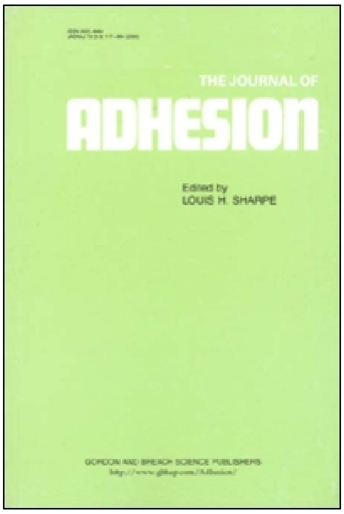

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Strength and Failure Mode of Adhesively-Bonded Joints at Different Loading Rates

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The time-dependent behaviour of adhesively-bonded double-lap joints has been tested. The adhesive used was FM300. Three different materials were used for the adherend, namely, carbon fibre reinforced composite with quasi-isotropic lay-up, aluminium and steel. The specimens were pulled at different speeds and the strength of the joints and failure patterns were recorded and analysed. The effect of different ratios of overlap length *vs.* adherend thickness was tested. The results indicate that in the room temperature-dry environment for reasonably long joints, the effect of pulling speed on the strength of the joints is negligible. In the hot-wet environment this effect becomes significant for the composite specimens tested.

Keywords: Adhesive; bonded joints; time-dependent behaviour; composite material; coupon tests; strength

1. INTRODUCTION

Adhesively-bonded joints are increasingly used in the aerospace industry to join structural components together. The components can be either both metallic, a combination of metallic and composite, or both composite.

Most adhesives are polymers and, as such, have time-dependent behaviour. Their stress-strain relations are rate-sensitive and moduli

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and strength properties are susceptible to environment effects, especially temperature and moisture. The time-dependent properties of adhesives may raise serious questions regarding their reliability and durability under various loading conditions and in various temperature and moisture environments.

Quite a few publications have appeared in the last twenty years concerning analysis of the time-dependent behaviour of the joints [1 – 8]. Some recent publications [1, 2] suggested that the time-dependent behaviour is so important that the conventional theory, where the time-dependent behaviour of the adhesive is ignored or simplified, has to be revised. However, regarding the time-dependent behaviour of the whole joint, most of the above work provides theoretical analysis only. Very limited experimental investigation has been reported in this field.

Hence, this experimental research was carried out to investigate the time-dependent behaviour of some typical adhesively-bonded joints. The main objectives of this research are: (1) to gain solid conclusions regarding the significance of rate-dependent behaviour of the joints; and (2) to achieve a better understanding on the trends of how each parameter of the joint, such as overlap length and adherend material, and environmental effects such as temperature-moisture, affects the rate dependence.

Double-lap joints were tested in room temperature-dry (RD) and hot-wet (HW) environments. The specimens were pulled at different speeds and the strength of the joints and failure patterns were recorded and analysed.

2. LITERATURE REVIEW

Shannon *et al.* [9] and Hart-Smith [10] reported important experimental results regarding the time-dependent behaviour of the adhesively-bonded joints during the Primary Adhesively Bonded Structure Technology (PABST) program. It was observed in the experiment that, for the same hot-wet environment and time, the failure load of a specimen subjected to a slow-cycle load was lower than that subjected to a sustained load and the latter was, in turn, lower than the failure load of the specimen subjected to a (short time) static load. These results manifest both fatigue and creep features of the joint. It was also observed that use of adequately long overlap effectively prevented the joints from creep failure and the reason was explained by Hart-Smith [10]. For the joint with a long overlap there is a lightly-loaded central area which restricts cumulative creep damage.

The analysis of the time-dependent behaviour of the joint has been conducted by quite a few researchers [3–7]. In these analyses, the adherends were generally considered as elastic materials and the adhesives as linearly or non-linearly viscoelastic materials. Moisture diffusion was considered by Roy and Neddy [6]. The relaxation and creep behaviour was predicted by most authors and the results indicate that over a long period of time under a relaxaion condition the stress at the ends of the overlap significantly decreases. Under a creep condition, at the ends creep strain develops and the stress decreases but in the central region the stress increases, resulting in a more uniform stress distribution. Jones *et al.* [7] considered different load rates and their results suggested that the strain energy did not vary much for the same load with different load rates.

