock-down (or correction) factors to account for these effectss can be estimated using similar analysis presented in Sections 2.3 and 2.4. The endurance limit for the strength of the joint to decrease to a given percentage of the ambient static strength can be read directly from the plots of the relative property value (%) against number of cycles for the various test temperatures. Alternatively, endurance limits can be calculated from fitted equations, such as Equations (1) and (2).

3. TAPERED-STRAP JOINT

This section examines the combined effect of cyclic loading and hot/wet exposure on the residual strength of a tapered-strap joint (Figures 7 and 8) with external tapered (bevelled) straps (see also [1]). An attempt is made to determine the synergism between the degrading factors and possible extrapolation to design.

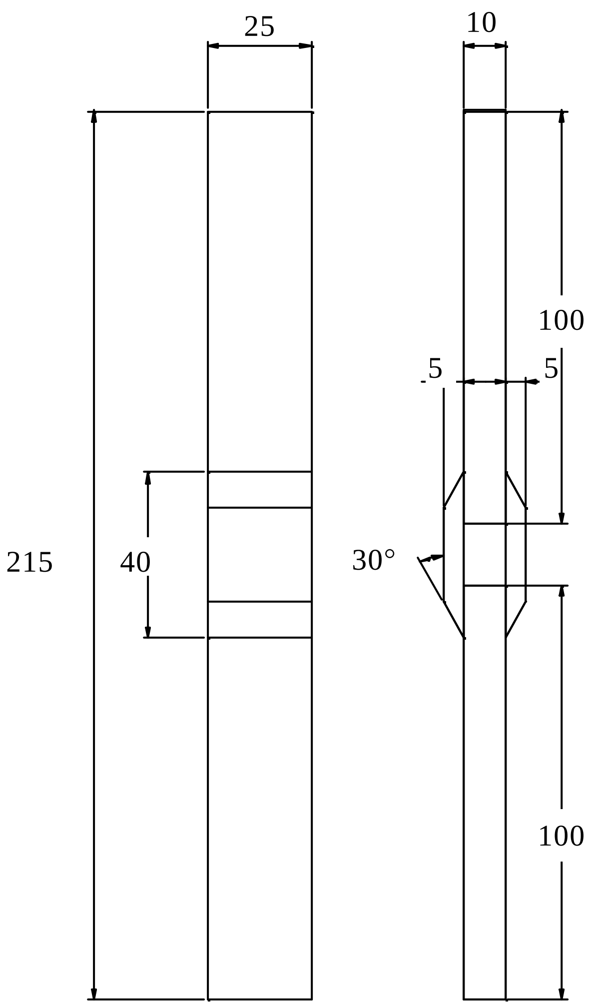

Figure 7 Schematic of tapered-strap joint (dimensions in mm).

3.1 SPECIMEN GEOMETRY AND PREPARATION

The residual strength was measured for 5251 aluminium alloy specimens (Figures 1 and 2) bonded with AF126-2 epoxy film adhesive (supplied by 3M, UK). The adhesive contains a carrier fabric for bondline thickness control. Specimens were clamped in a special bonding jig and then heated to 120 ^{o}C for 90 minutes. Prior to bonding, the surfaces of the aluminium alloy sections to be bonded were chromic acid etched.

