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Stress-Strain Behavior of Adhesives in a Lap Joint Configuration at Ambient and Cryogenic Temperatures

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Stress-Strain Behavior of Adhesives in a Lap Joint Configuration at Ambient and Cryogenic Temperatures

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SUMMARY

An experimental technique has been developed at McDonnell Douglas Corporation (MDC) that can be used to derive the shearing stress-strain distribution in an adhesive-bonded joint and therefore its shear modulus. The MDC technique uses a double-lap joint model instrumented with either photostress coatings or strain gauges. The technique was used to determine the effects of different bond thickness on the stress-strain behavior of an epoxy adhesive and the effect of a cryogenic environment on the stress-strain characteristics of a polyurethane adhesive.

The shearing stress-strain characteristics were compared for an epoxy adhesive with joint thicknesses of 0.010 and 0.063 in. and indicate that the epoxy adhesive in the thin joint is softer at low strain levels. A polyurethane adhesive was tested at both room temperature and -320°F. The results clearly indicate the stiffening effect of the polyurethane adhesive at cryogenic temperatures.

The use of photoelastic coatings or strain gauges to measure the strain distribution has proved to be both accurate and reliable. The use of either method is dependent on the particular application. Photoelastic coatings offer the advantage of whole-field strain measurements, while strain gauges permit measurements in extreme temperature environments.

NOMENCLATURE

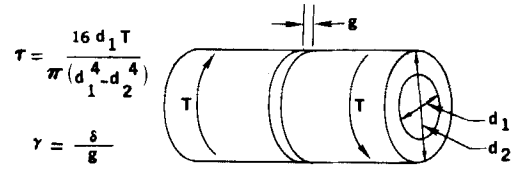
$a_1, a_2, \ldots, a_m$	polynomial coefficients
b	width of joint, in.
d	diameter
E	modulus of elasticity of adherends, 10×10^6 psi
E_p	modulus of elasticity of photoelastic coating, 450,000 psi
g	thickness of glueline, in.
G	shear modulus of adhesive, psi
h_1, h_2	thickness of adherends, in.
h_p	thickness of photoelastic coating, in.
k	photoelastic coating fringe constant, 0.108 in/in.-fringe
ℓ	length of overlap, in.
n	fringe order, fringes
m	degree of polynomial curve
p_t	correction factor
P	load, lb
$P_2(x)$	load on adherend 2 at location x, lb
T	torque, lb
tot	total
x,y	Cartesian coordinates
δ	shear deformation
γ_0	shear strain in adhesive at x = 0, in./in.
$\gamma(x)$	shear strain in adhesive at location x, in./in.
ϵ_1, ϵ_2	principal strains, in./in.
$\epsilon_2(x), \epsilon_2(y)$	normal strains in adherend 2 at location x, in./in.
λ	wavelength of white light, 2.27×10^{-5} in.
ν	Poisson's ratio of adherend, 0.3
$\tau(x)$	shear stress at adhesive at location x, psi

INTRODUCTION

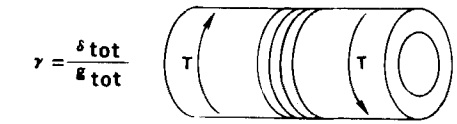
The analysis of the stress distribution in the glueline of adhesive lap joints requires that the shear modulus of the adhesive be known. Previous experiments by many investigators [1] indicate that the shear modulus of the thin film of adhesive in a lap joint cannot be predicted using simple bulk specimen tests (tensile coupon or bulk shear specimen). Some adhesives exhibit higher shear moduli and ultimate shear strengths as the glueline thicknesses are reduced. Thus, for accurate determination of adhesive shear modulus the test specimen must be constructed so that the glueline thickness is the same as that in the lap joint to be analyzed. The shear modulus specimen should also meet the following additional requirements: (1) The adhesive film should be subjected to shear stress only, (2) it must be possible to determine the shear stress and shear strain in the adhesive accurately, and (3) the specimen should be relatively simple to construct and test.

One of the most commonly used tests for determining adhesive shear modulus is a torsion-type test. Experiments using this type of test specimen are reported in Refs. [2-4]. A thin layer of adhesive joins the ends of thin-walled pipes or rings which can be subjected to torsion (Figs. 1a and 1b). The shear stress is calculated from the torsion load and the cross-section area of the adhesive layer. The shear strain is determined from the relative shear deformation across the adhesive layer. The strain measurements are difficult to obtain since the shear deformation across the layer is very small. In an attempt to overcome this difficulty several layers of the adhesive, separated by thin rings, are built up so that the total angular displacement is larger and more easily measured (Fig. 1b). The multiple-adhesive-layer torsion test has inherent complexities in specimen preparation which make it difficult to maintain uniform-thickness adhesive layers.

Lap-type specimens (Fig. 1c), which use either deformation data or joint strength, have also been used to determine adhesive shear modulus [5-8]. If one assumes that uniform shear stress exists in a lap joint, it is possible to relate the lap joint deformation to the applied load and find the adhesive shear modulus. This assumption appears to be valid only for lap joints composed of rigid adherends joined by a low-modulus adhesive. The method which utilizes the lap joint strength to determine the adhesive shear modulus is based on an analysis of the stress distribution in a lap joint subjected to a shear load. This technique gives a value of adhesive shear modulus based on results of tests where the adhesive has exceeded the elastic limit and its relation to the elastic shear modulus is not known.



