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The Sandwich Bending Specimen for Characterizing Adhesive Properties

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Abstract. Techniques to characterize the mechanical properties of adhesives in a bonded geometry are important because the behavior can differ from that of bulk adhesive samples. Although there are a number of such tests, the simplicity of the sandwich beam specimen makes it attractive. This test involves three-point bending of a beam made by bonding together two metal strips with the adhesive. For linear elastic materials, the shear modulus of the adhesive can be calculated from the bending stiffness of the beam with a number of published analyses. This paper conducts experiments to examine the sandwich test and the potential to extend it to viscoelastic adhesives since standard viscoelastic test equipment can easily measure three-point bending. The results show that the stiffness of the sandwich beam is sensitive to the presence of the adhesive throughout most of the interesting range for adhesive properties. Second, when tested as a function temperature and time (or frequency), the stiffness of the beam behaves like a classic viscoelastic property. Finally, in the rubbery, elastic range, the shear moduli calculated from beam tests with thick bonds agreed with those obtained from tests on bulk samples for adhesives. In the temperature range where the adhesive is hard (glassy behavior), however, problems were observed for the geometries tested here. Some of these problems may be attributable to assumptions made in the analyses used, and this suggests the need for a new analysis that addresses these limiting assumptions and extends the test to viscoelastic materials.

Key words: adhesives, bending, epoxy, shear modulus, superposition, viscoelasticity

1. Introduction

There is considerable interest in the mechanical properties of adhesive resins when they are in an adhesive bond. These properties can differ from those for bulk samples of the adhesive due to changes in chemistry resulting from variations in the thermal history during cure or affects of the adherends. Moreover, the properties of the adhesive in the bond provide insight into the state of the resin and how that state changes as a function of time due to aging or environmental attack. Finally, when the bond is very thin, the adhesive may respond in unexpected ways due to residual stresses or the constraints imposed by the adherend interface. To study such effects, a number of experiments have been designed to measure the adhesive

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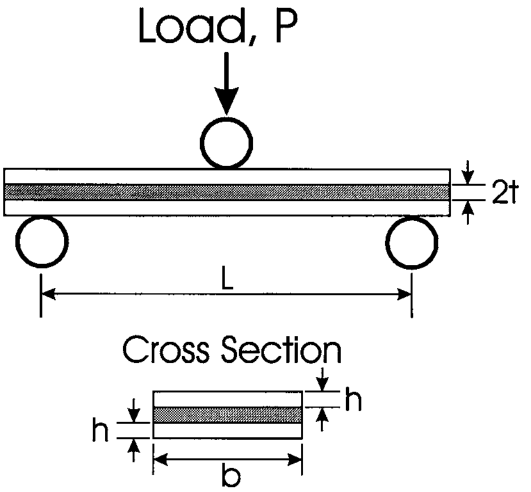

Figure 1. Diagram of three-point bend specimen. The adhesive (gray) is between two steel strips.

behavior, particularly the shear modulus. Two of the most popular measurements for the shear properties of an adhesive are the thick adherend test (ASTM E-5656, 1995) and the napkin ring experiment (ASTM E-229, 1995). Both give good results and can provide complete stress-strain behavior of the bonded adhesive in shear when done properly. Unfortunately, both experiments are difficult and expensive to do. They require very accurate machining and fabrication of specimens, exacting alignment of samples during the test, careful analysis of results, and specialized test equipment. Some years ago an alternative experiment was proposed by Moussiaux et al. (1987), and Roy et al. (1987). It is based on bending of a beam specimen made by bonding together two metal strips with the adhesive. When this sandwich beam is subjected to bending, the adhesive is deformed in shear. With an appropriate analysis and knowledge of properties such as the tensile modulus of the metal, the shear modulus of the adhesive can be deduced from the bending stiffness of the sandwich beam. Since the work of Moussiaux et al., a number of authors (Brinson et al., 1995; Morman et al., 1992; Sharm and Rao, 1982; Spigel and Roy, 1993) have explored this measurement method. Moreover, a number of papers were published even before the work cited above that analyzed the bending of a sandwich structures (March, 1935; Hoff, 1956; Stavsky and Hoff, 1969; Adams and Weinstein, 1975). These studies provide alternatives to the Moussiaux et al. analysis. Although these papers consider a number of loading geometries, the focus in the current study is the three-point bending test (Figure 1).

Unlike the thick adherent experiment and the napkin ring test which can generate complete stress-strain curves, the sandwich beam bending test focuses just on the small-strain modulus. On the other hand, the bending experiment has advantages since the specimens are inexpensive and easy to make. Moreover, bending is a well-established experiment that is easy to do. What makes the sandwich beam particularly attractive and motivated the current study, however, is the fact that standard viscoelastic test equipment can easily measure three-point bending. This means the potential exists for an experiment that would characterize viscoelastic properties of the adhesive as a function of temperature in both transient and dynamic modes in a fully automated manner. Since the adhesive is supported with metal adherends, the test minimizes problems associated with creep of the adhesive during the test in temperature ranges where it is soft. It should be noted, however, that the use of any particular viscoelastic test device generally limits the sample geometries that can be examined, and this has consequences that will be discussed later in the paper.

