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**Creep Testing of Adhesive Joints
Analysis of Creep Rupture Data**

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ABSTRACT

This report examines the combined effect of constant applied load and environmental exposure (i.e. elevated temperature and heat/humidity) on the time-to-failure of adhesively bonded joints. T-peel, thick adherend shear, perforated single-lap and tapered-strap 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 static loading and environmental agents (i.e. temperature and moisture).

Durability data, supplied to the programme by Daimler Benz Forschung und Technik (courtesy of British Aerospace, Sowerby), from the ABHTA "*Adhesives Bonding for High Temperature Applications*" Brite-Euram Project BE-5104 have been analysed. This work involved the combined effect of mechanical loading and elevated temperature titanium alloy joints bonded with either epoxy FM 350NA or bismaleimide HP655 adhesives. In addition, durability data generated from Project 3 "The Environmental Durability of Adhesive Bonds" of the DTI funded MTS programme ADH were also examined. Data generated within the project. The results of work conducted within the programme on tapered-strap and T-peel joints were also analysed.

The report demonstrates that a systematic approach, albeit empirical, can be used to determine the time-to-failure for different combinations of test variables on different adherend/adhesive/surface treatment combinations. Simple relationships can be used for interpolation purposes to determine failure times for intermediate stress levels. The large uncertainty associated with creep test results, especially those obtained under hot/wet conditions, requires considerably more data points than currently being used to generate full creep rupture curves for design purposes.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head of Centre for Materials Measurement and Technology.

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1. INTRODUCTION

The natural process of moisture absorption in bonded structures is normally very slow, and this makes it very difficult to reach an adequate degree of degradation in a structural test element in practical time-scales. To evaluate the durability of adhesive joints it has been found necessary, therefore, to speed up the moisture diffusion process by employing accelerated conditioning techniques with the intention of ensuring a representative level of degradation in a significantly reduced time. A number of approaches have been employed in an attempt to achieve this objective (i.e. elevated temperature and humidity and the use of perforated joints) [1-5] and to extrapolate the data from short-term tests to long-term performance [6]. It is worth noting that reliable durability data can only be obtained by conducting long-term tests that actually duplicate service conditions.

Accelerated testing often involves adhesive joints being subjected to the combined effect of constant mechanical load and environmental exposure. The extent of creep damage and its importance is dependent primarily on the stress level at which irreversible damage occurs relative to the stress for complete failure (i.e. ultimate static strength). The degradation process is exacerbated under hot/wet conditions with the rate of degradation increasing with increasing temperature, humidity and mechanical stress. Mechanical acceleration methods tend to use stress levels that are significantly higher than stress level limits used in design, thus the limiting design strains are reached in shorter times than in actual service. Two approaches have been adopted for assessing the degree of degradation under combined static load and environment:

Rate of strength loss with time (i.e. residual strength): This approach determines the time taken for the strength of the joint to decline to a design stress limit, below which the joint is no longer considered safe.

Time-to-failure: This approach attempts to determine the probable average life expectancy of a bonded joint at a prescribed stress level or to determine the percentage of failures that can be expected to occur within a given exposure period. A major disadvantage with this approach is the large variation associated with time-to-failure measurements.

This report will concentrate mainly on the second approach using data sourced from industry and data generated within the ADH and the PAJ programmes. **Throughout this report, statements of particular importance or relevance are highlighted in bold type.** The report consists of six sections including the introduction (Section 1). Creep results for tapered-strap and T-peel joints are examined in Sections 2 and 3, respectively. Section 4 evaluates data obtained using the perforated stress humidity test configuration (i.e. single-lap joint). The test data were obtained from Project ADH3 Report Number 8 “Experimental Assessment of Durability Test Methods” [7] as part of research work for the DTI funded Adhesives Programme. Creep data supplied by Daimler Benz Forschung und Technik (courtesy of British Aerospace, Sowerby) are evaluated in Section 5. The data are from ABHTA “Adhesive Bonding for High Temperature Applications” Brite-Euram Project BE-5104 [8]. Concluding remarks and discussion are presented in Section 6.

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”.

2. ROOM TEMPERATURE

This section examines the time-to-failure (t_f) of tapered-strap joints subjected to constant mechanical load. Testing was conducted under ambient conditions (i.e. 23 °C, 50% relative humidity (RH)). The test geometry used in the study is shown in Figures 1 and 2 (see also [9]). Tapering the bridging adherends (i.e. straps), minimises peel stresses, increases bond efficiency (i.e. strength) and alters the failure mode from peel to shear. It has been purported that the peel stresses virtually disappear when using 30° fillets [10-11]. This is not strictly correct, finite element analysis (FEA) carried out at the National Physical Laboratory (NPL) has shown that both peel and shear stress concentrations are still present at the ends of the overlap [9]. The FEA also showed that the dimensions of the gap between the inner adherends had a marginal effect on the stress and strain distributions along the bondline and therefore could be omitted. The introduction of the gap was to allow for certain types of extensometers, which can be difficult to attach to the specimen, to be inserted within the central gap to monitor shear deformation. Experimental results have shown that the tapered-strap joint is potentially suitable for determining shear behaviour under monotonic and cyclic loading conditions [9].

2.1 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. The adherends were bonded whilst held securely in a clamping fixture to ensure accurate alignment of the adherends. **A 15 mm thick strip of polytetrafluoroethylene (PTFE) was inserted in the gap between the adherends after the application of the adhesive and prior to curing.** These spacers were removed after the adhesive was cured. The cure cycle was 120 °C for 90 minutes.

The inner and bridging (i.e. straps) adherends were milled to the required dimensions from 10 mm and 5 mm thick 5251 aluminium alloy plate, respectively. Horizontal notches (1.5 mm wide and 1.5 mm deep) were machined in the central adherends, 5 mm either side of the central gap. The adherends were surface treated (chromic acid etch) and then adhesively bonded within one hour of pretreatment.