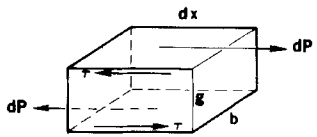
a) SINGLE ADHESIVE LAYER SPECIMEN



b) MULTI-LAYER SPECIMEN

c) LAP-TYPE SPECIMEN

Fig. 1. Adhesive specimens.



ELEMENT OF ADHESIVE

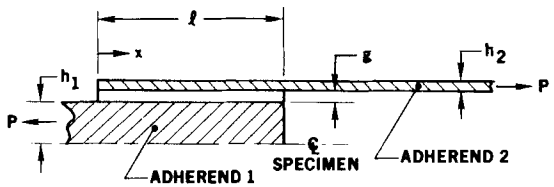


Fig. 2. Geometry of lap joint.

The method of obtaining the shearing stress-strain distribution in the adhesive reported in this paper employs a technique proposed by Hahn [9] in which double lap joints (Fig. 1c) instrumented with photostress coatings or strain gauges are used. This technique is based on the equilibrium condition that exists between the shear forces in the adhesive and the tensile forces in the adherend. This equilibrium condition must be satisfied at each location along the glueline. It is shown that the shear-stress and shear-strain distributions along the glueline can be determined by an exact strain measurement of the adherend adjacent to the adhesive layer. From the shear-stress and shear-strain distributions the adhesive stress-strain relationship can be plotted, and from the slope of this curve the adhesive shear modulus can be found.

THEORY

The analysis of the shearing stress and shearing strain distribution in the adhesive was developed by Hahn [9] and is based on the following assumptions (refer to Fig. 2). (1) There is no bending in the joint. (2) The adherend thickness (h_2) is sufficiently small so that there is no stress gradient between the adhesive-adherend interface and the external surface of the adherend. (3) The widths of both adherends (b) are the same. (4) Both adherends have the same modulus of elasticity ($E_1 = E_2 = E$). (5) The shear stress (τ) is uniform through the thickness (g) of the adhesive. Using these assumptions, the equilibrium equation for an element of the adhesive (Fig. 2) can be written as

$$\tau(x)bdx = dP(x) \tag{1}$$

The tensile strain in adherend 2 is

$$\epsilon_2(x) = \frac{P_2(x)}{Ebh_2} \tag{2}$$

and can be measured using either a photoelastic coating or strain gauges. Equation (2) can be rewritten as

$$P_2(x) = \epsilon_2(x)Ebh_2$$

Differentiating Eq. (2)

$$dP_2(x)/dx = Ebh_2(x)dx/d\epsilon_2$$

and rewriting Eq. (1) as

$$dP(x)/dx = \tau(x)b$$

and incorporating the derivative of Eq. (2) in Eq. (1), we find

$$\tau(x) = Eh_2 \frac{d\epsilon_2(x)}{dx} \tag{3}$$

This is the shear-stress distribution in the adhesive in terms of the strain in adherend 2.

The shear strain of an adhesive element in the glueline is determined from the difference of the integral values of the adherend strain between the limits of x = 0 to x = x and the shear strain of the adhesive at x = 0.

$$\gamma(x) = \gamma_0 \, 3 \frac{1}{g} \int_0^x \epsilon_2(x)dx - \frac{1}{g} \int_0^x \epsilon_1(x)dx \tag{4}$$

The strain in adherend 1 follows from

$$\epsilon_1(x) = \frac{P - P_2(x)}{Ebh_1} \tag{5}$$

$P_2(x)$ is expressed in Eq. (2) and when combined with Eq. (5) gives

$$\epsilon_1(x) = \frac{P}{Ebh_1} - \frac{h_2}{h_1} \epsilon_2(x) \tag{6}$$

Equation (4) can now be rewritten as

$$\gamma(x) = \gamma_0 + \frac{1}{g} \int_0^x \epsilon_2(x)dx - \frac{1}{g} \int_0^x \left[\frac{P}{Ebh_1} - \frac{h_2}{h_1} \epsilon_2(x)\right] dx$$

or

$$\gamma(x) = \gamma_0 + \frac{1}{g} \left(\frac{h_1 + h_2}{h_1}\right) \int_0^x \epsilon_2(x)dx - \frac{Px}{gEbh_1} \tag{7}$$

This is the shear-strain distribution in the adhesive in terms of the strain in adherend 2.

From Eqs. (3) and (7) it is seen that the only quantities to be measured are the tensile strain in adherend 2 $[\epsilon_2(x)]$ and the applied load P. The strain measurement can be accomplished with a high degree of accuracy using either the photoelastic coating technique or strain gauges.

However, coating the surface with a photoelastic material affects the strain distribution in adherend 2, and in order to account for this stiffening effect Eq. (2) is modified as follows

$$P_2(x) = \epsilon_2(x) E b h_2 p_t \tag{8}$$

where

$$p_t = 1 + \frac{E_p h_p}{E h_2} \tag{9}$$

p_t is known as the "coating correction factor" [10]. Equation (3) is then changed to

$$\tau(x) = E h_2 p_t \frac{d\epsilon_2(x)}{dx} \tag{10}$$

Similarly, Eq. (5) becomes

$$\epsilon_1(x) = \frac{P - E b h_2 p_t \epsilon_2(x)}{E b h_1} = \frac{P}{E b h_1} - \frac{h_2}{h_1} p_t \epsilon_2(x) \tag{11}$$

which in turn modifies Eq. (7) to

$$\gamma(x) = \gamma_0 + \frac{1}{g}\left(\frac{h_1 + h_2 p_t}{h_1}\right) \int_0^x \epsilon_2(x)dx - \frac{Px}{E b h_1 g} \tag{12}$$

Equations (10) and (12) are those used in determining the adhesive shear modulus when the photoelastic coating technique is used. If strain gauges are used to measure $\epsilon_2(x)$, then $h_p = 0$ and $p_t = 1$ in these equations.