Chiu *et al.* [1] and Jones *et al.* [2] emphasised the difference between the strength of the adhesive tested at an extremely low speed and that tested at the standard speed of 1.27 mm/min. For those adhesives with creep behaviour, the former is lower than the latter. Hence, for a joint subjected to a sustained or slow-cycle load, the true load capacity will be lower than the expected value if this difference is not considered. The authors suggested a simple way to revise Hart-Smith's analysis methodology [11] to take this difference into account. When the strain energy is calculated the stress-strain curves from low speed tests should be used. The authors also presented a comprehensive analysis method which extends Hart-Smith's methodology by incorporating a non-linear viscoelastic stress-strain relation. The results were compared with a rate-independent solution where the stress-strain relation was from the manufacturer of the adhesive. The conclusion was made that use of the rate-independent analysis procedure gives results for the adhesive shear stresses and strains which were not generally conservative.

In contrast to the amount of analytical work, very limited experimental investigation on the time-dependent behaviour of the joints has been reported. Mignery and Schapery [8] conducted both experimental and analytical research on the time-dependent behaviour of a single-lap joint. Unlike many researchers, they assumed the adhesive to be an elastic material and the adherend a viscoelastic material, which was considered to be true for adherends of matrix-dominated layup (angle-ply) and a brittle expoxy adhesive layer. They conducted experiments with two different load rates and measured the strains at several locations on the surface of the adherends. The finite element method was applied to calculate the strains and the results were compared with the test measurements. It was concluded that the time-dependent mode agreed with test results quite well, in most cases. In the experiment an interesting phenomenon was observed. The joint failed in the angle-ply adherend at the highest rate and in the adhesive at the lowest rate. However, no attempt was made to predict or explain such a phenomenon.

Molent *et al.* [12], in a report regarding repairs to F-111 C aircraft in service with the Royal Australian Air Force, documented some failures of adhesive bonding in the repair program. Some of these failures occurred during strain holds. Generally, these failures did not occur instantaneously, upon commencement of the strain holds. Jones *et al.* [2] cited the above as practical examples illustrating the importance of analysis allowing for strain holds and creep effects.

3. EXPERIMENTAL METHOD

3.1. Specimen Preparation

The adhesive used was FM300 K, a product of American Cyanamid Company, which is an epoxy-based film adhesive toughened with an elastomer and containing an embedded knit polyester carrier. It has 100% solids content and an amine-type curing agent. Its service temperature ranges from −55°C to 150°C. The measured rate-dependent stress-strain curves of FM300 at room temperature determined from thick adherend shear test specimens are given in Figure 1.

For the joint test conducted in this program, the adherend materials used and their properties are: (1) composite made of carbon fibre reinforced unidirectional tape, (FIBERITE ® 934). The ply thickness is 0.125 mm. The resin in the tape is FIBERITE 934 epoxy (glass transition temperature 194°C or 160°C, in dry or wet environment,

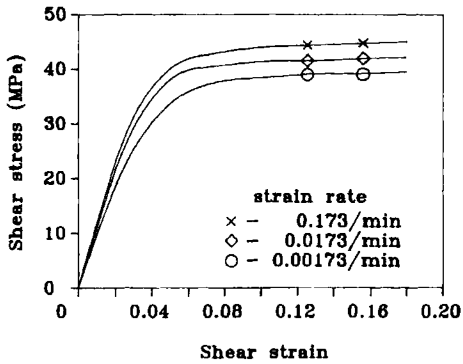

FIGURE 1 Measured stress-strain curves of FM300 adhesive.

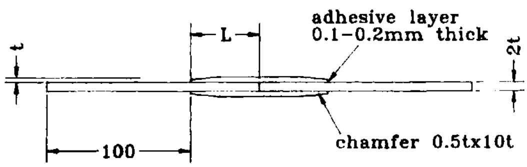

FIGURE 2 Geometry of double-lap joint specimens.

respectively). The mechanical properties of the material from the manufacturer are listed in Table I. The layup for doublers and central adherends are $[0, \pm 45, 90]_s$ and $[0, \pm 45, 90]_{2s}$, respectively. (2) high strength aluminium sheet (aircraft grade 202473) with yield strength 345 MPa and ultimate strength (UTS) 485 MPa; and (3) high strength steel sheet, yield strength 420 MPa, UTS 530 MPa.

TABLE I Typical properties of FIBERITE 934 unidirectional tape

Mechanical Properties	*Room Temperature*	*71°C*
0° Tensile Properties		
Strength, MPa	1586–1792	1586–1792
Modulus, GPa	124–138	124–138
Failure Strain %	1.0–1.2	1.0–1.3
0° Compression Properties		
Strength, MPa	1517–1724	1310–1517
Modulus, GPa	117–138	117–138
0° Flexural Properties		
Strength, MPa	1724–2068	1655–1861
Modulus, GPa	124–145	124–145
Interlaminar Shear Properties		
Strength, MPa	117–138	83–97

The geometry of the test specimen is illustrated in Figure 2, where L is overlap length and $2t$ is the thickness of the central adherend. For the composite adherends, the thicknesses of the doublers and the central adherends used were 1 mm and 2 mm, respectively, and for the metal adherends 1.5 mm and 3 mm. Several aspect ratios ranging from $L/2t = 7.5$ to 30 were used.

