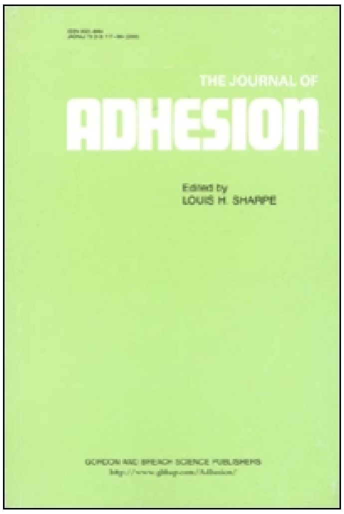

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Fatigue Behaviour of Adhesive Bonded Joints

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This paper presents experimental results of the fatigue behaviour of adhesive bonded plastic-to-plastic joints and metal-to-plastic joints under both dynamic and static loading. The fatigue life of the joints was found to be independent of the test frequencies and humidity for the range of values tested, but dependent on the mean stress level and test temperature with greater reduction in fatigue life observed in metal-to-plastic joints at higher temperature. Empirical equations from which the fatigue life of joints could be predicted were obtained by regression analysis.

KEY WORDS Exposure tests; fatigue life; fatigue tests; lap joints; metal-to-plastic joints; plastic-to-plastic joints.

INTRODUCTION

Plastics of high performance, with their durability and good mechanical and chemical properties, have been replacing other engineering materials in applications requiring demanding specifications. However, for large and intricate assemblies which cannot be moulded into one piece and for assemblies which involve integration of two incompatible materials such as metal and plastics, various joining techniques have to be employed in fabrication. Adhesive bonding has often proved to be the most efficient, economical and durable method for joining plastics and for joining plastics to other materials.

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Although research work on the fatigue strength of adhesive joint was reported as early as 1957,[1] it was only in recent years that considerable effort had been made in the study of fatigue behaviour of adhesive bonded joints. However, most of the research work was concentrated on metal-to-metal joints,[2-9] with plastic-to-plastic joints receiving little attention.

Grimes[10] studied fatigue testing of composite-to-composite bonded double-lap joints using different adherends and adhesives. The loading frequency was 1800 cycles per minute. Temperature rise during testing was found to be a function of the bond line stress level, as well as the type of adherend and adhesive material used.

The purpose of this investigation is to study the fatigue behaviour of adhesive bonded plastic-to-plastic joints and metal-to-plastic joints under static loading and intermittent dynamic loading at low frequency. An attempt has also been made to derive a theoretical model for the prediction of service life of the joints.

TEST SPECIMENS AND ADHESIVES

Three types of adherends were used namely, aluminium, polymethylmethacrylate (PMMA) made in Taiwan and general purpose polystyrene (GPPS) from Dow Chemicals. The dimensions of the specimens used were as in Table I(a), I(b).

TABLE I

(a) Specimen dimensions for static tests

Dimensions	Adherend	
	PMMA	GPPS
Width	25.4 mm	13 mm
Length	101.6 mm	101.6 mm
Thickness	4.3 mm	3 mm

(b) Specimen dimensions for fatigue tests

Dimensions	Adherend	
	Aluminium	PMMA
Width	25.4 mm	25.4 mm
Length	45 mm	45 mm
Thickens	1.6 mm	4.3 mm

The following two types of specimens were prepared.

(a) For joining PMMA to PMMA and aluminium to PMMA, the adhesive used was Araldite AW106/Hardener HV953U (Epoxy) from Ciba–Geigy.

(b) For joining GPPS to GPPS, the adhesive used was polychloroprene (3M1300) from 3M.

SPECIMEN PREPARATION

All specimens were of the single overlap type with an overlap of 12.7 mm (0.5 inch). Polymethylmethacrylate specimens were cut from cast sheet and then milled to obtain smooth edges, while aluminium specimens were cut from aluminium strips. General purpose polystyrene was injection moulded and cut to the desired length. Polymethylmethacrylate specimens were sanded with No. 220 sandpaper. Adhesive tapes of thickness 0.12 mm and width 0.8 mm were placed at the two longitudinal edges of one of the adherends so as to maintain a constant adhesive thickness as indicated in Figure 1. Specimens were then wiped with methanol/trichloroethylene to remove dirt, dust and grease.