After the strain $\epsilon_2(x)$, on the surface of adherend 2 has been determined experimentally, it is necessary to evaluate the derivative and integral of the strain function for use in Eqs. (10) and (12). Although any of a number of numerical or analytical techniques may be used, the use of a polynomial expansion provides both an accurate curve fit to the data and an analytical expression that is well suited for use with a computer.

A polynomial expansion using the method of least squares of the form

$$\epsilon_2(x) = \sum_1^m a_m x(m-1) \tag{13}$$

was fitted to the data. The degree of the polynomial curve, m, was varied until an accurate fit was obtained.

Equation (13) when differentiated is

$$\frac{d\epsilon_2(x)}{dx} = \sum_1^m a_m(m-1)\ x(m-2) \tag{14}$$

When Eq. (13) is integrated it becomes

$$\int \epsilon_2(x)dx = \sum_1^m \frac{a_m}{m} x^m \tag{15}$$

By substituting Eqs. (14) and (15) in Eqs. (10) and (12), the shearing stress, τ, and shearing strain, γ, can be evaluated at any location along the adhesive.

The shear modulus, G, which is the slope of the shear stress, τ, versus shear strain, $\gamma - \gamma_0$, can be obtained by plotting Eqs. (10) and (12).

$$G = \frac{d\epsilon}{d(\gamma - \gamma_0)} = \frac{d\tau}{d\gamma} \tag{16}$$

The more familiar stress-strain diagram, τ vs. γ, is obtained by extrapolating the curve τ vs. $(\gamma - \gamma_0)$ to intersect with $\tau = 0$ and shifting the curve by the amount γ_0 so that the curve passes through the origin, as shown in Fig. 3.

EXPERIMENTAL PROCEDURE

A total of three models were made to the dimensions shown in Fig. 4. The test parameters and the type of adhesive used are presented in Table 1.

The specimens were fabricated by assembling the adherends in a jig (Fig. 5) and casting the adhesive joint. The jig consisted of a center block which aligned the thick adherends with the center line of the specimen, and two cover plates which were clamped over the thin adherends and

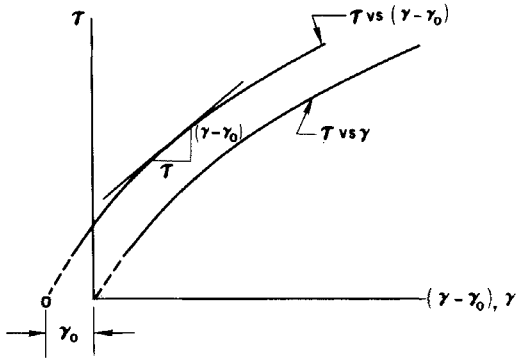


Fig. 3. Stress-strain diagram of the adhesive.

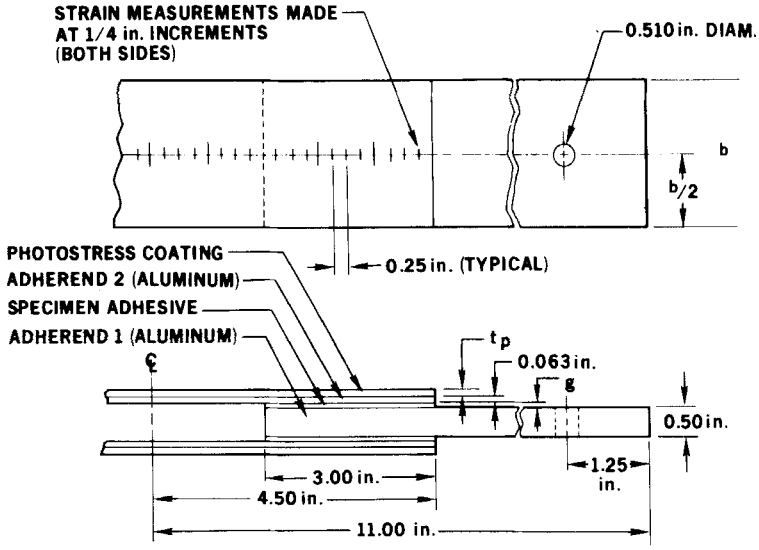


Fig. 4. Specimen geometry.

located them with respect to the specimen center line. The thickness of the adhesive joint was determined by varying the thickness of the center block and using shims at each end of the thin adherends. After the adhesive had cured, the center block was removed and the assembly was machined to the dimensions shown in Fig. 4 and Table 1. Using this procedure it was possible to make symmetric specimens of constant joint thickness.

Table 1. Specimen Parameters

Model	b, in.	g, in.	h_p, in.	Adhesive
1	2.00	0.063	0.117	Epoxy
2	2.00	0.010	0.117	Epoxy
3	1.83	0.063	0	Polyurethane

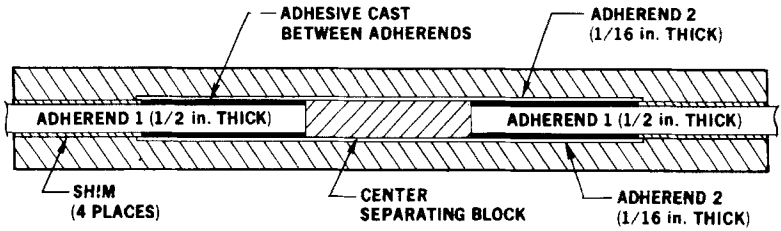


Fig. 5. Assembly jig used for casting joints. *Notes:* (1) Clamp assembly together before casting adhesive. (2) After curing remove outside plates, bond photostress to both sides, and machine to final size. (3) Remove center separating block.