In considering the sandwich beam as a viscoelastic test method, one problem is that the analyses discussed above are for linear elastic materials only. Moreover, the results from the experiments that have been conducted to date are somewhat contradictory. Some show good agreement between shear moduli calculated from the sandwich beam test and those obtained by measurements on bulk adhesive samples (Adams, 1999; Morman et al., 1992). In other cases, the agreement is not so good (Spigel and Roy, 1993; and Miyagi et al., 1999). When differences were observed, one explanation offered was that the properties of an adhesive in a thin bonded layer may be different from those of bulk samples. This may or may not be true, but the consequences are that the results do not serve to validate the test as a measurement method for determining adhesive properties. As a result, the current work conducts experimental studies to investigate the test. Relatively thick bond lines are used so comparisons can be made with tests on bulk samples of the adhesive. The work seeks to address three questions. First, is the contribution of the adhesive in this three-layer structure large enough to make measurement of adhesive modulus reasonable over the range of properties that would be of interest in viscoelastic characterization? Second, is the behavior of the sandwich beam viscoelastic and how does it compare with tests on bulk adhesive samples in the same range of temperatures and time scales? Finally, in the elastic range, do calculations of the adhesive moduli using the published analyses agree with measurements on bulk samples of the adhesive? If the answers to these questions are positive, then there is significant motivation to consider developing a new analysis that will extend the test to viscoelastic adhesives.

2. Theory

Before discussing the experiments, it is worthwhile to examine two of the published analyses for the sandwich beam in three-point bending (Figure 1). These two were chosen because they have been compared with experimental data, and because, in some ways, they represent limiting cases for the experiments performed here. To understand this, the following sections summaries both the analyses and the assumptions made in developing the equations. In both cases, the stiffness of the sandwich beam is described in terms of P/δ where P is the load applied to the center support and δ is the resulting displacement of that support. For a linear response, the displacement should vary with the load in such a way that this ratio is a constant, i.e. independent of load.

2.1. ANALYSIS 1

The first solution discussed here for the sandwich beam bending problem was proposed by Moussiaux et al. (1987). Their approach assumes that the adhesive layer deforms in pure shear which means that the thickness of the adhesive must be thin compared with the thickness of the adherend and the length of the beam. The analysis provides the following expression for stiffness:

$$\frac{P}{\delta} = \frac{4E_f}{\beta}\,\frac{b(2(t+h))^3}{L^3}, \tag{1}$$

where

$$\begin{aligned}
\beta &= \left(1+\frac{t}{h}\right)^3\left[4-\frac{4}{\gamma^2}+\frac{6E_f}{G_f}\left(\frac{h}{L}\right)^2+\frac{12}{\gamma^2}\left(\frac{1}{(\alpha\gamma)^2}-\frac{\tanh(\alpha\gamma)}{(\alpha\gamma)^3}\right)\right],\\
\alpha^2 &= \frac{3G_a}{4E_f}\left(\frac{L}{h}\right)^2\frac{[1+2(t/h)]^2}{(t/h)},\\
\gamma^2 &= 1+\frac{1}{3[1+2(t/h)]^2}.
\end{aligned}$$

E_f and G_f are the tensile and shear moduli of the metal adherends; h, t, b, L are the geometry parameters shown in Figure 1; and G_a is the shear modulus of the adhesive. Once the stiffness is measured experimentally, these equations can be used to determine G_a. Note that Equation (1) is the expression that would be obtained for a homogeneous beam with a modulus of (E_f/β). Consequently, (E_f/β), which is a normalized stiffness, will be termed the pseudo-modulus in the discussions here.

2.2. ANALYSIS 2

The second analysis was developed by Adams and Weinstein (1975) for a structure with thin face sheets on a thick core material. When applied to a bonded joints, the core material is taken as the adhesive. Because the face sheets are thin compared to their length, the analysis does not include shear effects in these layers. On the other hand, this solution, unlike the previous analysis, does includes both shear and bending deformations in the adhesive. The final expression for beam stiffness is

$$\frac{P}{\delta} = \frac{6K_T}{\ell^3}\left[1+\left(\frac{3(K_T-K)}{\ell^3K\alpha^2}\right)\left(\ell-\frac{\tanh(\alpha\ell)}{\alpha}\right)\right]^{-1}, \tag{2}$$

Table I. Test sample dimensions.

Adherent thickness, h (mm)	Adhesive thickness, $2t$ (mm) Thin	Mid-thickness	Thick
0.254	0.120 ± 0.010	0.740 ± 0.020	1.402 ± 0.090
0508	0.152 ± 0.008	0.573 ± 0.017	1.297 ± 0.066
0.762	0.131 ± 0.010	0.571 ± 0.016	1.139 ± 0.050

where

$$\begin{aligned} K &= E_a I_a + 2E_f I_f, \quad K_T = E_a I_a + 2E_f I_{fa}, \\ \alpha^2 &= G_a \left(\frac{2K + (2t+h)^2 E_f\, bh}{K E_f\, h(2t)} \right), \quad \ell = L/2, \quad I_f = \frac{bh^3}{12}, \\ I_a &= \frac{b(2t)^3}{12}, \quad I_{fa} = I_f + \frac{bh(2t+h)^2}{4}. \end{aligned}$$

2.3. COMPARISON

For the tests conducted here, the constraints imposed by the test machine dictate that the thicknesses of the adhesive and the adherends are not dramatically different. As a result, neither analysis is ideal. On the other hand, they are, in a sense, limiting cases. The first derivation is designed for systems with thick adherends and a thin adhesive layer while the second analysis best describes a situations with thin adherends and a thick adhesive layer. As a result, two equations are a useful starting point for the geometries used here.