The tape, which was left in place, could have been removed by machining the edges. However, this might have produced unwanted stress in the specimens. In any case, with its relatively low adhesive strength, the tape should have had only minimal effect on the strength of the joint.

Epoxy adhesive mix was prepared in the weight ratio of 100:80 and then applied to one side of each adherend, and the mating parts

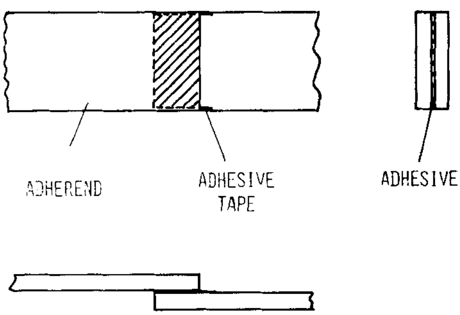


FIGURE 1 Test specimen.

were assembled in a specially constructed fixture to ensure accurate overlap and proper alignment. A constant weight of 0.9 N was placed over each joint to squeeze out excessive adhesive from the bonded area. Excess adhesive was removed before the adhesive had set.

Chloroprene adhesive was applied to one side of each GPPS adherend and the mating parts were assembled and kept in position by a 20 N clip.

Specimens were allowed to cure at ambient conditions for 3 days, during which period the temperature varied from 20°C to 24°C and relative humidity from 50% to 80%.

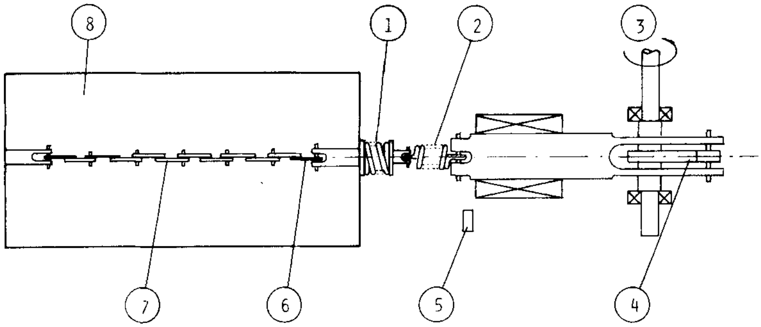
TEST PROCEDURES

(A) Static tests

Initially five specimens were tested in order to determine their tensile strength prior to static loading. The remaining specimens were then hung on a rack and exposed to ambient conditions in a laboratory over a period of twelve weeks, during which the temperature varied between 15°C and 28°C and relative humidity from 40% to 95%. Half of the specimens were subjected to a constant loading of 20 N while the remainder were not loaded and used as control specimens. Daily temperature and humidity variations were recorded. Specimens were removed and tested at two-week intervals.

(b) Fatigue tests

A fatigue testing machine (Fig. 2) was designed and constructed to conduct the fatigue tests. It consisted of a spring and cam mechanism which generated a sinusoidal load at a frequency between 33 and 90 rev/min. Ten specimens (3 metal-to-plastic, 7 plastic-to-plastic) were prepared for each trial. Four of the plastic-to-plastic joints were tensile tested prior to fatigue testing to make sure that their strength was within the expected range. The remaining six specimens were fatigue tested all at the same time, to minimize variations caused by difference in degree of curing and environmental conditions which might arise if they were tested at



1. COMPRESSION SPRING
2. EXTENSION SPRING
3. VARIABLE SPEED DRIVE
4. CAM
5. PHOTO SENSOR CONNECTED TO COUNTER
6. TYPE MP SPECIMEN
7. TYPE PP SPECIMEN
8. ENVIRONMENTAL CHAMBER