Note that two factors were considered when the thickness and aspect ratio were selected; that is (1) the selected values should be within or close to the practical application range; and (2) the selection should be favourable to revealing the time-dependent behaviour of the joint. For instance, for a joint with thin metal adherends, failure tends to be tensile failure of the central adherend outside the overlap region, which is obviously not time-dependent, hence 3 mm thickness, which is at the upper limit of the recommended values [14], was considered. (Refer to Reference [15] for a more detailed discussion).

The specimens were made by professional technicians and the manufacturer recommended cure cycle was followed. For the metal specimens used in the HW test, the adherend was coated with BR127 corrosion-inhibiting primer before bonding.

The specimens used in the HW test were pre-conditioned in a humidity chamber with around 85% relative humidity and 71°C temperature until they reached an equilibrium moisture content. The equilibrium moisture content was considered to have been reached when the daily increase in weight of the specimen is less than 1% of the total increase in weight of the specimen during its pre-conditioning period. The whole pre-conditioning time lasted for over 6 weeks.

3.2. Test Machine and Procedure

The tests were conducted on an Instron tensile test machine mounted with a load cell of 100 kN full scale. When the HW test was conducted, a high-temperature chamber attached on the Instron machine was actuated and the test temperature was controlled to be 92 ± 1°C. The experiment was started after the specimen reached the specified temperature measured using a thermocouple connected to the specimen.

Note that for epoxy cured at 177°C the upper limit temperature for long-term service is 93°C [16]. Thus, this was considered to be the test temperature in the HW test. This temperature is much lower than the upper limit of the service temperature of the FM300 K adhesive (150°C, according to the manufacturer) but slightly higher than the temperature of 82°C used in PABST HW test [9] where adhesives cured at 121°C were used.

In both RD and HW tests, the specimens were pulled at constant speeds until broken. Four test speeds were utilised, namely, 0.1 mm/min, 1 min/min, 10 mm/min and 100 m/min. Note that the highest speed corresponded to about 3 seconds test duration and the test speed in the relevant ASTM standard is 1.27 mm/min. The force-displacement relation was recorded. The broken sections of the specimens were observed to study the failure patterns.

3.3. One-way Analysis of Variance

Since the measured data in the test with the composite specimens showed considerable scatter, it is necessary to use an effective statistical method to process the test results. Thus, one-way analysis of variance, as briefly described in the following part, was adopted.

In the analysis the following two variables are calculated:

$$\mathrm{Sa} = \frac{1}{k-1} \sum_{i=1}^{k} n_i (\bar{x}_i - \bar{x})^2 \tag{1}$$

and

$$\mathrm{Se} = \frac{1}{n-k} \sum_{i=1}^{k} \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2 \tag{2}$$

where

k = the number of crosshead speeds (levels), $k = 4$ in this test.
n = the total number of tests.
n_i = the number of tests at each speed.
$\bar{x}$ = the average value of all measured loads
$\bar{x}_i$ = the average value of measured loads at each crosshead speed (level)
x_{ij} = individually measured load

Sa reflects the effect of different speeds (levels) on the total variance of the measured data. Se reflects the random error. Thus, Sa/Se indicates the significance of time dependency in terms of statistics. Under the hypothesis that there is no time-dependent effect, (i.e. all x_{ij} have the same expected value) $f = \mathrm{Sa}/\mathrm{Se}$ is distributed as an F-distribution with degrees of freedom $(k-1)$ and $(n-k)$.

Using the calculated f from test results, the corresponding probability, α, can be found according to the F-distribution function. When α is less than a specified value α_i (normally 0.10) the hypothesis should be rejected, that is the time-dependent effect does exist. The following relations are equivalent:

$$\alpha < \alpha_i \tag{3}$$

or

$$f > F(\alpha_i; k-1, n-k) \tag{4}$$

Thus, Eq. (4) is used to check the statistical significance. When Eq. (4) is satisfied we believe there is a time-dependent effect. Otherwise, we believe random error is dominant. In the following part, F_α is used as a simple form of $F(\alpha; k-1, n-1)$.

Note that statistical significance is not necessarily equivalent to the significance from an engineering point of view. The former only means that the difference of the results is caused by different speeds rather than by random errors.