3. Experimental Section[1]

The sandwich specimens were constructed by bonding two steel strips together with an adhesive. The metal strips are normally used as spacers so they have a very uniform thickness. They were cut to a length of (60.00 ± 0.05) mm (± indicates standard uncertainty throughout the text and in the tables) and cleaned thoroughly prior to bonding. A di-functional epoxy (diglycidylether of bisphenol A, Dow Chemical) was degassed and mixed with a stoichiometric concentration of a di-functional amine curing agent (Jeffamine D-400, Texaco). The epoxy mixture was placed between the metal strips, and spacers were used to control the bond thickness. The samples were allowed to cure at room temperature for 90 h and then placed in a 100°C oven for 24 h. At the end of that time, the oven was turned off and allowed to cool slowly which provided a standard thermal history for all specimens. Tests were performed on nine different geometries made by combining three bond

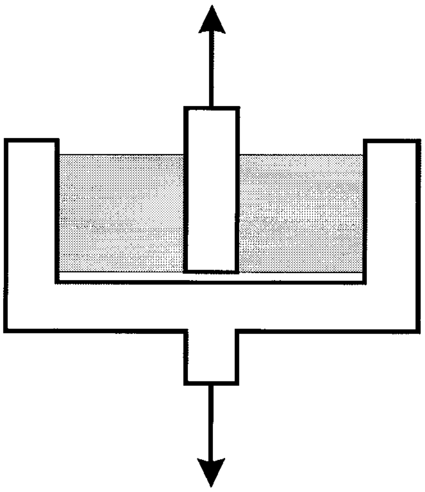

Figure 2. Diagram of double lap test for adhesive (gray) properties.

thicknesses with three adherend thicknesses. The dimensions (see Figure 1) were $L = (40.88 \pm 0.05)$ mm and $b = (12.70 \pm 0.05)$ mm for all samples while the adherend thicknesses (h) were: (0.254 ± 0.002) mm, (0.508 ± 0.002) mm, and (0.762 ± 0.002) mm. The bond thicknesses were nominally 0.15, 0.6, and 1.2 mm but varied from sample to sample as shown in Table I. In addition to the sandwich specimens, bulk samples of the adhesive were made so its properties could be measured directly. These samples were prepared with exactly the same procedure described above except that the epoxy mixture was poured into open face molds and cured to produce small plates. The plates were machined to get specimens with the needed dimensions.

The sandwich beam samples were characterized in three-point bending using a Dynastat mechanical spectrometer with the three-point bending attachment. Tests were conducted over the temperature range from 20 to 45°C using both transient mode (1 to 20,000 s) and dynamic mode (0.05 to 50 Hz). The dynamic tests were performed by imposing a sinusoidal deformation on top of a static deformation where the amplitude of the static deformation was chosen so that the load and displacement were always positive. At selected temperatures and frequencies, tests were conducted at a variety of strain amplitudes to be sure that the response was linear (amplitude independent). For five of the samples, short term stress relaxation tests were also performed (1 to 200 s). The specimens were selected so that the adhesive thickness varied at a fixed adherend thickness (0.508 mm) or the adherend thickness varied at an approximately constant adhesive thickness (nominally 0.6 mm). The specimens were run at two temperatures chosen so that the behavior was expected to be elastic. Since the glass transition temperature of the epoxy is approximately 30°C, the selected temperatures of 5 and 55°C should produce a glassy and a rubbery response, respectively. For each sample and temperature, between five and ten tests were run at different strain levels to test for linear elastic behavior and to estimate the experimental uncertainty in the measurement. The steel strips used to make the sandwich specimens are expected to be linear elastic for all the test conditions measured here. To demonstrate this, temperature-frequency scans were performed on the steel strips over the range of conditions used to test the sandwich beams. In addition, transient stress-relaxation experiments were run at 5 and 55°C on the three different thickness steel strip at six different strain amplitudes. The maximum strain examined was larger than that used in any of the sandwich specimen tests. These measurements not only demonstrated linear elastic behavior but also established the tensile modulus of the steel, E_f, and the experimental uncertainty in the measurement: (200.9 ± 10) GPa. The shear modulus for the steel, G_f, which was calculated assuming a Poisson's ratio of 0.3 (Moussiaux et al., 1987), was (77.3 ± 3.9) GPa. For comparison, three different measurements of shear modulus were made on bulk samples of the epoxy adhesive. First, a bar specimen was fabricated with dimensions (35.19±0.20) mm by (11.02±0.05) mm by (1.42 ± 0.05) mm. The dynamic mechanical response of the bar was measured using torsional deformations about the long axis of the bar. Although this torsional deformation does not produce perfect shear, experiments have shown that the shear modulus calculated from such a test agree with values obtained with other techniques. The measurements were conducted on an ARES Mechanical Spectrometer (Rheometric Scientific Inc.) over a temperature range from 0 to 60°C at frequencies between 0.016 and 16 Hz. This same bar was also examined with transient tests (1 to 200 s) in three-point bending at 5°C using the Dynastat. In addition to the time range, the properties were determined at various amplitudes to be sure the behavior was approximately linear elastic. The shear modulus was then estimated by assuming a Poisson's ratio of 0.35 for the epoxy. The third test on bulk adhesive involved a double lap specimen (Figure 2). Two identical epoxy blocks measuring (21.05 ± 0.05 by 15.21 ± 0.05 by 5.20 ± 0.05) mm were bonded in the jig. Pulling the jig in tension generates shear in the epoxy. Again, the tests were performed at 5°C over a time scale (1 to 200 s) and range of strains to assure the behavior was approximately linear elastic.