FIGURE 2 Schematic diagram of fatigue testing machine.

different times. Two groups of specimens were tested, namely, aluminium to PMMA (Type MP) and PMMA to PMMA (Type PP). The adhesive used was Araldite AW106/HV953U. The specimens were placed in series in an environmental chamber and were pin loaded at both ends. Specimens were initially prestressed to the desired stress level and then subjected to tensile loading at

TABLE II
Test matrix for fatigue testing

		No. of replicates for each testing condition					
		Test conditions temperature					
	Mean	45°C				55°C	
	stress	Wet (90% R.H.)		Dry (30% R.H.)		Dry (30% R.H.)	
Frequency (rev/min)	level MPa	Type MP	Type PP	Type MP	Type PP	Type MP	Type PP
54	1.07			3	3		
	1.20			3	3		
	1.50			3	3		
	1.80			3	3		
90	0.60					3	3
	0.90			6	6	3	3
	1.07	3	3	6	6		
	1.20	3	3	6	6	3	3
	1.50	3	3	6	6	3	3
	1.80	3	3	6	6		

the predetermined temperature, relative humidity (R.H.) and frequency, test conditions as described in Table II. Failed specimens were replaced by dummy specimens and tests were continued until all the specimens had failed. For specimens that did not fail at a runout cycle of 2×10^5 cycles, residual shear strengths were determined. In order for test conditions to resemble normal service conditions, intermittent testing with over-night stops were carried out. This type of intermittent testing should produce different results from continuous testing.

DISCUSSION OF RESULTS

Static test

Strength of joints exposed to the environment varied widely with the adhesive and adherend used. In general, there was an improvement in joint strength in both types of specimen after the first two weeks of exposure (Figure 3). Polychloroprene joints increased in strength by about 2.7 times their initial strength while epoxy joints showed only 10% improvement in joint strength. According to the manufacturer, epoxy joints should attain maximum strength after 3 days of curing, therefore one does not expect much improvement of strength thereafter. However, for polychloroprene joints where the adhesive setting process was affected by the evaporation of the solvent, maximum strength could only be attained at around 40 days, when residual solvent was completely removed.

Joints with epoxy adhesive were almost unaffected by the sustained load since no significant difference in joint strength was observed between the loaded and unloaded specimens. But for joints with polychloroprene adhesives, unloaded specimens invariably exhibited a higher joint strength than the loaded specimens. This discrepancy could be due to the difference in the time taken for the two different adhesives to cure completely. In addition, for epoxy joints, the static load of 20 N was only 2% of its original strength (1000 N) prior to loading and was perhaps too small to have any effect on the joint. However, for polychloroprene joints which had an original strength of only 140 N, the applied load was about 15% of its original strength. Visual examination showed