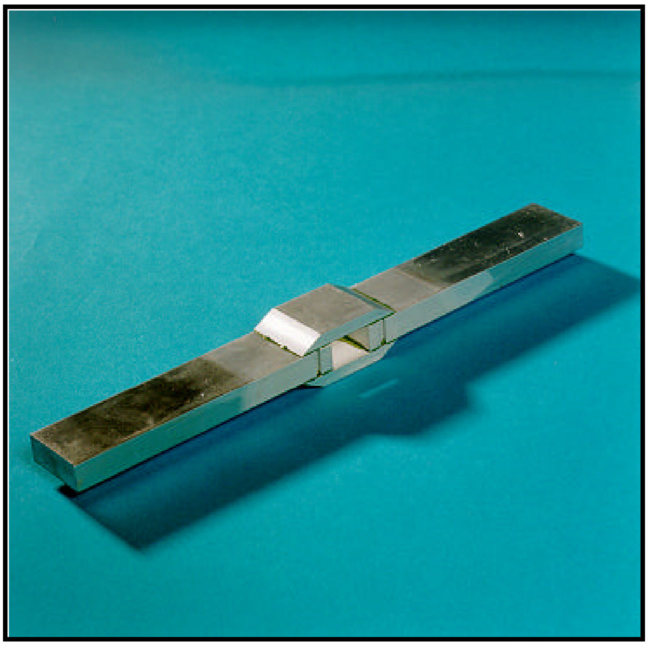

Figure 8 A 5251 aluminium alloy / AF126-2 tapered-strap joint.

A description of the surface pre-treatment technique employed is described below.

Stage 1 - Grit Blast + Degrease: The adherends were first degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina to produce an uniform matt finish. A pressure of 85 psi was used for grit-blasting the areas to be bonded. Any dust remaining after grit blasting was removed with clean compressed air. The surfaces to be bonded were then degreased again with 1,1,1-trichloroethane and dried. Specimens were bonded within 1 hour of pretreatment.

Stage 2 - Chromic Acid Etch: The grit blasted / degreased specimens were then immersed for 30 minutes in a chromic acid etch solution at a temperature of 60-70 ^{o}C. The specimens were removed from the etch solution and washed in cold tap water and then hot tap water. Finally, the specimens were rinsed with acetone and allowed to dry in a fan oven for a few minutes at 120 ^{o}C. Specimens were inverted to enable the water to drain from the areas to be bonded. The etch solution consisted of 500 ml of distilled water with 75 ml of sulphuric acid (H_2SO_4) and 37.5 gm of sodium dichromate ($Na_2Cr_2O_7.2H_2O$).

3.2 TEST CONDITIONS

Unconditioned and conditioned tapered-strap specimens were tested under ambient conditions (i.e. 23 °C, 50 % relative humidity (RH)) in accordance with BS EN 1465 [4]. The four conditions considered are listed below:

(a) Unconditioned (3 days at 23 °C, 50 RH);
(b) Conditioned at 70 °C, 85 % RH for 1,000 hours (6 weeks);
(c) Cyclic loaded for 100,000 cycles at 50 % of static joint strength; and
(d) (b) + (c)

Following conditioning, the specimens were loaded in tension to failure. An Instron 8501 servo-hydraulic test frame was used to load the specimens. The specimens were held by a pair of well aligned servo-hydraulic operated wedge-action grips with a lateral pressure of 100 psi. Instron Series IX software was used to control the test machine and to collect the test data. Five specimens per condition were tested.

3.2.1 Environmental Conditioning

Environmentally conditioned test specimens were exposed to 70 °C and 85% RH for 1,000 hours. This particular environmental conditioning regime is commonly used within the aerospace/defence industry to obtain knock-down factors for design purposes. Conditioning was undertaken using a Climatic System environmental chamber. The temperature and humidity were controlled to within ±2 °C and ± 5% RH, respectively. **Humidity control (% RH) can also be achieved at various temperatures by saturated solutions of salts and salt mixtures [3].**

3.2.2 Cyclic Loading

Specimens were subjected to constant amplitude (sinusoidal waveform) tension-tension cyclic fatigue loading for 100, 000 cycles. The test frequency was 5 Hz. Constant amplitude fatigue tests were carried out in load control using an Instron 8501 servo-hydraulic test machine. The stress ratio **R** was equal to 0.1. The maximum load was 50% of the ultimate tensile shear strength of the joint. This conditioning regime is being used in the aerospace industry to determine safety factors for design of bonded and bolted structures under worst case scenarios. All fatigue loading was carried out under standard laboratory conditions to BS EN ISO 9664 [5]. Instron MAX software was used to control the servo-hydraulic test machine and to collect the test data.

3.3 TEST RESULTS AND DISCUSSION

The results of the tensile tests, presented in Table 10, clearly show distinct reductions in the tensile shear strength of the bonded joints due to environmental exposure. For this adherend/adhesive system, there is insufficient evidence (see Table 1) to conclude if a synergistic effect exists between the cyclic loading and environmental exposure. There was no evidence of material degradation (stiffness or strength) due to cyclic loading at 50% of the ultimate static strength for 10^5 cycles (see also [1]). In fact, previous results have shown that damage induced degradation of joint stiffness only becomes evident in the last 1% or less of the life of bonded joints [1]. Damage onset is sudden and catastrophic.