Detailed description of the analysis of variance can be found in statistics books (e.g. Reference [17]).

4. RESULTS AND DISCUSSIONS

The average value of the measured ultimate load and its standard deviation are listed in Table II. The results of one-way analysis of variance are listed in Table III. The increase of the average ultimate load as test speed increased from the lowest to the highest was calculated for each case and the results are listed in Table IV.

4.1. RD Test Results

The results for the composite specimens with aspect ratio $L/2t = 15$ (Fig. 3 and Tab. II) show that the measured ultimate load values are quire scattered and the average load slightly increased as crosshead speed increased from 0.1 mm/min to 10 mm/min and then decreased. The calculated f in this case is much less than even $F_{0.25}$ (Tab. III). Thus, the time-dependent effect is not statistically significant.

The results for the composite specimens with aspect ratio $L/2t = 7.5$ are shown in Figure 4. In order to see the overall trends, two drawings with different scales are given in the figure. The results show that the average load slightly increased as the crosshead speed increased in all the speed range. The f value is higher than $F_{0.05}$ (Tab. III). Thus the time dependent effect is statistically significant in this case.

The results for aluminium-adherend specimens (Tab. II) are very similar to those with composite-adherend specimens; that is, in the case of $L/2t = 15$, the average load was lower at higher speed but this time dependency is statistically insignificant (Tab. III) and in the case of $L/2t = 7.5$ the average load increased slightly as the speed increased in the whole speed range and this is statistically significant (Tab. III).

The results with steel adherend specimens (Tab. II) show that in both cases, of $L/2t = 15$ and $L/2t = 7.5$, the average load increased

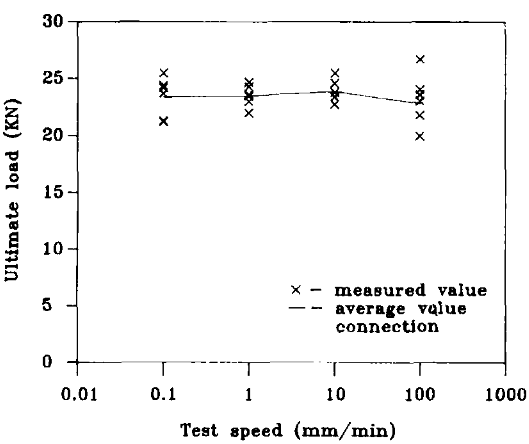

FIGURE 3 Measured ultimate load *vs* test speed, composite adherend, $L/2t = 15$, RD test.

TABLE II Average value of ultimate load and the standard deviation

Environment	*Material*	*L/2t*	*Load, kN*	*Test speed (mm/min)*			
				0.1	1	10	100
	Composite	15	P_{ult}	23.38	23.52	23.90	22.85
			S_d	1.60	0.87	0.92	2.47
		7.5	P_{ult}	21.16	22.00	22.50	22.69
			S_d	0.61	0.35	0.31	0.60
RD	Aluminium	15	P_{ult}	31.70	31.80	31.52	31.58
			S_d	0.23	0.46	0.35	0.25
		7.5	P_{ult}	29.53	29.58	30.55	30.80
			S_d	0.11	0.54	0.48	0.71
	Steel	15	P_{ult}	37.25	37.988	39.15	40.15
			S_d	0.11	0.44	0.36	0.52
		7.5	P_{ult}	38.00	38.78	39.13	40.55
			S_d	0.14	0.49	0.54	0.89
HW	Composite	30	P_{ult}	26.30	30.38	31.60	36.90
			S_d	1.75	0.33	0.33	1.21
		15	P_{ult}	15.70	17.02	21.92	25.11
			S_d	0.74	0.12	1.14	0.77
		7.5	P_{ult}	7.93	9.81	12.31	13.98
			S_d	0.33	0.17	0.02	0.94
	Aluminium	26	P_{ult}	34.00	38.88	33.98	34.06
			S_d	0.42	0.12	0.09	0.12
		15	P_{ult}	33.67	33.95	34.53	34.61
			S_d	0.18	0.12	0.25	0.10

P_{ult} – average ultimate load, S_d – standard deviation.