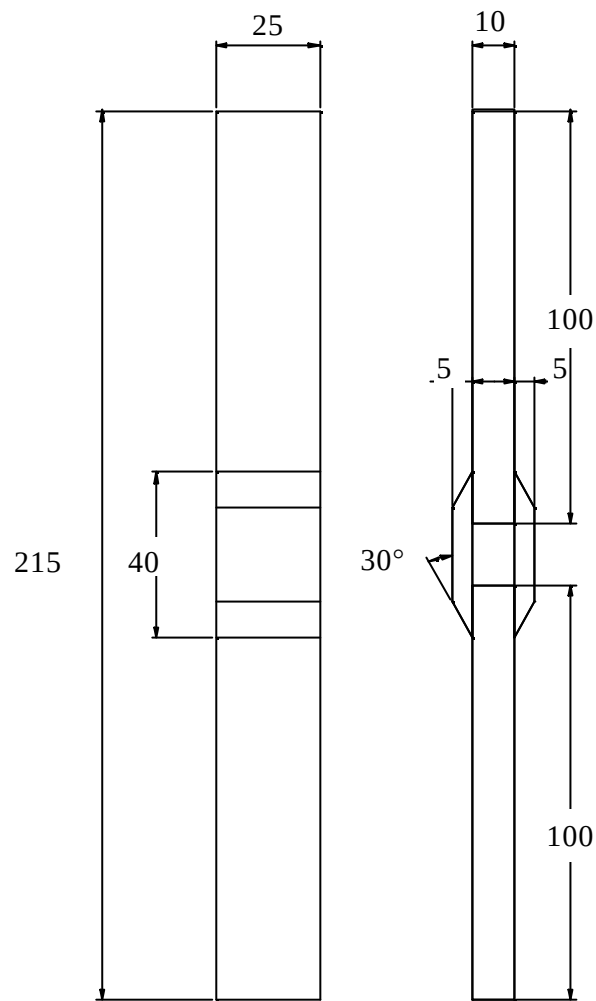


Figure 1 Schematic of tapered-strap joint (dimensions in mm).

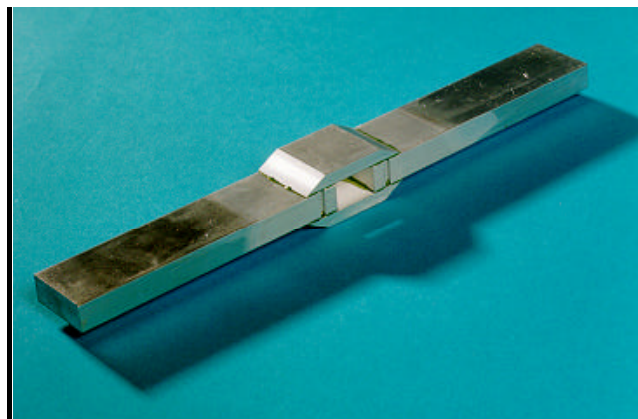


Figure 2 A 5251 aluminium alloy / AF126-2 tapered-strap joint.

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. **For reasons of health and safety, 1,1,1 trichloroethane is not recommended as degreasing agent.**

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 °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 °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 (H₂SO₄) and 37.5 gm of sodium dichromate (Na₂Cr₂O₇·2H₂O).

2.2 EXPERIMENTAL RESULTS

Tensile creep tests were conducted on tapered-strap specimens under ambient conditions in accordance with BS EN 1465 [12]. Tests were conducted at loads corresponding to 90, 85, 80, 75 and 70 % of the maximum short-term strength of the joint (28.8 ± 1.1 MPa), which was calculated using Equation (1). The number of tests was limited to one per stress level. 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 (Table 1). The system was capable of measuring time-to-failure to within one second accuracy.

The shear strength τ is given by:

$$\tau = \frac{P_{MAX}}{2bL} \quad (1)$$

where P_{MAX} is the maximum load, b is the joint width and L is the joint overlap length.

Table 1 Normalised Stress Rupture Data

Time-to-Failure (secs)	Normalised Applied Stress
1	1.00
262	0.90
6631	0.85
49262	0.80
82556	0.75
315790	0.70

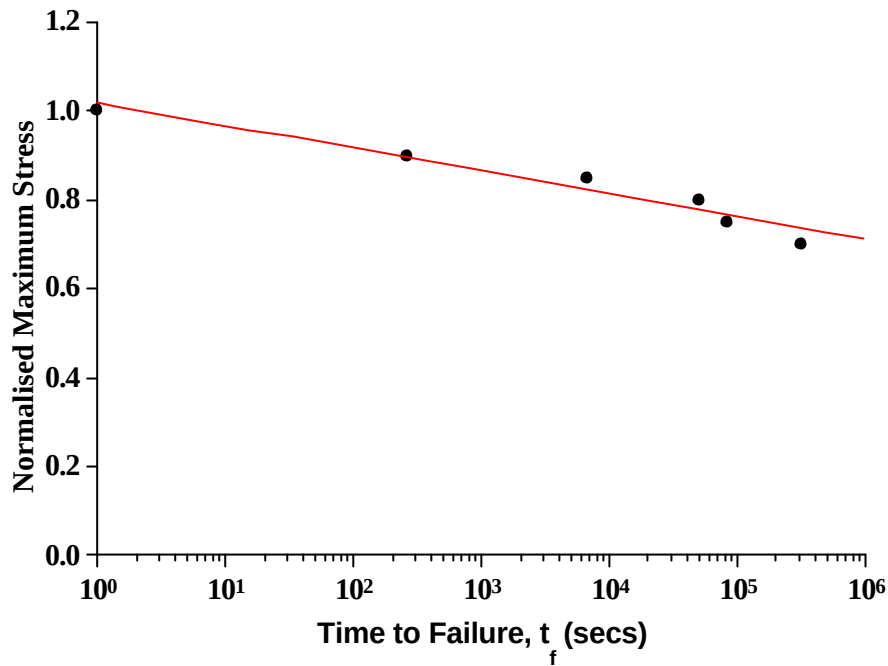


Figure 3 Time-to-failure for 5251 aluminium / AF126-2 tapered-strap joint.