4. Results and Discussion

The first issue addressed in this study is the sensitivity of the sandwich beam test to the properties of the adhesive. This question was examined in two ways. First, the analytical solutions (Equations (1) and (2)) were evaluated numerically to determine the predicted dependence of the experimentally measured quantity (beam stiffness, S) on the adhesive shear modulus, G_a. Clearly, with this approach, the conclusions are valid only for the range of conditions where the assumptions involved in deriving the equations are valid. The results are shown in Figure 3 for the mid-thickness adhesive bond with 0.508 mm adherends. Despite the fact that the assumptions made in the two derivations are quite different, the predicted

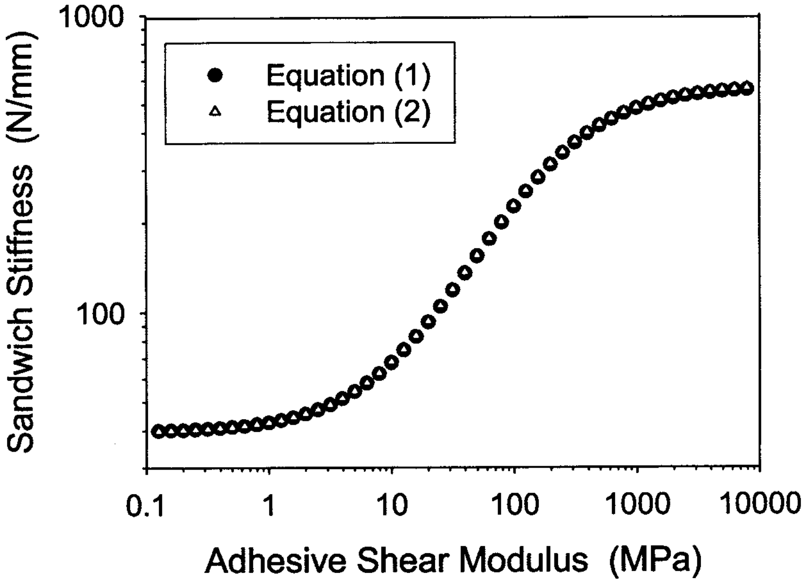

Figure 3. Plot of Equations (1) and (2) for mid-thickness adhesive bond with 0.508 mm adherends.

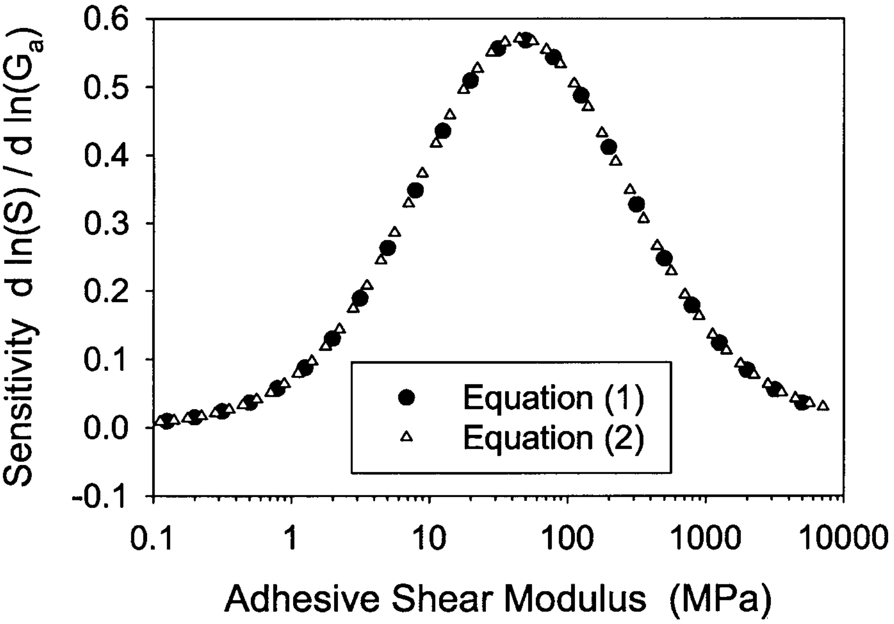

Figure 4. Sensitivity as a function of G_a calculated from Equations (1) and (2) for the mid-thickness adhesive bond with 0.508 mm adherends.