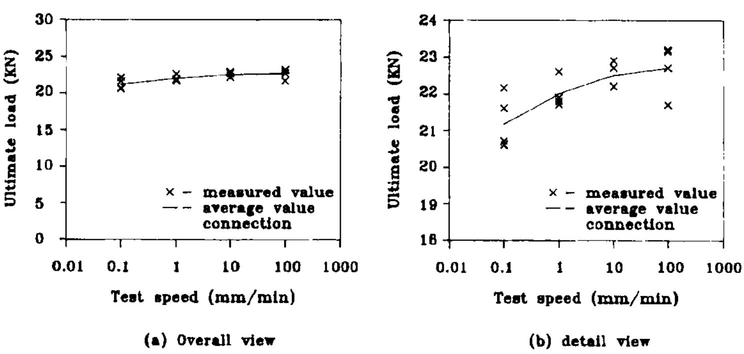

FIGURE 4 Measured ultimate load *vs* test speed, composite adherend, $L/2t = 7.5$, RD test.

slightly as the speed increased in the whole speed range and this is statistically significant (Tab. III).

The values of increase of the average ultimate load as the test speed increased in Table IV are lower than 10%. Hence, from an engineering

TABLE III Results of one-way analysis of variance

Environment	*Material*	$L/2t$	n	k	f	*Result*	*Significant in Statistical terms*
	Composite	15	24	4	0.35	$f < F_{0.25}$	No
		7.5	16	4	5.805	$F_{0.05} < f < F_{0.01}$	Yes
RD	Aluminium	15	20	4	0.563	$f < F_{0.25}$	No
		7.5	16	4	5.060	$F_{0.05} < f < F_{0.01}$	Yes
	Steel	15	16	4	30.49	$f > F_{0.01}$	Yes
		7.5	16	4	10.23	$f > F_{0.01}$	Yes
		30	14	4	129.4	$f > F_{0.01}$	Yes
	Composite	15	20	4	139.9	$f > F_{0.01}$	Yes
HW		7.5	12	4	129.5	$f > F_{0.01}$	Yes
	Aluminium	26	16	4	0.28	$f < F_{0.25}$	No
		15	14	4	293	$f > F_{0.01}$	Yes

point of view the time-dependent effect is insignificant in all the cases tested.

The failure patterns in the case of composite specimens with aspect ratio $L/2t = 15$ are summarised in Figure 5. The delamination cracks in the sides of the joints (Fig. 5a) occurred in every specimen. Figure 5b shows the front view of the overlap section, where only a little adhesive bond separation along one end of the overlap region was observed. In most areas, the adhesive layer was covered by a thin layer of fibres from the other part (from doubler to central adherend or *vice versa*). This pattern is also observed in every specimen. Figure 5c shows local

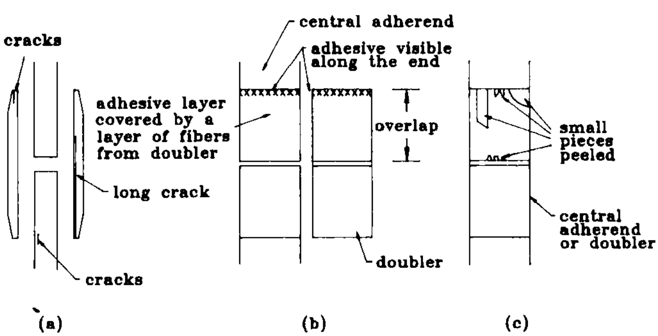

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FIGURE 5 Failure pattern of joint with composite adherends, $L/2t = 15$, RD test.

TABLE IV Average increase of ultimate load as test speed increased from 0.1 to 100 mm/min

Environment	*Material*	*L/2t*	*Average increase (%)*	*Significant in engineering terms*
	Composite	15	−2.3	No
		7.5	7.2	No
RD	Aluminium	15	−3.8	No
		7.5	4.3	No
	Steel	15	7.5	No
		7.5	6.7	No
		30	40	Yes
	Composite	15	60	Yes
HW		7.5	76	Yes
	Aluminium	26	0.3	No
		15	2.8	No

peel of small pieces which occurred in many specimens. It is clear that the composite failure (delamination) is the predominant pattern in this case.

The major difference of the failure pattern in the case of composite specimens with aspect ratio $L/2t = 7.5$ is that the adhesive separation, as shown in Figure 5b, extended to adbout one-half of the overlap area and the failure patterns shown in Figures 5a and 5c were observed in fewer than one third of the specimens. These suggested a mixed failure form of a composite delamination-adhesive separation.

The ultimate failure of all the specimens with metal adherends was adhesive bond failure. However, before the specimens were broken, yield of adherend, due to the tensile stress being higher than the yield strength, occurred in all cases, as illustrated in Figure 6, at either position A or B or both.