The normalised creep rupture data (Table 1) when plotted on a linear-log plot (Figure 3) can be approximated by a straight line fit as follows:

$$\tau_{\text{APP}} / \tau_{\text{ULT}} = 1 - k \log t_f \quad (2)$$

where t_{APP} is the applied load (or stress), t_{ULT} is the maximum short-term strength of the unconditioned material, k is the slope and t_f is time to failure in seconds. For these tests, k is approximately equal to 0.051. Further work is needed in order to ascertain if short-term data can be extrapolated to predict the average life expectancy of specimens loaded at lower loads.

3. ELEVATED TEMPERATURE

Creep rupture of bonded joints was examined at a range of temperatures and stress levels. The work was carried out by Daimler Benz Forschung und Technik as part of the ABHTA “Adhesive Bonding for High Temperature Applications” Brite-Euram Project BE-5104 [8]. The data were supplied to the PAJ programme courtesy of British Aerospace, Sowerby. Two adhesive systems, epoxy FM 350NA and bismaleimide HP655, were examined using the thick adherend shear test (TAST) specimens manufactured from thick sections of titanium alloy (Ti-6Al-4V). Specimens were mechanically loaded using the test rig shown in Figure 4 and placed in an oven at elevated temperatures (i.e. 130 °C, 180 °C and 200 °C). Creep loads ranging from 70% to 90% of the static tensile shear strength (Table 2) were employed. This section evaluates the data generated within the Brite-Euram programme [8], and provides a simple analytical approach to data analyses. The data

used in the analyses has been extracted directly from creep rupture plots as the raw data was unavailable in tabulated form.

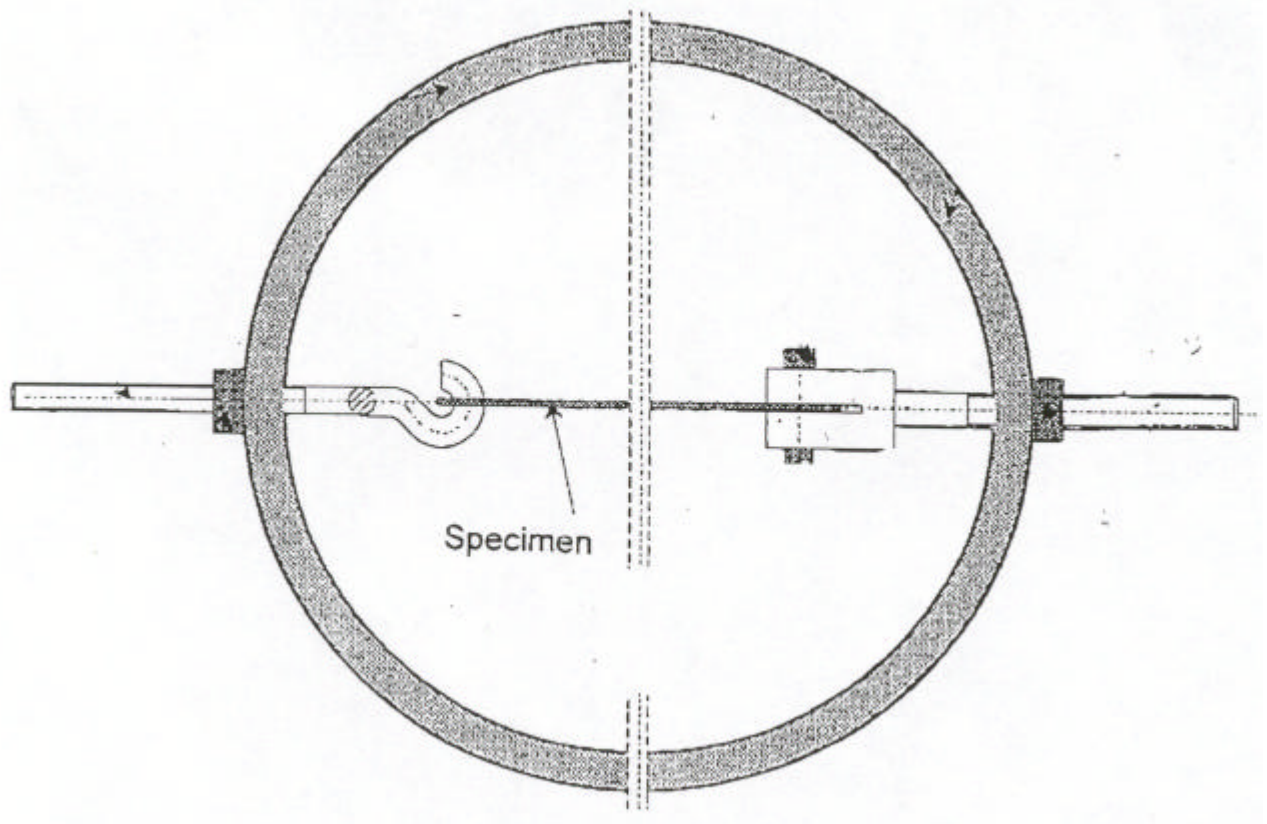


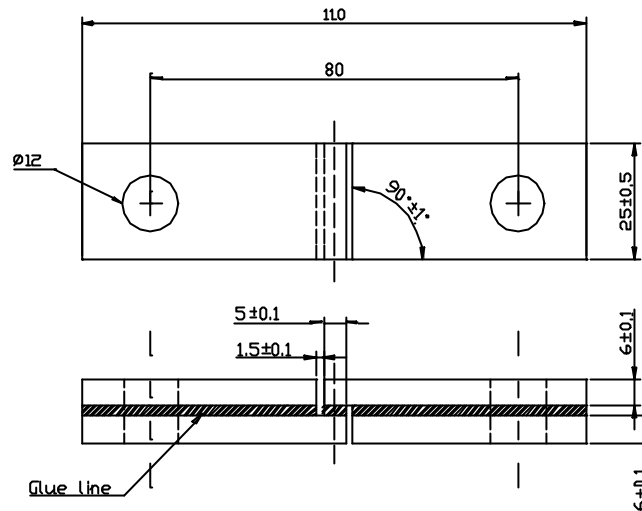
Figure 4 Test rig used for loading TAST specimens [8].