For pre-conditioned specimens, cyclic fatigue loading may have alleviated stresses at the ends of the overlap. It is more probable, however, that the conditioned specimens dried out during the period of pre-fatiguing. This is understandable considering the relative insensitivity of the mechanical properties of the cured adhesive to moisture and the fact that the bonded joint failed in a cohesive manner through the adhesive. Although the glass-transition temperature **Tg** of AF126-2 decreases with increasing moisture content [3], the tensile modulus and tensile strength remain relatively constant for moisture gains up to 2.63% of the total weight of the sample. The results imply that for this particular combination of adherend/adhesive system and surface treatment, moisture effects are partially reversible.

Table 10 Residual Strength of Tapered-Strap Joints

Pre-Conditioning	Residual Strength (MPa)
a) Unconditioned	28.8 ± 1.1
b) 70 °C, 85% RH (1,000 hrs)	14.2 ± 2.7
c) Pre-fatigued for 100,000 cycles	30.7 ± 2.6
d) (b) + (c)	20.5 ± 1.4

4. SCARF JOINT

Tensile tests were also carried out to determine the combined effect of cyclic loading and water immersion at elevated temperatures on the residual strength of on simple scarf joint specimens with a 30° taper angle (Figure 9) [1].

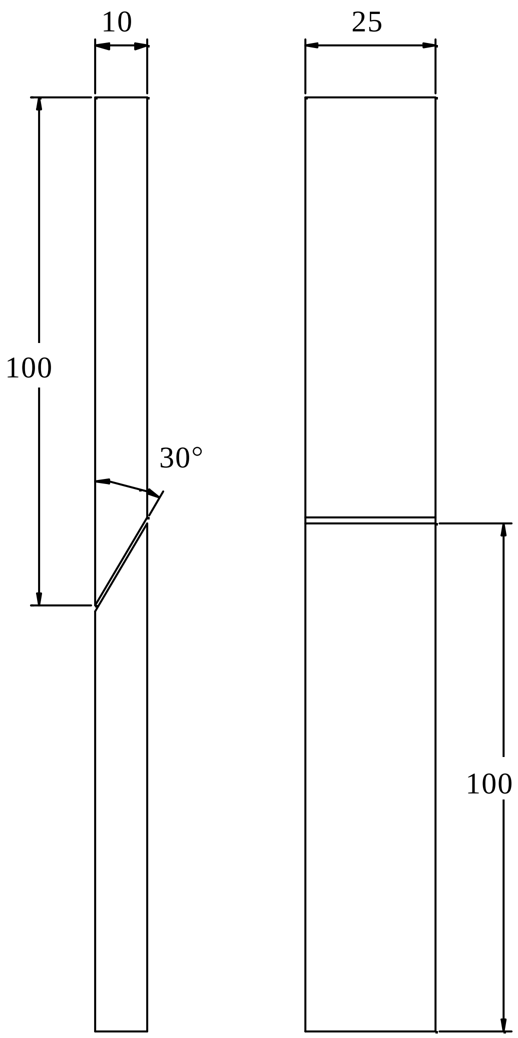

Figure 9 Schematic of scarf joint with taper angle of 30°.

4.1 SPECIMEN PREPARATION AND TESTING

Tests were conducted on unconditioned and conditioned 5251 aluminium alloy scarf joints bonded with AV119 (Araldite 2007®), a one part epoxy adhesive supplied by Ciba Speciality Chemicals. Prior to bonding, the adherends were degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina. A pressure of 85 psi was

used to grit-blast the bonded areas. The surfaces to be bonded were then degreased again with 1,1,1-trichloroethane.
The bondline thickness (0.25 mm) was controlled using 250 μm ballontini glass spheres. A small quantity of the glass spheres, 1% by weight, was mixed into the adhesive. Specimens were clamped in a special bonding jig [3] and then heated to 140°C for 75 minutes to cure the adhesive.