4.2. HW Test Results

The results for the composite specimens (Fig. 7) show that the strength of the joints was strongly dependent on the test speed. The increase of the average ultimate load as test speed increased from the lowest to the highest is 76%, 60% and 40% for $L/2t = 7.5$, 15 and 30, respectively. The f values in Table III are much higher than $F_{0.01}$. Thus, the rate dependency is highly significant in both statistical and engineering senses. The results also show that the strengths of the joints with

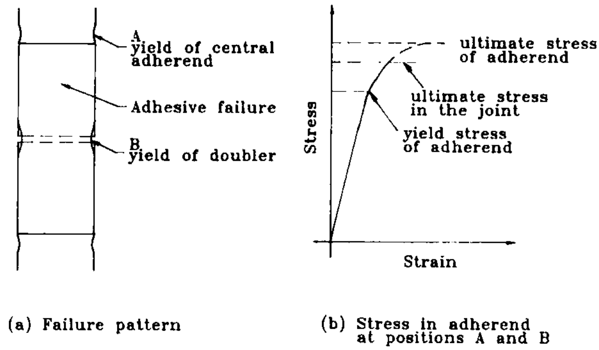

FIGURE 6 Failure pattern of joint with metal adherends, RD test.

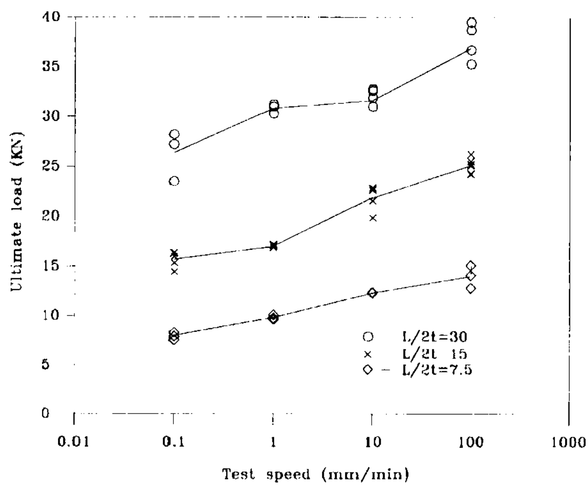

FIGURE 7 Measured ultimate load *vs* test speed. Composite adherend, HW test.

higher aspect ratio were clearly higher than those with lower aspect ratio for the same test speed.

On the other hand, the results for the aluminium specimens show negligible speed dependence (Tab. II). The increase of the average ultimate load as test speed increased from the lowest to the highest is 2.8% and 0.3% for $L/2t = 15$ and 26, respectively (Tab. IV).

In all the composite specimens with $L/2t = 7.5$ and 15 adhesive failure clearly occurred. In the composite specimens with $L/2t = 30$, depending on the crosshead speed, different failure modes occurred as illustrated in Figure 8. Delamination failure (Fig. 8a) occurred in all tests with speed 0.1 mm/min and some of the tests with speed 1 mm/min. Central adherend failure (Fig. 8c) occurred in all the tests with speed 100 mm/min and some of the tests with speed 10 mm/min. Doubler failure (Fig. 8b) occurred in some of the tests with speed 1 mm/min and in some of the tests with speed 10 mm/min.

The failure pattern of the aluminium specimens was the same as that in the RD test (Fig. 6).

4.3. Discussion

(1) For the specimens with homogeneous metal adherends, there are three main factors affecting the time-dependent behaviour. These are the time-dependent behaviour of the adhesive stress-strain relation, the overlap length (or aspect ratio, or rigidity ratio between the adhesive and adherend) and the tensile strength of the adherend (or strength ratio between the adhesive bonding and adherend).

When the overlap length is extremely short (or the adherends are extremely thick), the time dependence is as significant as that in the test of adhesive stress-strain relation using thick adherends (Fig. 1). A short specimen, therefore, tends to have higher speed dependence if the failure form is adhesive failure.

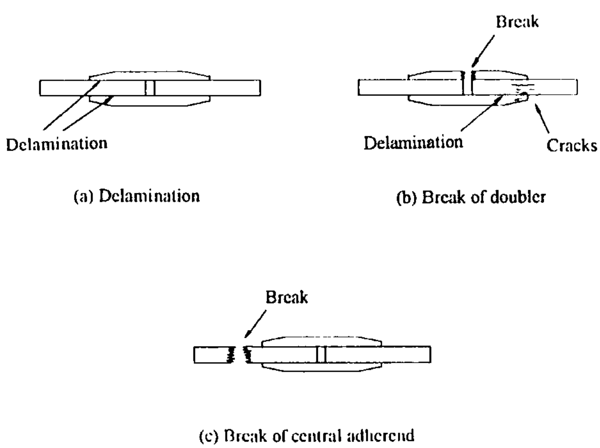

FIGURE 8 Failure pattern of joint with composite adherends, $L/2t = 30$, HW test.