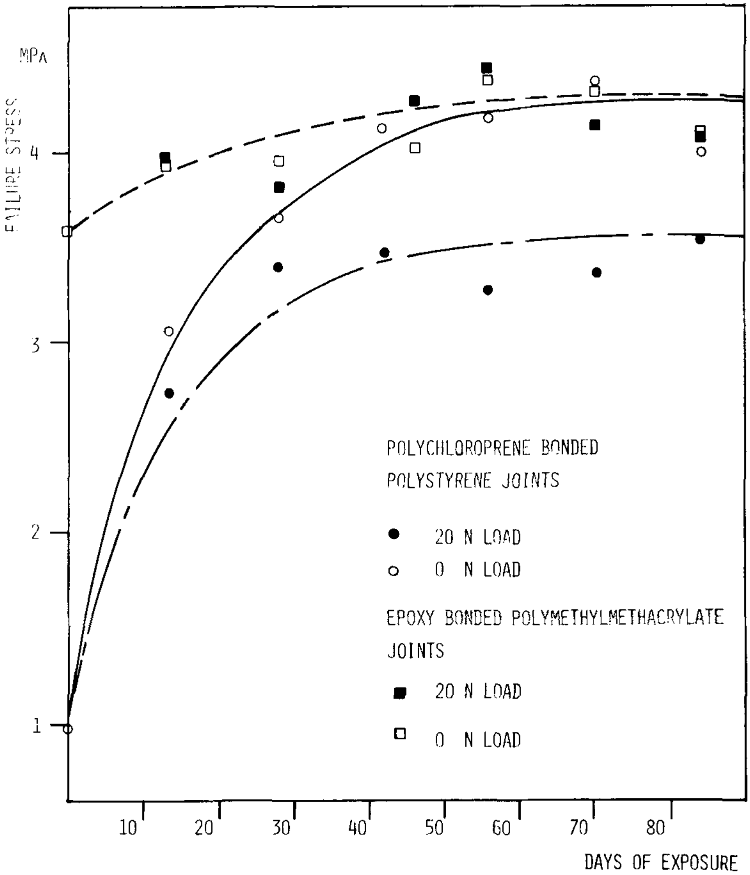


FIGURE 3 Environmental exposure of adhesive boned joints under sustained load.

that some of the joints had partially failed hours after the application of the load but were able to remain intact for the duration of the tests. Applying load when the joint was not fully cured weakened the joints, resulting in the lowering of joint strength as compared to the unloaded ones.

Daily recording of the relative humidity and temperature revealed only slight changes of environmental conditions.

Fatigue tests

The results of fatigue tests are presented in the form of S–N diagrams relating number of cycles to failure to mean stress level. Empirical equations from which the fatigue life of joints can be predicted were obtained by regression analysis.

Backward regression was used to eliminate variables which have little or no effect on the fatigue life. It was found that the fatigue performance of epoxy loaded joints was not dependent on the test frequency (within the range of 55 to 90 rev/min) and humidity but rather on the test temperature and mean stress level.

For PMMA-to-PMMA joints which were exposed to 45°C temperature and loaded under different humidity and frequencies, the relationship between fatigue life and mean stress level can be expressed as follows:[11]

$$\frac{1}{\log N} = 1.59 \times 10^{-1} S + 0.49 \times 10^{-1}$$

where N = No. of cycles to failure and S = Mean stress level in MPa.

For aluminium-to-PMMA joints under the same conditions, the following relationship was obtained:

$$\frac{1}{\log N} = 6.9 \times 10^{-2} S + 0.12$$

The regression curves with the upper and lower confidence bound at 95.5% confidence are shown in Figures 4 and 5.

If temperature is introduced as an additional variable, the following equations were obtained.

(a) For PMMA-to-PMMA joints:

$$\frac{1}{\log N} = 1.48 \times 10^{-1} S + 9.6 \times 10^{-3} T - 3.64 \times 10^{-1}$$

where T = Temperature °C

(b) For aluminium-to-PMMA joints:

$$\frac{1}{\log N} = 7.95 \times 10^{-2} S + 1.465 \times 10^{-2} T - 5.53 \times 10^{-1}$$