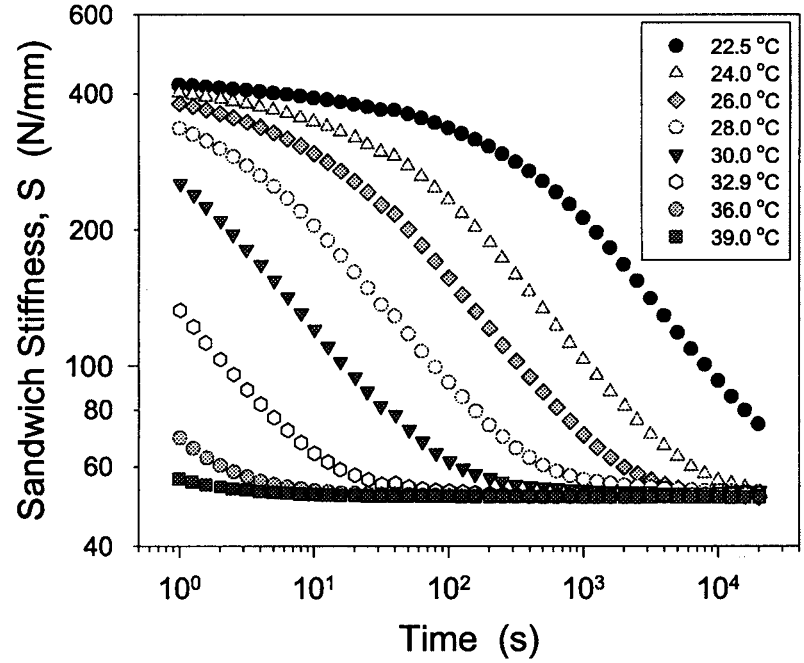

Figure 5. Transient data for mid-thickness adhesive bond with 0.508 mm adherends. The fractional uncertainty in the stiffness data is 2%.

behaviors for this particular geometry are surprisingly similar. When the adhesive modulus is very low, numerical calculations indicate that both analyses approach the result for bending of two independent metal bars. In the limit of high adhesive shear modulus, calculations show that the stiffness of the sandwich approaches the behavior of a solid metal bar with thickness, $(2h + 2t)$. Between these limits, both equations give almost identical predictions for the variation of sandwich beam stiffness with adhesive shear modulus. With regard to sensitivity, the figure indicates that the beam stiffness changes only when the adhesive shear modulus varies between about 1 MPa and 1 GPa. Within this range, the equations suggest that the test has the potential to determine G_a from bending stiffness. Fortunately, this is the range of properties that is generally of interest for an adhesive. On the other hand, the stiffness changes only one order of magnitude for a three order of magnitude change in G_a. As a result, the stiffness needs to be measured very accurately to get a good estimate of the adhesive shear modulus. If sensitivity is defined as the fractional change in stiffness that results from a fractional change in adhesive shear modulus, the result is the slope in a log-log plot $(d\ln(S)/d\ln G_a)$. Figure 4 shows a plot of sensitivity for the two equations. Both give similar results with a maximum between 1 MPa and 1 GPa and lower sensitivity as you move away from the maximum. Of course, these curves depend on the geometry so by adjusting the sample dimensions, the position of the maximum can be changed.

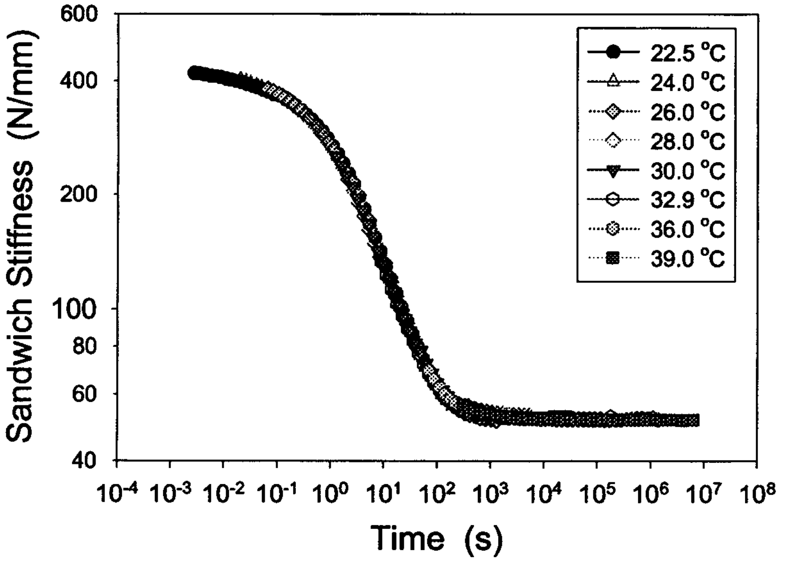

Figure 6. Master curve for data in Figure 5. The reference temperature is 30°C.

The second approach to examining sensitivity involves measuring the stiffness of a sandwich beam as a function of temperature. The T_g of the model adhesive used here is approximately 30°C so a temperature scan from 20 to 45°C will cover the range from glassy behavior to rubbery behavior. Since the adherends are metal, any change in beam stiffness is attributable to the adhesive. Figure 5 shows the experimentally measured beam stiffness for the mid-thickness adhesive with 0.508 mm adherends as a function of time for eight different temperatures. The results indicate that the stiffness changes by almost an order of magnitude between 20 to 40°C. This is similar to the predictions discussed above for the elastic models even though the experimental results are clearly viscoelastic.

The oscillatory experiments were analyzed by treating the beam stiffness in the same way that a dynamic modulus is handled. The stiffness is expressed as a complex number with real and imaginary components, S' and S'', respectively. The loss tangent is defined as (S''/S'). A plot of S' *versus* frequency looks similar to Figure 5 except that going up in time is equivalent to going down in frequency. Consequently, these results generally support the assertion made above that the sandwich test is sensitive to the adhesive properties and, therefore, has potential as a characterization method for adhesives. All of the nine samples tested gave qualitatively similar results. As might be expected, when the thickness of the adhesive layer was larger, the range of stiffnesses covered in going from low to high temperatures increased significantly. Larger adherend thicknesses gave stiffer samples with a reduced range of stiffnesses covered in the temperature sweep.