When the overlap length is long enough, if Hart-Smith's prediction Eq. (6) is considered [11], the ultimate load due to the strength of the adhesive bond is proportional to the square root of adhesive strain energy density.

$$P_{\max} = 4\sqrt{Et_a\,tw} \tag{6}$$

where

$P_{\max}$ = maximum load per unit width
E = elastic modulus of adhesive
t_a = thickness of adhesive layer
w = maximum strain energy density of adhesive
t = thickness of doubler

If we extrapolate the curves in Figure 1 to cover a factor of 10^3 in the strain rate range and integrate the strain energy density, we can obtain the ratio between the strain energy density at the highest strain rate and that at the lowest strain rate. The result is about 1.25 and its square root is about 1.12. As a rough estimation, the latter value sets the upper limit of the time-dependent effect to be about 12% for test speed varying within 3 orders of magnitude in the RD environment. For adherends having relatively high yield strength, this time dependency may be fully present. On the other hand, if the load capacity due to the ultimate tensile strength of the adherends is lower than the load capacity of the adhesive bond calculated using the creep threshold strain energy, the failure will be adherend failure outside the joint without time dependency.

In this test, as indicated in Figure 6, at positions A and B the tensile stress corresponding to the failure load is higher than the adherend yield stress but lower than its ultimate tensile strength. The failure first occurred in the form of adherend yielding, then the adhesive failure followed due to the effect of the stiffness decrease of the metal at the yielding part. Moreover, if the adherend is considered not to be allowed to yield in use, the failure is not time dependent at all.

(2) For the composite specimens the failure mode is further complicated by the factors of delamination and time and environment dependence of strength and stiffness of the adherends under a complicated stress state.

In the RD test with $L/2t=15$, the time-dependent effect is insignificant as indicated by the analysis of variance. The reason is probably that the failure pattern is delamination of the composite material which is not significantly time dependent in the RD environment. The phenomenon that the average ultimate load was lower at the highest speed may be related to the load path moving towards the end of the joint due to the adhesive being stiffer at the highest speed, but this conclusion is uncertain due to the statistical insiginificance. For the composite specimen with $L/2t=7.5$, the measured ultimate load showed a little rate dependency which is statistically significant and the failure pattern is mixed delamination-adhesive failure. This can be considered to be due to the lower aspect ratio as discussed above.

In the hot-wet environment the adhesive tends to be weaker and presents stronger viscous behaviour. This reasonably explains the experimental results with aspect ratios 7.5 and 15. The failure form was adhesive failure and the strength of the joints decreased, particularly at lower deformation rates.

In the HW test the effect of the aspect ratio on the strength of the joints was more significant than that in the RD test. Probably this is because the stiffness of the adhesive became lower at higher temperature [18], resulting in a more uniform stress distribution along the bonding line, hence, the longer overlap length contributed more to the strength of the joint.

In the case of $L/2t=30$ the failure occurred only in the adherends. As the speed increased the failure mode changed from delamination to doubler failure then to central adherend failure outside the overlap region. This phenomenon can be attributed to the speed, temperature and moisture dependent behaviour of the composite material of the adherend. It is worthwhile to note the work of Yaniv *et al.* [20] regarding measurement of the effects of temperature, moisture and strain rate on the properties of a graphite/epoxy composite. They reported that the transverse modulus increases with strain rate. However, the transverse tensile strength and ultimate strain do not exhibit a uniform trend. They both increase with strain rate; however, at a certain stain rate they reach a local maximum, and thereafter the trend is reversed. The in-plane shear modulus exhibits a small increase with increasing strain rate, the shear strength increases significantly, and the ultimate shear strain shows a small decrease with increasing strain rate. The effect of increase of temperature or moisture is somehow equivalent to decrease of strain rate. On the other hand, as expected, the longitudinal tensile properties of the composite material, which are fibre-dominated, do not vary significantly with temperature, moisture or strain rate. Based on the above information it is evident that the speed, temperature and moisture dependent behaviour of the composite material is quite complicated and to explain fully the results in this test a numerical simulation of the time-dependent behaviour of the joints in the hot-wet environment, based on experimental investigation of the properties of the composite material in the same condition, needs to be carried out.

5. CONCLUSIONS

(1) In the room temperature-dry test of the specimens with composite adherends, the failure pattern of the joint was delamination of composite and the speed-dependent effect on the strength of the joint was negligible.

(2) In the room temperature-dry test using the specimens with aluminium and steel adherends and in the hot-wet test using the specimens with aluminium adherends, the failure pattern was initial yielding of adherend followed by adhesive failure and the speed-dependent effect was negligible.