Table 2 Tensile Shear Strength (MPa) [2]

Adhesive	Test Temperature (°C)		
	23	130	180
HP 655	55.36	30.72	29.44
FM 350NA	57.28	28.32	17.04

3.1 EXPERIMENTAL PROCEDURE

This section summarises the specimen geometry, surface preparation, test procedure and test conditions employed in the creep testing. As previously mentioned, creep tests were conducted on TAST specimens (Figure 5) at a range of temperatures and stress levels. The test conditions and number of specimens per condition are shown in Table 3. The AESP surface treatment was used for titanium.



dimensions in millimetres

Figure 5 TAST specimen.

Table 3 Number of Creep Tests Performed at each Test Condition

Creep Load (%)	Test Temperature (°C)		
	23	130	180
70	3	3	3
80	3	3	3
90	3	3	3

The test rig consisted of a ring and two clamping devices; as shown in Figure 4. Four strain gauges were bonded to the ring to monitor deformation. A constant force is applied to the specimen via screws, located diametrically opposite each other along the central axis, which deform the ring a known amount. The strain measurements can be directly related to applied force. The strain level was measured to be constant during the test by monitoring a strain gauged aluminium specimen in a control experiment. Calibration of the test rig was achieved by loading the fixture in a static test machine and then measuring the force-strain behaviour of the ring. This operation was performed for each test rig. The loading fixture with specimen was positioned in a heated oven. Specimen failure was detected electronically using an electrical probe. This technique enables the time-to-failure (t_f) to be recorded for each specimen.

3.2 EXPERIMENTAL RESULTS

The creep rupture behaviour of the two adhesives at 23 °C, 130 °C and 180 °C are shown in Tables 4 to 6 and Figure 6. As expected, the results show a considerable degree of scatter thus reflecting the technical difficulties associated with conducting creep rupture tests using self-stressing fixtures.

Table 4 Failure Times at 23 °C

Creep Load (%)	Failure Time (hrs)	
	Fail 1	Fail 2
<u>70</u> FM 350NA HP 355	433 1.7	471 92
<u>80</u> FM 350NA HP 355	15.2 5.8	262 5.8
<u>90</u> FM 350NA HP 355	0.01 0.02	0.01 0.02

Table 5 Failure Times at 130 °C

Creep Load (%)	Failure Time (hrs)	
	Fail 1	Fail 2
<u>70</u> FM 350NA HP 355	480 400	480 400
<u>80</u> FM 350NA HP 355	480 1.6	480 580
<u>90</u> FM 350NA HP 355	2.8 1.8	3.6 -

Table 6 Failure Times at 180 °C

Creep Load (%)	Failure Time (hrs)	
	Fail 1	Fail 2
<u>70</u> FM 350NA HP 355	210 15	236 45
<u>80</u> FM 350NA HP 355	36 0.8	280 4.0
<u>90</u> FM 350NA HP 355	30 2.1	280 2.2