The second issue addressed in this study is the degree to which the sandwich beam exhibits behavior resembling viscoelasticity in the temperature range where

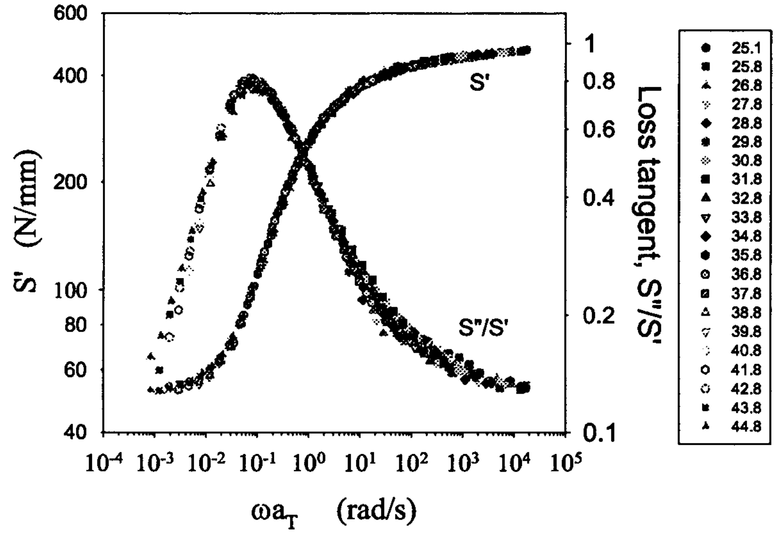

Figure 7. Master curve for dynamic data on mid-thickness adhesive bond with 0.508 mm adherends. The reference temperature is 30°C. The fractional uncertainty in stiffness S' is 2%.

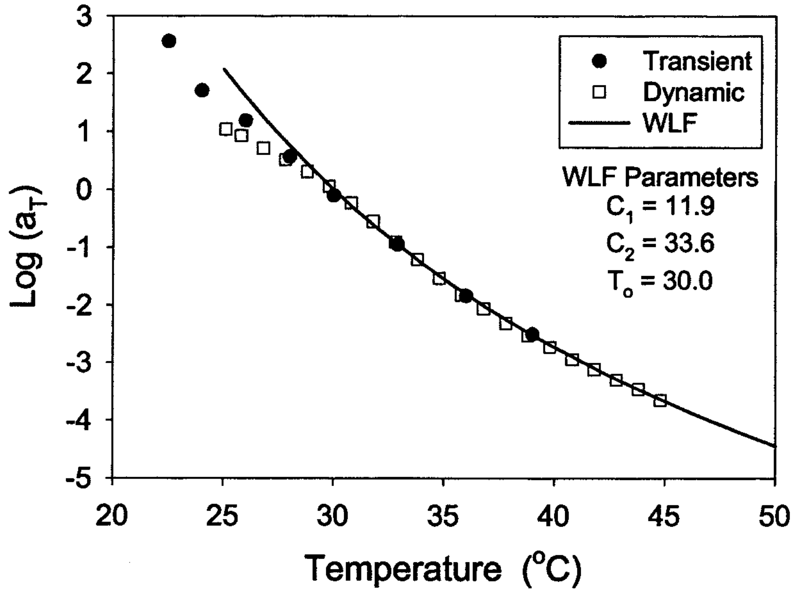

Figure 8. Shift factors for data in Figures 6 and 7.

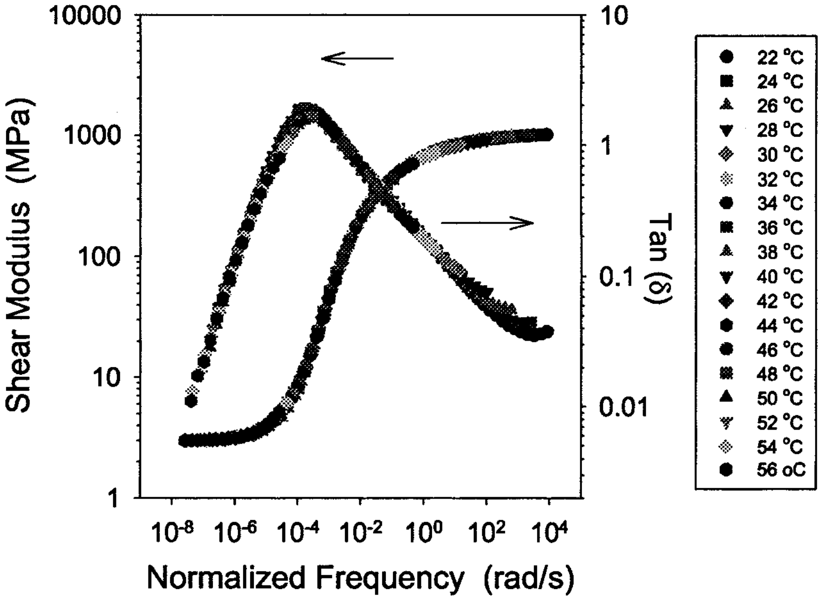

Figure 9. Master curve for bulk adhesive sample. The reference temperature is 30°C. The fractional uncertainty in the shear storage modulus is 6%.

the adhesive is viscoelastic. Figure 5 suggests not only that the beam stiffness behaves like a classic viscoelastic properties, but also that the behavior may be thermo-rheologically simple. If so, it should be possible to shift the curves until they collapse into a single master curve. This is show in Figure 6, and the superposition is quite good. A similar analysis was attempted on the results from the dynamic mechanical tests, and the results are shown in Figure 7. Again, the superposition is very good. The shift factors, a_T, required to get superposition in the two experiments are shown in Figure 8. Above T_g, both tests superimpose with the same shift factors while below T_s, the shift factors are somewhat different as would be expected since the thermal histories of the samples were not the same. In the region above T_g, the shift factors can be described quite well with the WLF equation:

$$a_T = \frac{-C_1(T - T_0)}{(C_2 + T - T_0)}, \tag{3}$$

using $C_1 = 11.9$, $C_2 = 33.6$, and $T_0 = 30.0$°C (Figure 8).