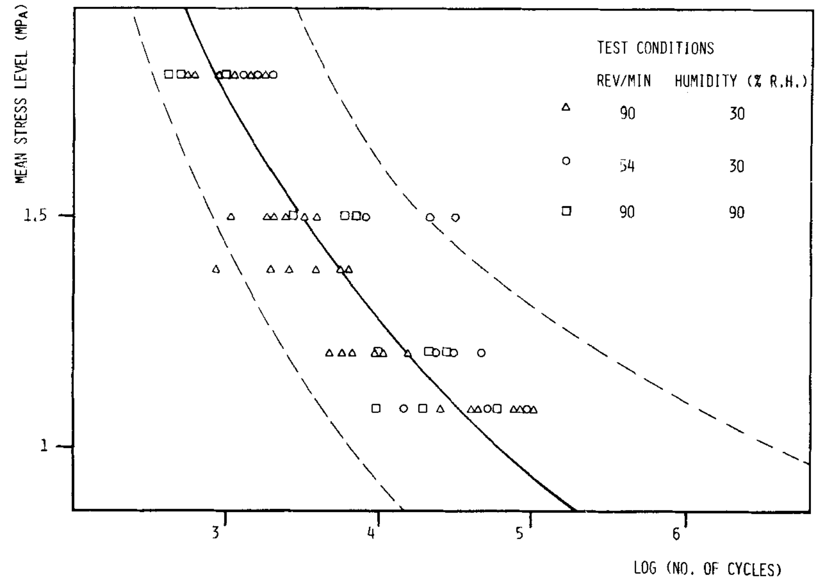


FIGURE 4 S-N Diagram of type PP joint at 45°C.

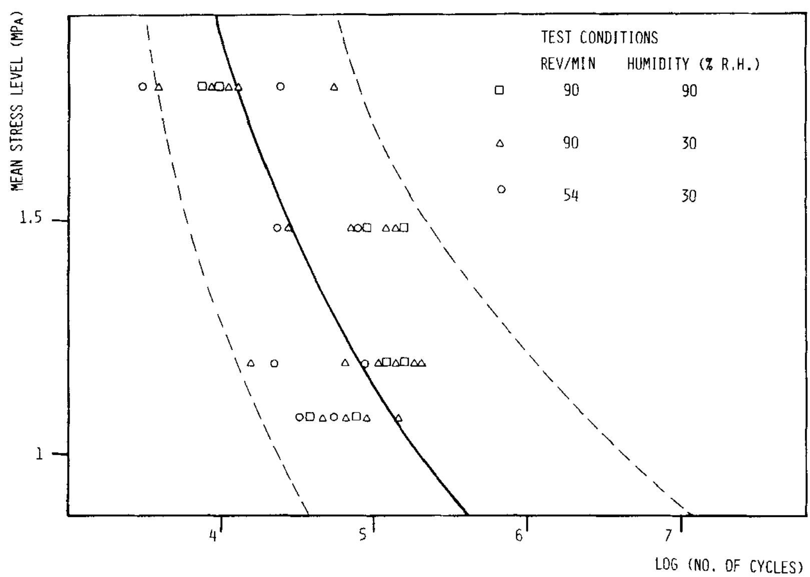


FIGURE 5 S-N Diagram of type MP joint at 45°C.

Regression lines at 45°C and 55°C for different joints are shown in Figures 6 and 7.

It can be seen that the fatigue life of plastic-to-plastic and metal-to-plastic joints are temperature dependent, and is dependent of cyclic frequency (within the range of 55 to 90 rev/min) and humidity.