The epoxy adhesive used for models 1 and 2 consisted of 100 parts by weight of Hysol 2039 and 29 parts by weight of Hysol 3561. The epoxy adhesive was cured at room temperature. The cryogenic adhesive, EC-3515, is a polyurethane adhesive made by 3M Company. It is composed of 100 parts by weight of resin and 11 parts by weight of MOCA hardener. It was mixed and cured according to the manufacturer's instructions.

The models were instrumented on the thin adherends with either photostress coatings or strain gauges, as shown in Figs. 6 and 7. A reference grid was scribed on the photostress coatings at 0.25-in. intervals and birefringence measurements were made at these locations for the photostress tests. The uniaxial strain gauges (Micro Measurements, EA-13-062ED-120) were located at the same 0.25-in. intervals for the remaining tests.

The test schedule for the three models tested is presented in Table 2. All tests were made by recording the initial strain readings, applying the tensile load in Table 2, and monitoring the strain readings until the gauges had stabilized. For the adhesives used in these tests, this condition occurred in less than 1 hr, and the strain measurements used in this paper are those made after 1 hr under load. The photostress measurements were made with a reflection polariscope, and the test setup and a typical fringe

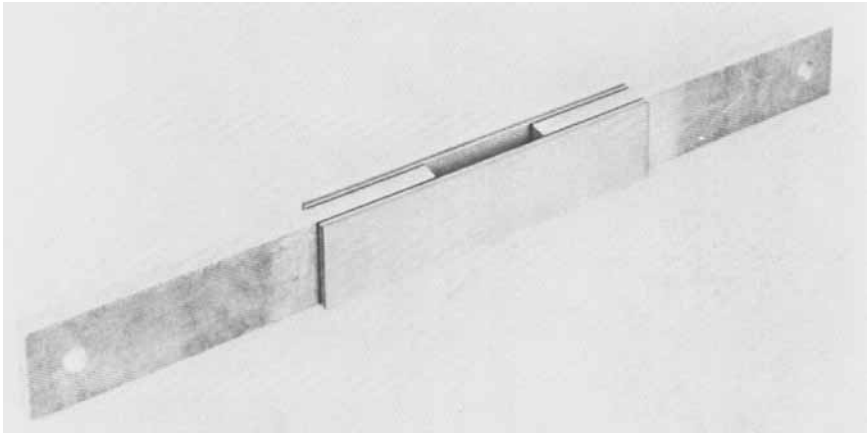


Fig. 6. Photostress test specimen.

Fig. 7. Strain gauge test specimen.

Table 2. Test Program

Test	Model	Adhesive	g, in.	Instrumentation	Test temperature	2P, lb.
1	1	Epoxy	0.063	Strain gauges	Ambient	2000
2	1	Epoxy	0.063	Photostress	Ambient	2000
3	2	Epoxy	0.010	Photostress	Ambient	2000
4	3	Polyurethane	0.063	Strain gauges	Ambient	1830
5	3	Polyurethane	0.063	Strain gauges	-320°F	1830

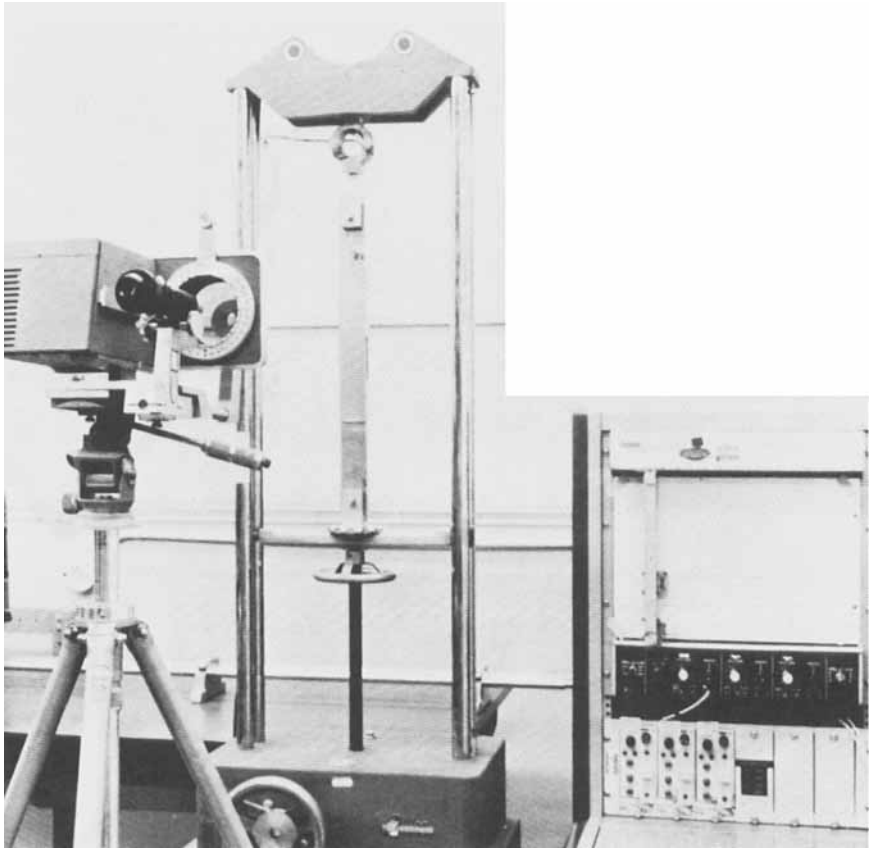


Fig. 8. Photostress technique test setup.

pattern are shown in Figs. 8 and 9. The test setup for the strain-gauged specimens was essentially the same except for the instrumentation.