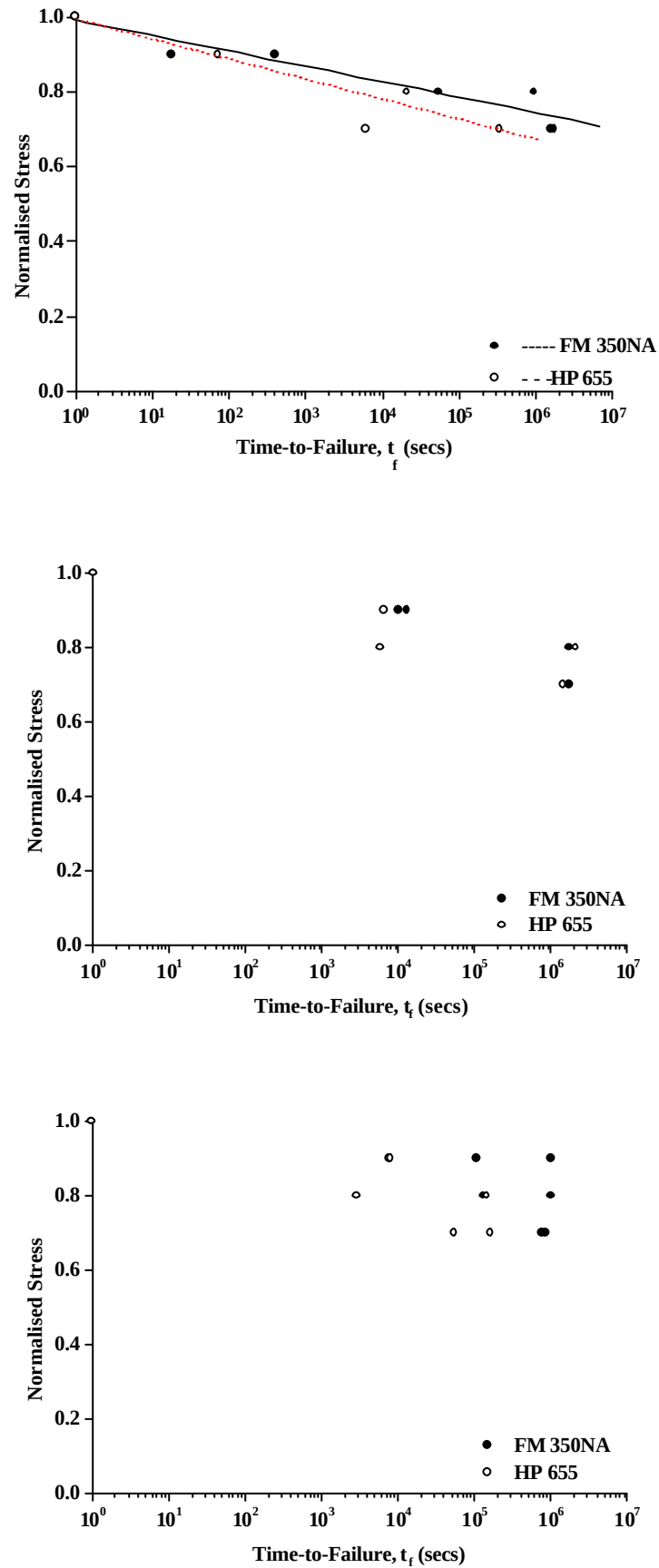


Figure 6 Creep rupture curves at 23 °C (top), 130 °C (middle) and 180 °C (bottom).

The creep rupture (i.e. time-to-failure) results (Tables 4 to 6 and Figure 6) can be summarised as follows:

Room-temperature (23 °C): FM 350NA data when plotted on a linear-log plot (Figure 6) can be approximated by a straight line fit (i.e. Equation (2)) as follows:

$$\tau_{APP} / \tau_{ULT} = 1 - 0.04 \log t_f \quad (3)$$

Similarly, the normalised creep rupture data for HP 655 can be approximated by:

$$\tau_{APP} / \tau_{ULT} = 1 - 0.05 \log t_f \quad (4)$$

The above relationships only applied to data generated under ambient test conditions.

Elevated temperatures (130 - 180 °C): There was no evidence of a relationship between time-to-failure and applied stress. It can be seen from the experimental data that there is a large uncertainty associated with the data, particularly at elevated temperatures. The scatter could be reduced with additional testing at each stress level.

The results show that the epoxy FM 350NA adhesive performs slightly better under creep loading at both room temperature and at elevated temperatures than the bismaleimide HP655 adhesive. **It is important when conducting test with self-stress mechanisms to constantly check applied loads. Stress relaxation is a common occurrence, which is more pronounced at elevated stress levels and temperature.**

4. PERFORATED HYDROTHERMAL STRESS (STRESS HUMIDITY) TEST

The primary aims of Project 3 “The Environmental Durability of Adhesive Bonds” of the DTI funded MTS programme ADH were (i) to provide a comparative assessment of the relative effectiveness and suitability of durability test methods; and (ii) to provide experimental data on the durability of different joint combinations [7]. The work was carried out by five collaborating laboratories. A number of test techniques were evaluated within the research programme. This section examines some of the results from the experimental work relating to the experimental assessment of the perforated hydrothermal stress (stress humidity) test. It attempts to determine empirical relationships that can be used to extrapolate the short-term data to longer times. This test configuration (Figure 7) was used to investigate the combined effects of mechanical loading, temperature and humidity on different combinations of adherend, adhesive and surface treatment. The experimental work was carried out by Oxford Brookes University, Loughbrough University of Technology and the Defence Evaluation and Research Agency (DERA) at Holton Heath.

4.1 EXPERIMENTAL PROCEDURE

Perforated single-lap joints (Figure 7) were constructed from rectangular strips of either aluminium 5251 alloy or CR1 mild steel. Two adhesive systems, Araldite® 2001 (a two part epoxy) and Araldite® 2007 (a one part epoxy) supplied by Ciba Speciality Polymers, were used in the test programme. The adherends were 60 mm long and 20 mm wide. The overlap length was 10 mm and the thickness was 1.2 mm and 1.6 mm for the mild steel and aluminium substrates, respectively. The coupons were precisely drilled to produce a line of three holes of 4 mm diameter across the specimen width with a 5 mm separation between the hole centres. Specimens were then assembled and bonded with excess adhesive removed prior to curing.

Joints bonded with Araldite® 2001 were cured at room temperature for 24 hours and then post-cured at 60 °C for 30 minutes. The cure schedule for Araldite® 2007 (also known as AV119) was 120 °C for 2 hours. The bondline thickness was controlled using 250 µm ballontini glass spheres. A small quantity of the glass spheres, 1% by weight, was mixed into the adhesive. Details of surface treatments considered in Project 3 are given in Part II “General Experimental Data” of Report Number 8 “Experimental Assessment of Durability Test Methods” [7].