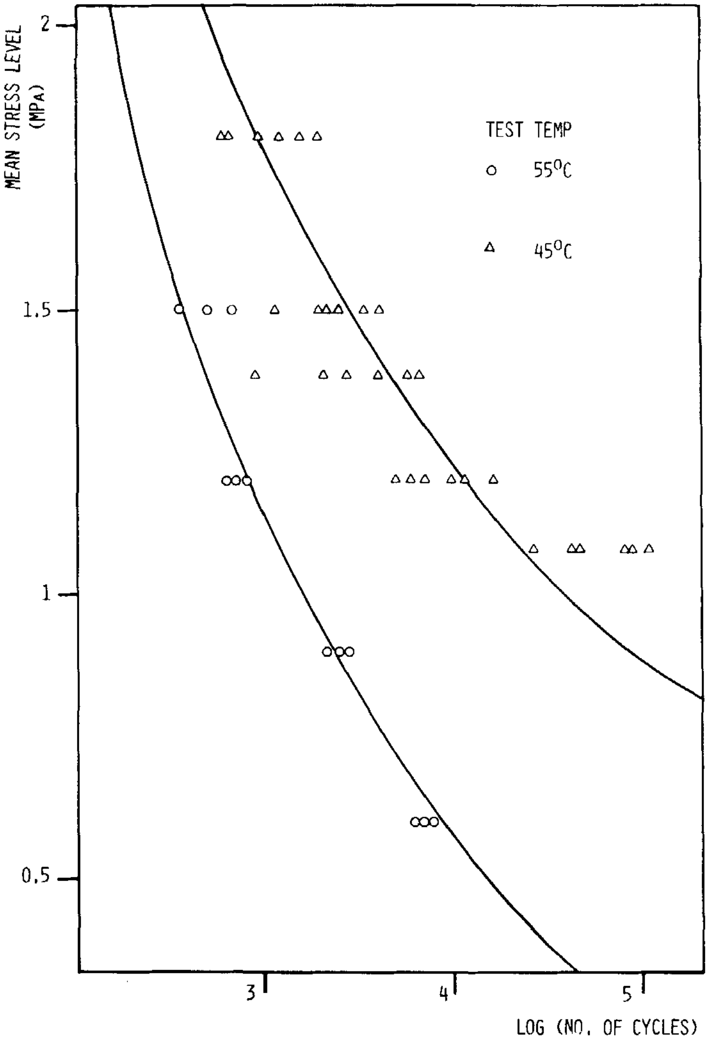


FIGURE 6 S–N Diagram of type PP joint at 90 rev/min and 30% R.H.

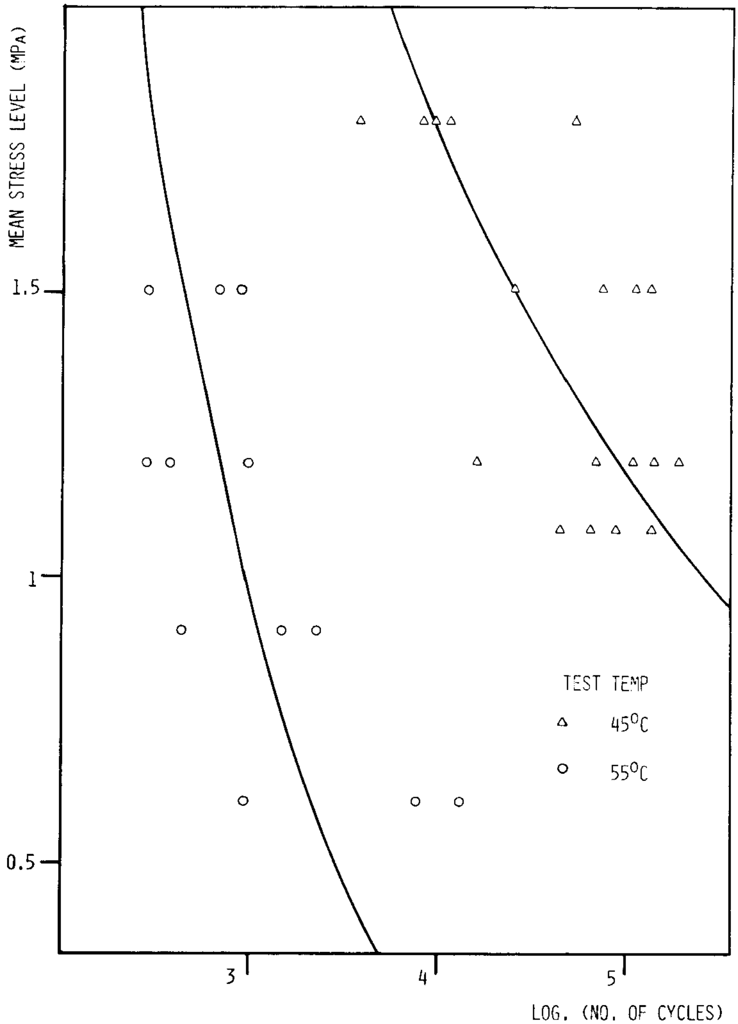


FIGURE 7 S–N Diagram of type MP joint at 90 rev/min and 30% R.H.

Both types of specimens exhibited significant decrease in life when test temperature was increased from 45°C to 55°C. However, this effect was more pronounced in metal-to-plastic joints.