Tests 1 and 2 were identical except for the instrumentation used to measure the strain in adherend 2 and were designed to form a comparison between the strain gauge data and the photostress data. The strain gauges were removed from the model after test 1 was completed and the photoelastic coatings were applied. The test was then repeated as test 2.

Test 3 was included to show the effects of varying the glue joint thickness. Tests 2 and 3 had different glue joint thicknesses, but were identical in all other respects.

Tests 4 and 5 were made to evaluate a polyurethane adhesive at both

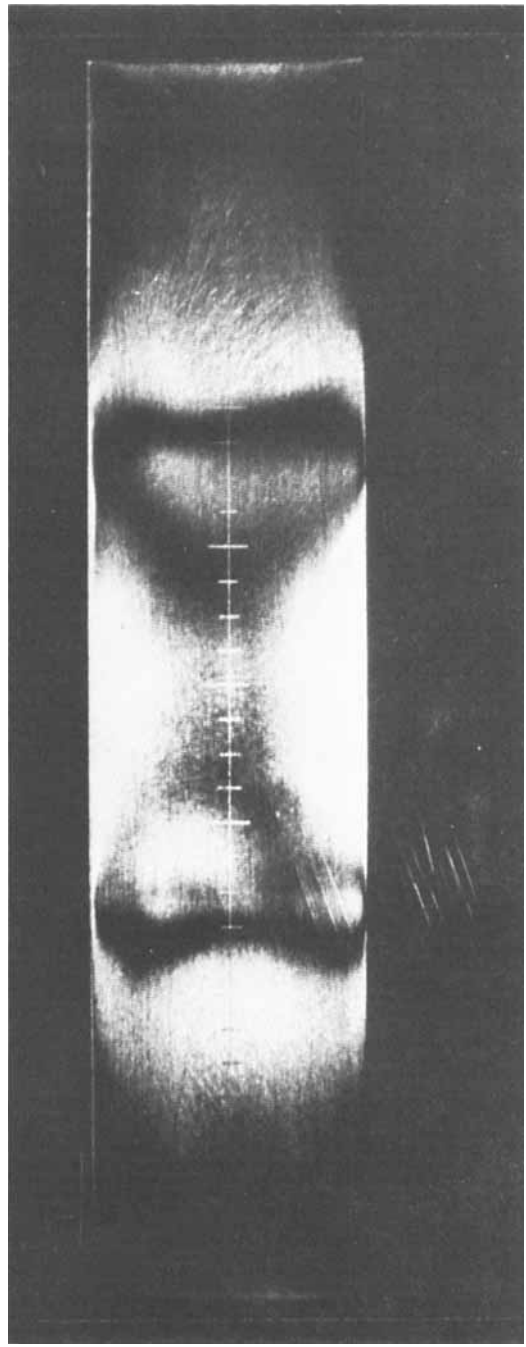


Fig. 9. Fringe pattern in photostress coating.

ambient and cryogenic temperatures. The same model and instrumentation were used for both tests. The only difference between the two tests was that the specimen was immersed in a cryostat containing liquid nitrogen for test 5. After the strain-gauged specimen had stabilized at -320°F, the test procedure used for all the other tests was followed.

RESULTS

The photostress fringe readings obtained from tests 2 and 3 were converted to the strains in adherend 2 using the strain optic law [11].

$$\epsilon_1 - \epsilon_2 = \frac{\lambda}{3h_p k} n \tag{17}$$

For these tests, the principal strains are

$$\epsilon_1 = \epsilon_2(x) \tag{18}$$

and

$$\epsilon_2 = \epsilon_2(y) = -\nu\epsilon_2(x) \tag{19}$$

Using Eqs. (18) and (19), the strain in adherend 2 is

$$\epsilon_2(x) = \frac{1}{(1+\nu)} \frac{\lambda}{2h_p k} n \tag{20}$$

The strain distributions from tests 1, 4, and 5 were found directly from the strain gauge readings.

The polynomial expansion was fitted to each set of test results using the method of least squares to minimize any errors. It was found that for tests 1, 2, 4, and 5 a fourth-degree polynomial was the lowest-order polynomial that would accurately fit the experimental data. Because of the constant strain level in test 3 from x = 0.5 in. to x = 1.5 in., it was necessary to match the experimental data in three segments. The first segment from x = 0 to x - 0.5 in. was matched by a fourth-degree polynomial curve. The second section was a constant value, and the third section from x = 1.5 in. to x = 3.0 in. was matched using a third-degree polynomial. Comparisons between the experimental strain values and the values calculated from the polynomial expansions are presented in Figs. 10 and 11.