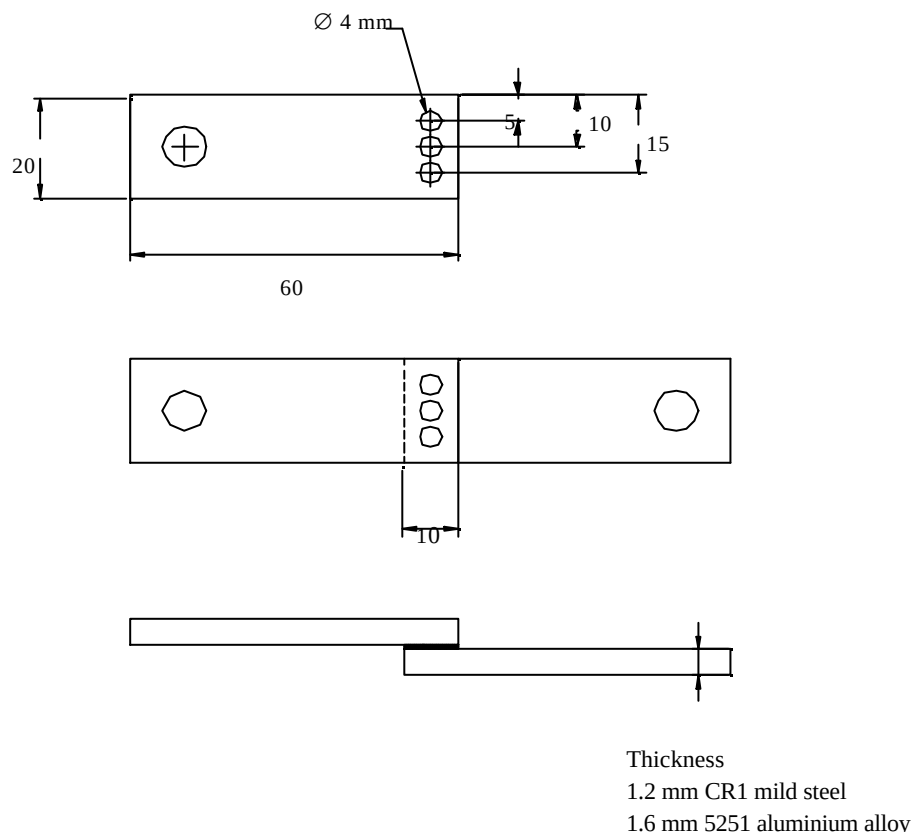


Figure 7 Perforated single-lap joint configuration (dimensions in mm).



Figure 8 Specimen loading tube.

Mechanical loading was carried out using self-stressing fixtures (Figure 8) where specimens were placed in a tube equipped with a pre-calibrated spring system for loading the specimens [13-14]. The spring system can be compressed and locked in place to apply the required load with the spring stiffness determining the load range. The amount of load is determined by measurement of the spring compression. The load levels applied to the specimens ranged from 0.2 kN to 2.5 kN. The stressed joints were then exposed to different ageing environments [7].

The stress tubes were inspected at frequent intervals to check on the condition of the test specimens (i.e. failed or intact). Failed joints were replaced with spacers and the remaining specimens re-stressed. The failure times were measured at which the first three specimens failed. When the third specimen failed, the remaining specimens were removed from the loading tube and tested to failure to determine residual strength. The average life-time of the failed specimens and the residual strength of the remaining specimens were recorded. A limited number of tests were also performed using a smaller loading tube that accommodates only one specimen.

4.2 ANALYSIS OF EXPERIMENTAL DATA

Individual time-to-failure data was published for only one of the three participating laboratories, hence the analysis will be confined to that set of data. For many adhesive/adherend/surface treatment combinations, there was insufficient data to conduct any form of analysis. **At least three and preferably four sets of stress level data, in addition to the static strength of unconditioned (i.e. unconditioned and unstressed) are required for analysis.** The time-to-failure of 5251 aluminium / Araldite® 2007 specimens for three different surface treatments (grit blast, PAA (Phosphoric Acid Anodise) and Optimised FPL (Forest Products Laboratory) etch) [7] that were immersed in water at 45 °C is shown in Table 7.

Table 7 Perforated Hydrothermal Stress Test Results for 5251 Aluminium/Araldite[®] 2007 (Water Immersion at 45 °C)

Stress Level (kN)	Individual Time-to-Failure (h)		
	Grit Blast	Optimised FPL Etch	PAA
0.375	1346, 1369, 1382	1572, 1718, 1910	-
0.75	500, 512, 596	319, 334, 368	2105
1.5	1*, 14, 23	5, 46, 56	875, 971, 1006
2.0	-	-	373, 562, 637
2.5	-	-	293, 418, 419

* Result was excluded from analysis.

The creep rupture data shown in Table 7 indicates that the durability performance of the Optimised FPL treatment under combined load and hostile environment was slightly better than the grit blasted surface treatment (Figures 9). The PAA surface treatment substantially increases the resistance of the adhesive joints to environmental attack compared with both the Optimised FPL etch and grit blast surface treatments (see Figures 9 and 10).

Key Observation

The environmental durability results for the hot/wet conditioned joints show considerable scatter. It was not possible with the limited amount of data available to determine relationships between applied load and failure time for the different adherend/adhesive/surface treatment combinations considered.

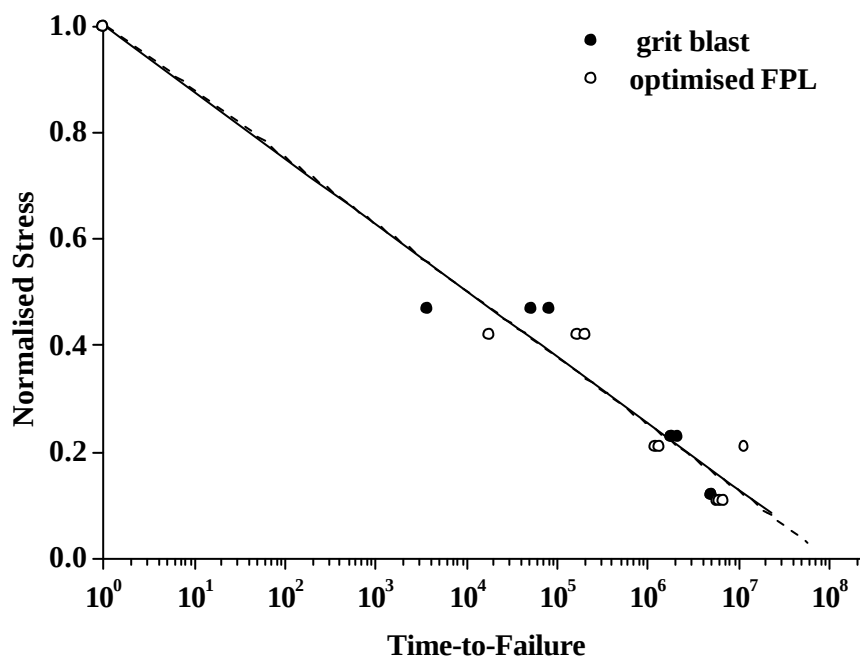


Figure 9 Creep rupture data for grit blast and FPL etch surface treatments.
(line added simply to guide the eye)