Tensile testing was essentially identical to that employed for the tapered-strap joints. The failure stress (Table 11) corresponds to the maximum applied load divided by the cross-sectional area of the specimen. The number of tests were generally limited to 2 or 3 per condition.

The four conditions considered are listed below:

(a) Unconditioned (3 days at 23 °C, 50 RH);
(b) Immersed in water at 60 °C for 168 hours (1 week);
(c) Cyclic loaded for 100,000 cycles at 50 % of static joint strength; and
(d) (b) + (c)

4.2 TEST RESULTS AND DISCUSSION

Tests results(Table 11) show that there is a synergism between cyclic loading and moisture for this particular adherend/adhesive system and surface treatment. The product of the individual knock-down factors is 0.60 (water immersion (0.73) x pre-fatiguing (0.82)). Using this knock-down factor it is estimated that the combined effect of cyclic fatigue and moisture degradation should result in a failure stress of 68 MPa. The actual failure stress measured was approximately 76 MPa. It is evident that moisture degradation had a far greater effect on the strength of the scarf joints. There may have also been a loss of moisture from the hot/wet conditioned specimens during the pre-fatiguing stage, thus resulting in an increase in joint strength.

Table 11 Residual Strength of Conditioned Scarf Joints

Pre-Conditioning	Residual Strength (MPa)	Failure Mode
a) Unconditioned	113 ± 5	cohesive
b) Water immersion at 60 °C (168 hrs)	82.6 ± 5.1	cohesive/interfacial
c) Pre-fatigued for 100,000 cycles	93.1 ± 2.9	cohesive
d) (b) + (c)	76.1	cohesive/interfacial

5. CONCLUDING REMARKS AND DISCUSSION

The results demonstrate the complexity of predicting fatigue performance due to the wide differences in the chemical and physical behaviour of adhesives to temperature and moisture, and also the role the interface in joint behaviour. However, a systematic approach similar to the procedure shown in Section 2 can be used to determine intermediate residual strength or endurance limits, and to estimate knock-down factors for the individual actions or the combined effects of the degrading agents. It is advisable to generate full **S-N** curves for design purposes rather than rely on a specific set of conditions to represent worst case scenarios.

A number of conclusions can be made in respect to the results obtained from combined environmental exposure and cyclic loading of adhesive joints.

- Fatigue resistance is dependent on joint geometry and test temperature, and on the effect of moisture on the mechanical properties of the adhesive and adherend and the interfacial bond between adhesive and adherend**.**

- **Joint stiffness remains constant throughout almost the entire life-time of the joint with the onset of failure marked by a rapid reduction in joint stiffness and an increase in the loss or damping factor (tan** d**)**. It is therefore difficult to estimate the remaining life of a bonded joint under cyclic loading conditions.
- Normalised **S-N** curves can be approximated by a straight line fit as follows:

  $$P_{MAX} / P_O = 1 - k \log Nf$$

  where **k** is the slope, **Nf** is the number of cycles to failure, **Pmax** is the maximum load applied to the specimen, $\mathbf{P_O}$ is the ultimate strength of identically conditioned specimens measured at the fatigue test loading rate.

- The above relationship can be applied to both dry and hot/wet conditioned joints tested over a wide range of temperatures. The value of **k** is dependent on the joint geometry, test temperature and the degree of moisture degradation. At ambient and sub-zero temperatures, **k** is approximately 0.08 to 0.10 for those joints (e.g. single-lap, double-lap and tapered-strap joints) where behaviour is governed by peel stress concentrations at the ends of the bonded regions. A reduction in peel stresses results in improved fatigue performance. Joint strength and thus fatigue performance tends to increase with a reduction in temperature. At elevated temperatures, **k** is reduced. However, the static strength of the joint is also reduced.

- The fatigue response of most joints bonded with structural adhesives is essentially independent of test frequency over the range 1 to 25 Hz. Although this frequency range is preferred for accelerated testing it does not necessary reflect actual service conditions. Experimental results obtained from tests conducted on glass fibre-reinforced laminates have shown that for strain-rate dependent materials the fatigue performance is **not** frequency dependent.

ACKNOWLEDGEMENTS

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