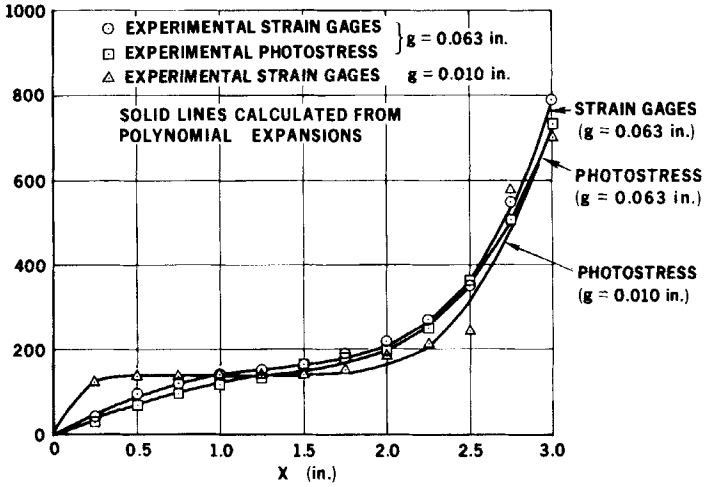


Fig. 10. Comparison of calculated and experimental strain distribution for epoxy adhesive.

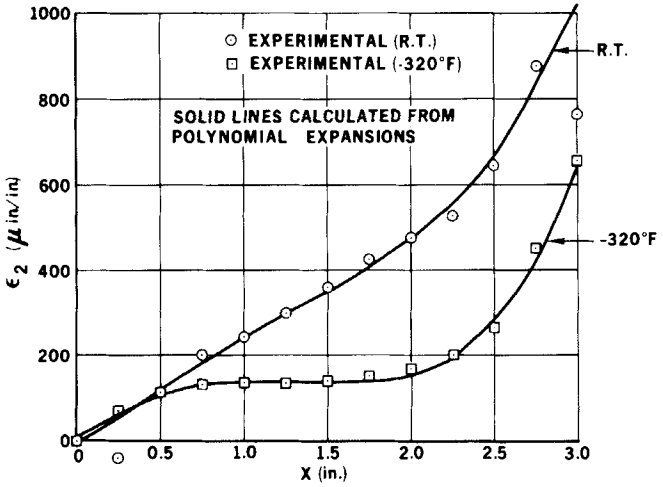


Fig. 11. Comparison of calculated and experimental strain distribution for polyurethane adhesive.

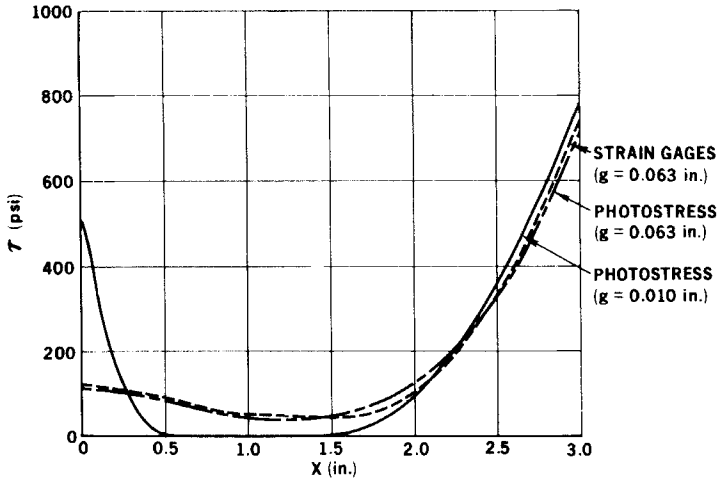


Fig. 12. Shearing stress distribution for epoxy adhesive.

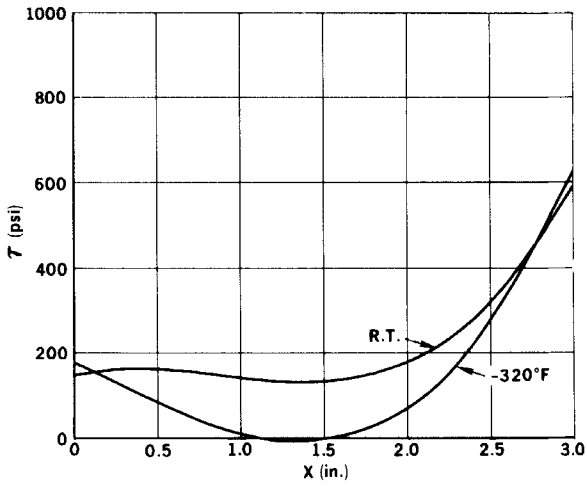


Fig. 13. Shearing stress distribution for polyurethane adhesive.

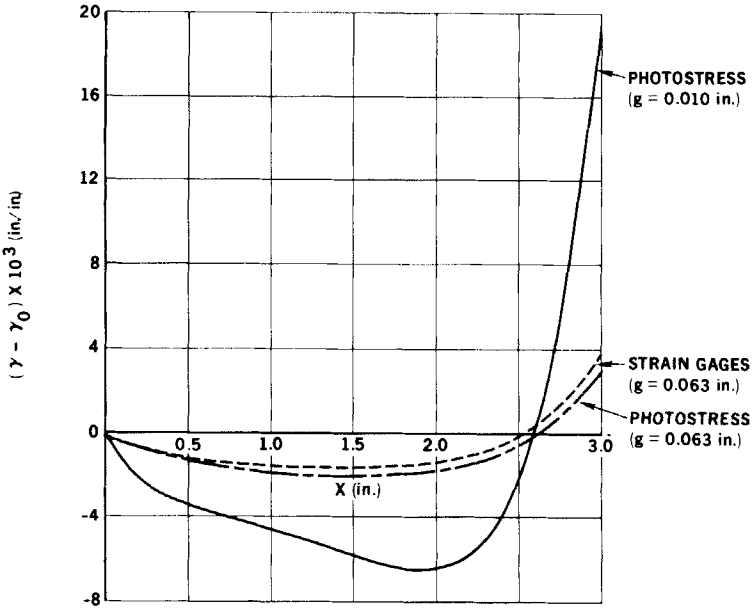


Fig. 14. Shearing strain distribution for epoxy adhesive.