It would be surprising for the sandwich beam data to superimpose unless the adhesive itself was thermo-rheologically simple. This question can be examined by considering the results of torsional tests on the bulk sample of adhesive. Figure 9 shows the master curve generated from the bulk data, and the results superimpose very well. The shift factors for the bulk data can also be described by the WLF

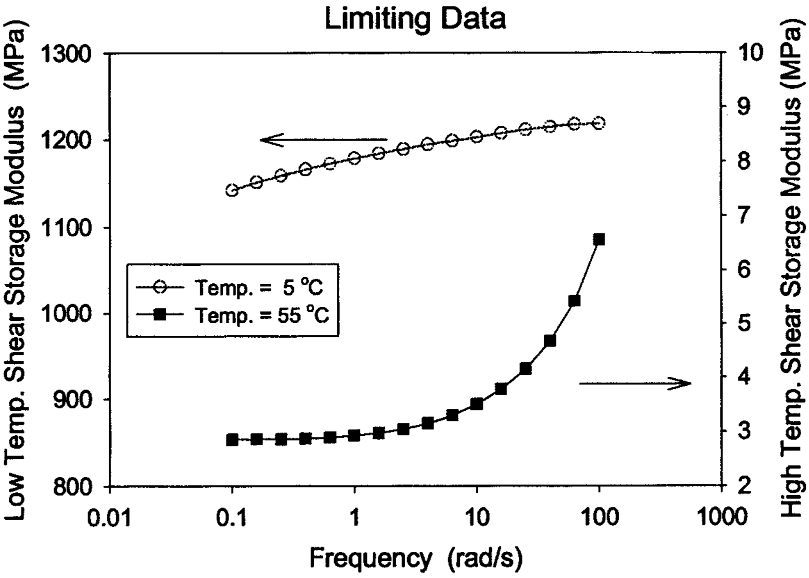

Figure 10. High and low temperature data for bulk adhesive sample. The fractional uncertainty in the shear storage modulus is 6%.

Table II. Shear modulus deduced from three-point bending of sandwich beam at 5°C.

Adhesive thickness (mm)	Adherent thickness (mm)	Exp. stiffness[a] P/δ (N/mm)	Calculated adhesive shear modulus (MPa)	
			Equation (1)	Equation (2)
0.152	0.508	218.4 ± 3.2	468 ± 336	444 ± 286
0.573	0.508	445.3 ± 7.4	636 ± 144	607 ± 130
1.297	0.508	882.2 ± 34.3	600 ± 95	568 ± 86
0.740	0.254	185 ± 4.1	547 ± 225	496 ± 197
0.571	0.762	918.3 ± 44	576 ± 114	508 ± 94

[a] Uncertainty in stiffness is 1 standard deviation for between 5 and 10 tests.

equation above T_g. The parameters ($C_1 = 13.0$, $C_2 = 27.4$, and $T_0 = 30.0$°C) obtained are similar although not identical to those found for the sandwich beam.

The final issue addressed in this study is a comparison of the predictions from Equations (1) and (2) with experimental results at temperatures where the behavior is expected to be elastic, i.e. well above (55°C) and well below (5°C) the glass transition temperature (about 30°C). The values of stiffness from the sandwich beam specimens were measured between 1 and 200 s. Within this range of time scales, the changes in stiffness were found to be very small which supports the assumption of elastic behavior. Tables II and III show the values of stiffness as

Table III. Shear modulus deduced from three-point bending of sandwich beam at 55°C.

Adhesive thickness (mm)	Adherent thickness (mm)	Exp. stiffness[a] P/δ (N/mm)	Calculated adhesive shear modulus (MPa) Equation (1)	Calculated adhesive shear modulus (MPa) Equation (2)
0.152	0.508	50.96 ± 0.89	2.89 ± 0.51	2.84 ± 0.50
0.573	0.508	48.45 ± 0.72	3.03 ± 0.62	2.99 ± 0.61
1.297	0.508	50.97 ± 0.40	3.13 ± 0.48	3.08 ± 0.47
0.740	0.254	11.3 ± 0.80	3.40 ± 0.40	3.31 ± 0.40
0.571	0.762	148.0 ± 1.7	3.46 ± 1.31	3.20 ± 1.23

[a] Uncertainty in stiffness is 1 standard deviation for between 5 and 10 tests.

Table IV. Shear modulus from measurements on bulk specimens.