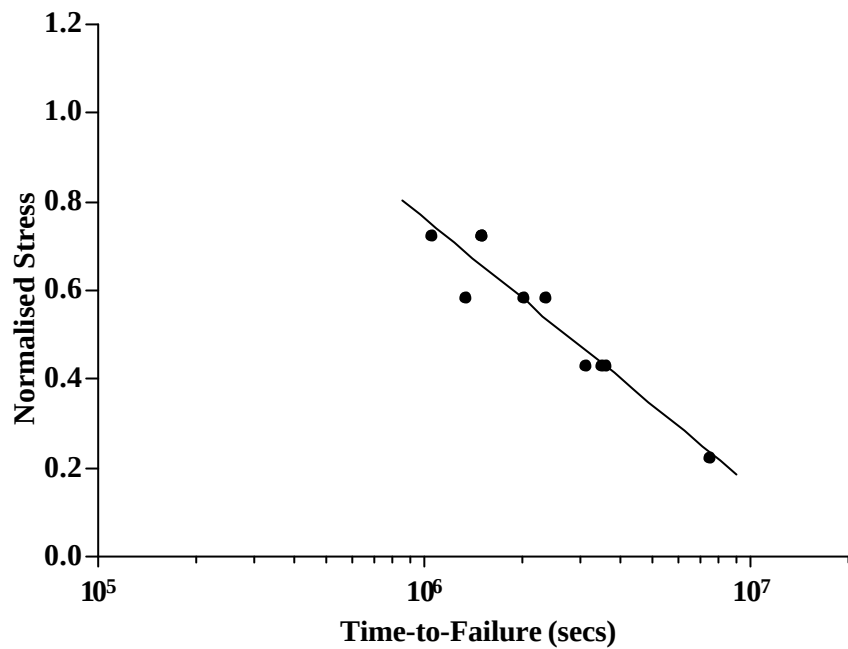


Figure 10 Creep rupture data for PAA surface treatment.
(line added simply to guide the eye)

5. T-PEEL TESTS AT ELEVATED TEMPERATURE AND HUMIDITY

This section examines the results from creep tests conducted on a small (non-standard) T-peel specimen, 25 mm wide, shown in Figures 11 and 12. Specimens were mechanically loaded at one of five stress levels (i.e. 80%, 70%, 55%, 40% and 25% of the maximum short-term strength of the joint) using spring loaded (self-stressing) fixtures (Figure 8).

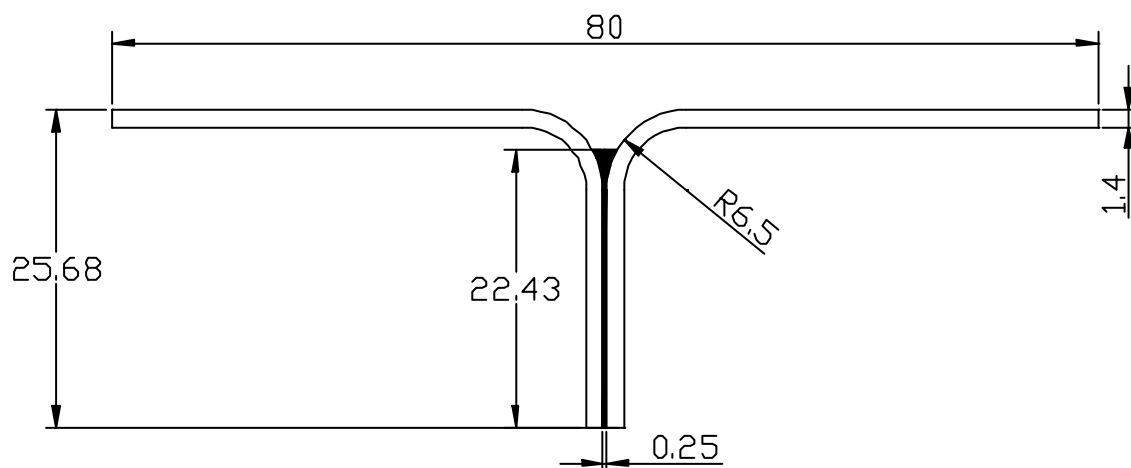


Figure 11 T-peel test geometry dimensions (mm) used for creep tests.

The specimen-loading tubes were suspended vertically within an environmental chamber for periods up to 500 hours (21 days) at either 23 °C and 50% RH or 70 °C and 85% RH. A few additional tests at higher stress levels were extended to 42 days exposure at 70 °C and 85% RH. Conditioning was undertaken using Climatic System environmental

chambers. The temperature and humidity were controlled to within ± 2 °C and $\pm 5\%$ RH, respectively. Loading procedure and monitoring of specimens was similar to that described in Section 4.



Figure 12 T-peel specimen.

Test specimens of the dimensions shown in Figure 11 were prepared individually from pre-shaped adherends. Rectangular sections of CR1 mild cold rolled steel (supplied by British Steel) were milled to the required length and width and then bent into a right angle. The right angled sections were bonded with Araldite® 2007(AV119) adhesive supplied by Ciba Speciality Chemicals. Specimens had a 6.5 mm external radius **Ro** and a 50% adhesive fillet (see [5]). Specimens were clamped in a special bonding jig and then heated to 140°C for 75 minutes to cure the adhesive.

Prior to bonding, the adherends were degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina. 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. Ballontini glass spheres may cause premature failure. A small quantity of the glass spheres, 1% by weight, was mixed into the adhesive.