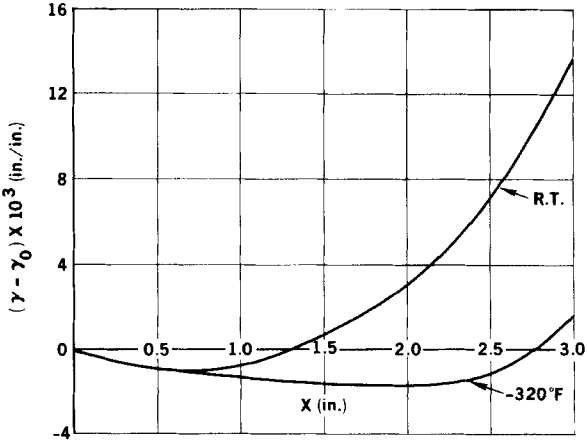


Fig. 15. Shearing strain distribution for polyurethane adhesive.

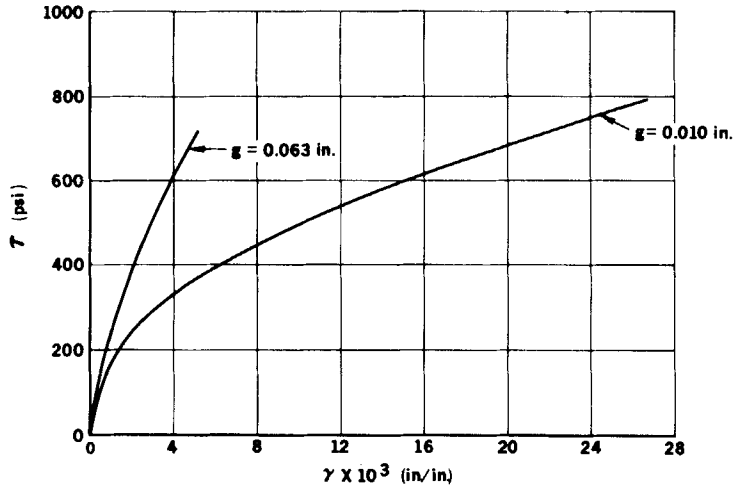


Fig. 16. Shearing stress-shearing strain diagram for epoxy adhesive.

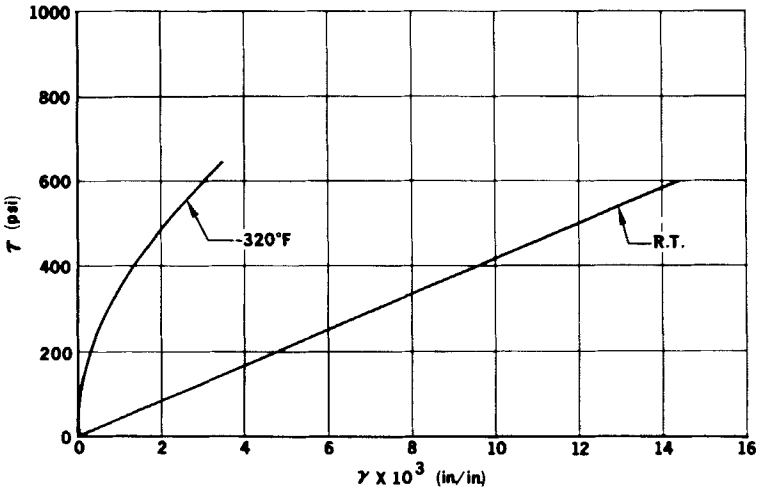


Fig. 17. Shearing stress-shearing strain diagram for polyurethane adhesive.

The shearing stress and shearing strain distributions were computed using the analytical expressions for the strain in adherend 2 and Eqs. (10), (12), (14), and (15). Figures 12 and 13 show the shearing stress, τ, at any position along the bond line for the epoxy and polyurethane adhesives. Figures 14 and 15 present the shearing strain distribution, $(\gamma - \gamma_0)$, at all locations for both types of adhesive.

The shear stress-strain diagram for the epoxy adhesive for g = 0.063 and 0.010 in. is shown in Fig. 16. The results have been extrapolated to intersect the $\tau = 0$ axis and shifted by an amount γ_0 to form the conventional shearing stress-strain diagram. The same information is presented in Fig. 17 for the polyurethane adhesive, EC-3515, and indicates the difference in the material behavior at ambient and cryogenic temperatures.

DISCUSSION OF RESULTS

The strain measurements from tests 1 and 2 (g = 0.063 in.) (Fig. 10) indicate that either strain gauges or the photoelastic coating method may be used with equally good results. The advantage of using the photoelastic coating method is that it is possible to view the fringe distribution and make the measurements at any points desired. Strain gauges are restricted to measurements at the gauge locations, but they can be used at cryogenic temperatures where other methods, including photoelastic coatings, cannot. Although the specimens were only moderately loaded, the strain distribution was easily measured using either technique.