The fact that the fatigue strength was temperature dependent has been reported by other researchers. In Mostovoy's experiment,[2,3] an increase in the test temperature resulted in the lowering of the fatigue resistance of adhesive bonded specimens. Marceau[4] also claimed that elevated temperature shortened the life of aluminium-to-aluminium joints, while Mays[5] reported a slight change in the performance of epoxy bonded steel lap joints over a temperature range of −25°C to 45°C, but the joints were significantly weakened at 55°C.

The difference in the coefficient of thermal expansion between metals and plastics could well have contributed to the marked decrease in fatigue life of metal-to-plastic joints when tested over a range of temperatures. As the expansion coefficient of polymeric materials is greater than that of metals as shown in Table III, significant stress could occur in the polymer and at the interface. This effect, which was more severe as temperature was increased, was responsible for the shortening of fatigue life in the joints.

It was found that frequency had no effect on the fatigue life of adhesive bonded joints. The test frequency range was probably not wide enough for any effect to be detected. Mostovoy[2] also reported similar findings where the da/dn against ΔG_i curve (crack growth per cycle against difference between the maximum and minimum value of the crack extension force) was independent of frequency within the range of 0.67 to 180 cycles/min. However, Marceau[4] showed that if the test frequency was significantly lowered to 0.8 cycles/hour, this would produce the most damage per cycle whereas those tested at 1800 cycles/min produced the least damage.

Humidity appeared to have little effect on the fatigue life of the adhesive bonded joints. Any degradation process would take several months or more. Thus, for the short exposure time involved in this fatigue test, the moisture from the atmosphere had little chance to attack the adhesive. When preparing the joint in a high

TABLE III
Coefficient of thermal expansion of selected materials

Material	Thermal expansion[12] (mm/mm°C)
Aluminium	20.9–23.8
PMMA	81
Epoxy	30.6–90

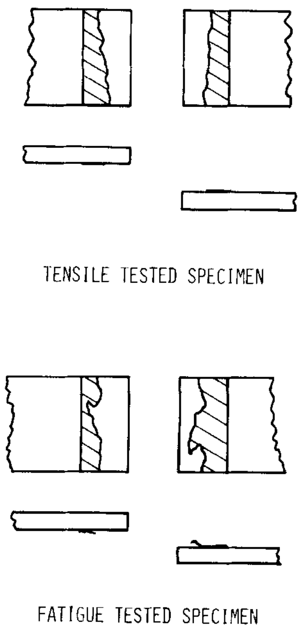


FIGURE 8 Failed test specimens.

humidity environment, there might well be moisture present at the bondline. The effect has not been investigated.

Regardless of the type of specimen, the mode of failure of the joints under the fatigue test was different from that subjected to a tensile test as depicted in Figure 8. There was visible separation of the adhesive layer from the adherend in the case of fatigue failure.

Source of scatter

Although maximum care had been taken in the preparation of specimens to eliminate the variability in joint strength, scatter still occurred. However, for fatigue tests, a high degree of scatter is not uncommon. Scatter in the low cycle fatigue regime, *i.e.*, 10^2 to 10^5 total number of cycles, has always been high with a standard deviation of log life ranging from approximately 0.3 to 0.7.[13] In the present case, the standard deviation is approximately 0.38. Thus the scatter in total life is considered acceptable.

CONCLUSIONS

Based on the results presented above, the following conclusions can be drawn:

1) Joint strength under static loading increased with time, attaining maximum at around 40 days, for polychloroprene bonded joints.

2) The fatigue life of adhesive bonded plastic joints and metal-to-plastic joints was independent of frequency and humidity, for the range of values tested.

3) The fatigue life of adhesive bonded plastic joints and metal-to-plastic joints was dependent on the mean stress level and test temperature, with greater reduction in fatigue life observed in metal-to-plastic joints at higher temperature.

4) Fatigue and tensile tested specimens failed in a different manner regardless of the type of specimen used.

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