The individual life-time of the failed specimens and the residual strength of the remaining specimens are presented in Table 8 (Figure 13). The results clearly indicate that the failure times for those specimens pre-loaded under ambient conditions (with the exception of the 80% results) were greater than 500 hours. An attempt was made to analyse the hot/wet results (Figure 13).

Table 8 Effect of Combined Loading and Environmental Exposure on T-Peel Joints

Applied Load (%USS)	Ambient	Hot/Wet Conditioned
0	1873 ± 123 N*	1330 ± 138 N
25	1623 ± 105 N	789 ± 153 N 792, 984, > 1,000 hrs (4 off)
40	1163 ± 235 N	192, 264, 264, 264 > 500 hrs (2 off) > 500 hrs (493 - 833 N)
55	1123 ± 248 N	168, 168, 168, > 500 hrs (3 off) > 500 hrs (658 ± 40 N)
70	1238 ± 90 N	1 - 16 hrs (6 off)
80	16, 156, 360, 408, 480, > 500 hrs (1 off) > 500 hrs (1213 N)	1 - 16 hrs (6 off)

- Specimens stored under standard laboratory conditions will degrade.

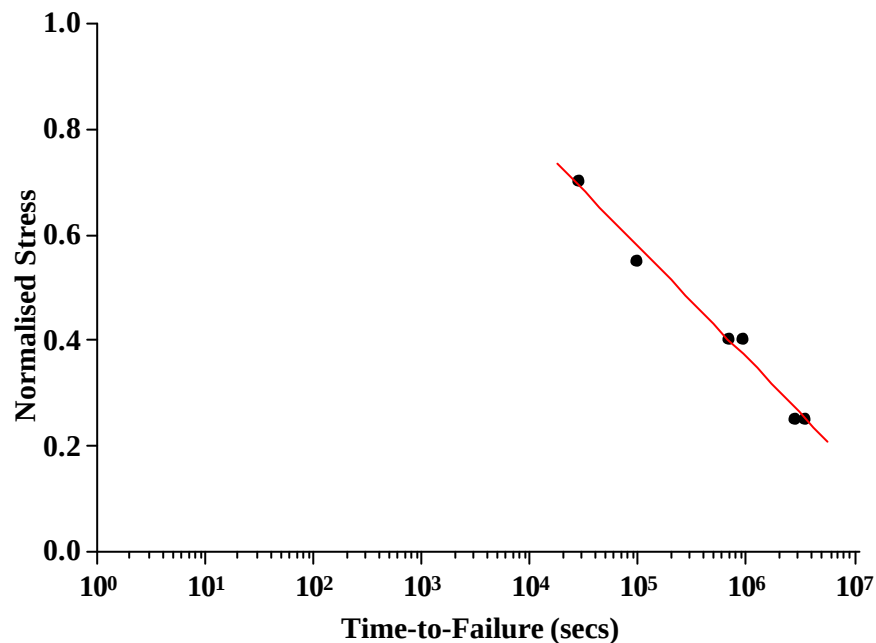


Figure 13 Creep rupture data for hot/ wet conditioned T-peel specimens.

The normalised creep rupture data ($0.25 \leq \mathbf{P_{APP}/P_{ULT}} \leq 0.7$) for the T-peel tests (Figure 13) when plotted on a linear-log plot can be represented by a straight line fit:

$$\mathbf{P_{APP} / P_{ULT} = 1.62 - 0.21 \log t_f} \quad (7)$$

The large uncertainty associated with time-to-failure measurements, especially at the high stress levels, demonstrates the need for an electronic monitoring system to accurately determine time-to-failure. Another concern is that specimens loaded by springs can often be in an unstressed state for a considerable period of time (overnight or weekends) before the failed joint is replaced by a solid “dummy” and the string re-tensioned. **There is also**

a tendency for surviving specimens to be damaged in the re-stressing process with the probability of occurrence increasing at high stresses. Creep/relaxation histories of specimens will be different due to the replacement of failed specimens and subsequent re-loading. This contributes further to the uncertainty of creep rupture data. For long term tests over months or years, this effect will probably be minimal.

6. CONCLUDING REMARKS AND DISCUSSION

The results demonstrate that a systematic approach, albeit empirical, can be used to determine the time-to-failure for different combinations of test variables on different adherend/adhesive/surface treatment combinations. Normalised creep rupture can be represented in some cases by a straight line fit as follows:

$$P_{APP} / P_{ULT} = A - k \log t_f$$

where P_{APP} is the applied load, P_{ULT} is the maximum short-term strength of the unconditioned material, k is the slope and t_f is time to failure. This simple relationship can be used for interpolation purposes to determine failure times for intermediate stress levels.

Normalised creep rupture data under ambient conditions can be approximated by the following relationship:

$$P_{APP} / P_{ULT} = 1 - k \log t_f$$

The results analysed in this report indicate that k is approximately equal to 0.05 for epoxy adhesives FM 350NA and AF126-2, and 0.04 for the bismaelamide HP655 adhesive. The value of k could be generic for the two types of adhesives, although confirmation would require further work.

There was no evidence of a relationship between time-to-failure and applied stress for those joints tested at elevated temperature (i.e. 130 °C - 180 °C). Analytical analysis proved impossible due to the large uncertainty associated with the data.

The complexity of environmental degradation makes it difficult to determine reliable generic design parameters or relationships which account for the combined effect of mechanical loading and moisture and that can be applied to different systems. The results indicate, however, that it may be possible to group the environmental response of different adherend/adhesive/surface treatments and in some cases the durability data can be approximated using linear-log relationships similar to those given above (Sections 4 and 5).

The large uncertainty associated with creep test results, especially those obtained under hot/wet conditions, implies that the current approach of conducting three tests per stress level is inadequate and that considerably more data points are required for generating reliable creep rupture curves for engineering design purposes. Five (preferably 10) per stress level with five stress levels (i.e. 80%, 70%, 55%, 40% and 25%

of maximum joint strength) per condition should provide a reasonable number of data points.

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