(3) In the hot-wet test using the composite specimens the speed dependence was significant. As the test speed increased from 0.1 mm/min to 100 mm/min, the average ultimate load increased by 76%, 60% and 40% for specimens with $L/2t=7.5$, 15 and 30, respectively. In the case of $L/2t=7.5$ and 15 the failure pattern was adhesive (cohesive) failure. In the case of $L/2t=30$ the failure mode was delamination, doubler failure and central adherend failure, respectively, as the speed increased. Shorter overlap length tends to reduce the joint strength and increase the time dependence.

(4) In a room temperature-dry environment, for long double lap joints with metal adherends with tensile strength higher than those used in this test (yield strength higher than 345 MPa for aluminium and

500 MPa for steel, which may find rather few applications) and FM300 adhesive, the increase of ultimate load over the speed range from 0.1 to 100 mm/min is expected to be limited to below 12%.

(5) Further investigation of the time dependence of the delamination strength of the adherend and tensile strength of the adherend under a complicated stress state in the hot-wet environment needs to be considered and numerical simulation of the time-dependent behaviour of the joints in the hot-wet environment needs to be carried out.

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References

[1] Chiu, W. K., Rees, D., Chalkley, P. and Jones, R. *Comput. Struct.* **28**, 19 (1994).
[2] Jones, R., Chiu, W. K., Tomas, J. and Trippit, B. *Polymers and Polymer Composites* **3**, 11 (1995).
[3] Nagaraja, Y. R. and Alwar, R. S. *Comput. Struct.* **11**, 621 (1980).
[4] Delale, F. and Erdogan, F. *J. Appl. Mech.* **48**, 331 (1981).
[5] Yadagiri, S., Papi Reddy, C. and Sanjeeva Reddy, T. *Comput. and Struct.* **27**, 445 (1987).
[6] Roy, S. and Reddy, J. N. *Compust. and Struct.* **29**, 1011 (1988).
[7] Jones, R., Chiu, W. K. and Paul, J. *Composite Structures* **25**, 201 (1993).
[8] Mignery, L. A. and Schapery, R. A. *J. Adhesion* **34**, 17 (1991).
[9] Shannon, R. W. *Primary Adhesively Bonded Structure Technology (PABST)*: General Material Property Data, USAF, AFFDL-TR-77-107, Douglas Aircraft Company (1978).
[10] Hart-Smith, L. J. *Adhesive Bonding of Aricract Primary Structures.* Douglas Paper 6979, SAE Trans. 801209, SAE Aero-Space Congress and Exhibition, Society of Automotive Engineers (1980).

[11] Hart-Smith, L. J. *Adhesive-Bonding Double Lap Joints* NASA Langley Research Center Report NASA CR-112235 (1973).
[12] Molent, L., Callinan, R. J. and Jones, R. *Structural Aspects of the Design of an All Boron Epoxy Reinforcement for the F111C Wing Pivot Fitting:* Final Report, ARL, Aircraft Structures Report 436 (1992).
[13] Lee, C. C., Crosky, A. and Kelly, D. *Determination of the Mechanical Properties of Adhesive for Use in Design of Bonded Joints in Composite Structures.* Presented at 10th International Conference on Composite Materials, Whistler, Canada, 14–18 Aug (1995).
[14] Hart-Smith, L. J. "Joints" in *Engineered Materials Handbook* Vol. **1**, *Composites* ASM International, Metals Park, OH, USA, pp. 480–495 (1987).
[15] Wang, J. and Kelly, D. *Experimental Investigation on Time Dependent Behaviour of Adhesively Bonded Joints. Research Report*, The University of New South Wales, Sydney, Australia (1995).
[16] Niu, M. C. Y. Composite Airframe Structures (Conmilit Press Ltd, 1992).
[17] Wadsworth, H. M. *Handbook of Statistical Methods for Engineers and Scientists Mcgraw-Hill* Publishing Company, New York (1990).
[18] Robert, J. A. *Proceedings of The International Symposium on Adhesively Bonded Joints: Testing, Analysis, and Design* Baltimore, Maryland, USA, 10–12 Sept. 1986, pp. 276–288.
[19] Wang, J. and Kelly, D. *Proceedings of the Second International Symposium on Aeronautical Science and Technology* Jakarta, Indonesia, June 24–27, 1996, pp. 630–645.
[20] Yaniv, G., Peimanidis, G. and Daniel, I. M. *Test Methods for Design Allowables for Fibrous Composites:* 2nd Volume, ASTM STP 1003, Chamis, C. C. Ed. (American Society for Testing and Materials, Philadephia, 1989), pp. 16–30.