The shear stress, τ, was found to be very dependent on the degree of the polynomial expansion used to describe the experimental strain values in adherend 2. As Eq. (10) indicates, the shear stress is directly related to the derivative of the calculated strain distribution. Consequently, the use of a high-order polynomial expansion (between the sixth and tenth degree) would produce a very accurate fit at the data points, but the derivative would fluctuate between the local maximum and minimum points on the curve. For this reason the lowest-order polynomial that would accurately fit the experimental data was used for the analysis.

The data from test 3, g = 0.010 in., were the most difficult to fit because of the constant portion of the curve between x = 0.5 in. and x = 1.5 in. An eight-degree polynomial matched the data, but the derivative, and consequently the shear stress, fluctuated to such an extent that the results were not reasonable. The problem was solved satisfactorily by fitting a fourth-degree polynomial to the first portion of the curve and a third-degree

polynomial to the last portion. Since the center section was constant, the derivative and therefore the shear stress were equal to zero.

The shearing strain, $\gamma - \gamma_0$, is associated with the area under the strain curve (for example, Figs. 10 and 11) and is relatively insensitive to the degree of the polynomial curve fit. Since the shearing strain as computed from Eq. (12) is the difference between two terms of nearly equal magnitude, it was necessary to use a double-precision computer routine to eliminate round-off errors.

In general, any numerical or analytical method may be used to describe the strain distribution provided that it matches the experimental strain data and the derivative or slope is a smooth curve. The polynomial expansions used in this study satisfied these requirements and were easily adapted to a computer solution.

The shearing stress-shearing strain diagrams, Figs. 16 and 17, have been extrapolated to $\tau = 0$ because of the difficulty in obtaining reliable results from the beginning of the joint. The trend of the curve from the remaining points, as discussed by Hahn [9], is due to the error associated with the small strain readings and the difficulties presented by the differentiation and integration processes. However, the initial slope of the stress-strain diagram for an adhesive is not as important as for other materials because of the generally nonlinear stress-strain relationship. A stress analysis for the adhesive in a lap joint would have to include large strain effects, and consequently the exclusion of data from the beginning of the stress-strain diagram would not be a serious handicap.

The effect of varying the joint thickness at higher strain levels is clearly shown in Fig. 16 for the epoxy resin. For clarity, only the results of the photostress tests with g = 0.063 and 0.010 in. are shown. For the larger strain levels, the shear modulus of elasticity (the slope of the stress-strain curve) was lower for the thin joint, g = 0.010 in., than for the thicker joint, g = 0.063 in. The shear modulus at small strain levels is not well defined in Fig. 16 but it would probably be greater for the thinner joint, as has been reported by other investigators [1].

A comparison of the stress-strain diagrams for a polyurethane adhesive tested at room temperature and -320°F is presented in Fig. 17. At room temperature the adhesive is relatively soft and consequently both the strain distribution in adherend 2 (Fig. 11) and the stress-strain diagram of Fig. 17 are gradual curves without any abrupt changes. However, at -320°F the material is much stiffer, and both the strain distribution shown in Fig. 11 and the stress-strain diagram presented in Fig. 17 are greatly changed.

CONCLUSIONS

The results of investigations in the area of adhesive-bonded joints have been previously found to be dependent on three major factors. These are: (1) The geometric similarity between the test specimen and the production adhesive joint, (2) the accuracy and reliability of the experimental measurements, and (3) the applicability of the test analysis to the actual conditions which exist in the joint. The results of this study have shown that it is possible to fabricate a model that closely simulates a production-bonded joint and to determine the adhesive joint properties using conventional test techniques.

The use of photoelastic coatings or strain gauges to measure the strain distribution has proved to be both accurate and reliable. The use of either method is dependent on the particular application. The use of photoelastic coatings offers the advantage of whole-field strain measurements, whereas the use of strain gauges permits measurements in more extreme environments.

The analysis and use of a lap joint specimen has proved to be of particular importance since the majority of the analytical work done on adhesive joints is based on variations of this configuration. Thus, the material properties as determined from this investigation are directly applicable to the present analysis methods. Because of the many variables associated with adhesive-bonded joints (such as joint thickness and elevated and cryogenic temperature environments), this type of analysis is a definite asset.

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Discussion of Paper by G. J. Tiezzi and H. M. Doyle

Stress-Strain Behavior of Adhesives in a Lap Joint Configuration at Ambient and Cryogenic Temperatures

M. B. Price: Does your adhesive test allow translation to dynamic systems, or does your requirement of static loading only permit interpretation in static applications?

H. M. Doyle: The only limitation to performing dynamic test analysis would be the stress analysis. The experimental techniques, particularly the strain guages, are capable of translation to dynamic systems. However, most adhesives are strain-rate sensitive and consideration must be given to this factor in the analyses. The stress analysis used for this study is valid for static conditions only. A new analysis would have to be developed for dynamic testing.

P. Throckmorton: What surface treatment is applied to the test adherends prior to application of the adhesive? Do you feel that different etch conditions might alter the stress-strain patterns for a given adherend-adhesive combination (thus complicating interpretation of the test data)?

H. M. Doyle: The surfaces of the aluminum adherends were treated for bonding by a sulfuric acid-dichromate etchant (British Etch). The stress-strain behavior of the adhesive should not be affected by the condition of the adherend if proper wetting of the adhesive to the adherend has been accomplished.