Test method	Shear modulus (MPa) at indicated temperature 5°C	Shear modulus (MPa) at indicated temperature 55°C
Dynamic mechanical test	1160 ± 64	2.88 ± 0.17
Double lap test	1400 ± 300	–
Bending test	1060 ± 70	–

well as calculations for adhesive shear moduli based on Equations (1) and (2). The tables show several interesting things. First, as expected from the results discussed previously, both equations produce very similar predictions. Second, within the experimental uncertainty, the values obtained for G_a are independent of both the adhesive and adherend thicknesses. This is consistent with the hypothesis that the bonds are thick relative to molecular and morphological dimensions so the behavior should look like bulk samples. Of course, the experimental uncertainties are rather large in some cases so only very significant differences in G_a could be detected. In light of these results, it is of interest to compare the data with the measured values of G_a from bulk samples. The transient tests on bulk adhesive produced single numbers, but the dynamic tests yielded curves (Figure 10). To include the dynamic tests in the comparison it is useful to note that the time scale in the sandwich beam experiments was 1 to 200 s, and this corresponds to 1 rad/s (radians per second) to 0.005 rad/s in the dynamic tests. In this range, the behavior in the dynamic tests is approximately elastic, but there is some viscoelasticity, particularly at the low temperature. Based on these curves, values for the shear moduli were estimated and included in Table IV. Also listed in the table are the values for G_a obtained

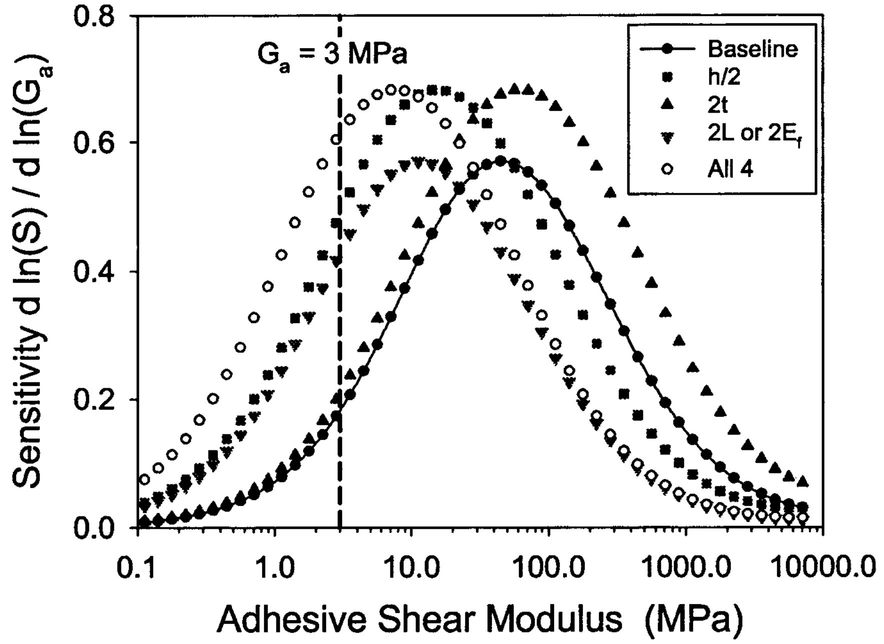

Figure 11. Sensitivity plot for mid-thickness adhesive bond with 0.508 mm adherends (baseline) and geometries where each of the various parameters are changed by a factor of 2. The open symbols are for a geometry where all four parameters are changed.

from the bending and double lap tests. These tests could only be applied in the glassy range, and the results agree well with the dynamic data.

Tables II to IV produce some interesting conclusions. First, both equations provide values for the of adhesive shear modulus in the rubbery range that agree with the values obtained on the bulk sample. This suggests that the sandwich test has potential as a characterization technique for determining the shear modulus of an adhesive in this range. The one concern is that the experimental uncertainties in the values of G_a determined with the sandwich test are larger than one might like, particularly with the thickest adherend. There are a number of factors that contribute to the uncertainty, but an important element is the sensitivity, such as plotted in Figure 4. As shown in that figure, 3 MPa is not in a range of high sensitivity so small errors in the measured stiffness produce significant changes in the calculated shear modulus. Fortunately, this particular constraint can be eased by adjusting the various experimental parameters: the four geometry values and the modulus of the adherend. As an example, Figure 11 shows the sensitivity based on Equation (2) calculated for the mid-thickness, adhesive bond geometry with 0.508 mm adherends (baseline) and then for geometries where the sandwich length or adhesive thickness is doubled or the adherend thickness is halved. Doubling the modulus of the adherend has the same effect as doubling the length while doubling the sample width does not change the sensitivity as defined here. The figure also shows the results if all four changes are made at once. The curves show that the sensitivity at 3 MPa can be significantly increased. It is interesting to note that the trends seen in the actual experiments (Tables II and III) are in most cases consistent with the results in Figure 11: increasing the thickness of the adhesive layer improves sensitivity, particularly in the glassy range, while decreasing the adherend thickness is beneficial in the rubbery range but somewhat detrimental for glassy adhesives. Of course, the experimental uncertainty depends on a number of factors in addition to sensitivity so the trends are not always consistent. Consequently, improving sensitivity is just a first step in optimizing the experiment for a given range of G_a values.

In the glassy range, the results in Tables II to IV indicate that both equations produce values of shear moduli that are only about half of those obtained for bulk samples. This is a very large discrepancy. One possibility is that the adhesive in the bonded specimen is actually softer than in the bulk samples. Several factors argue against this answer. First, the behavior seems to be independent of adhesive thickness, and at some thickness, the behavior must approach that of bulk specimens. Second, the transient experiments indicate that the behavior is glassy, and it would be unusual to get such a low modulus, 0.5 GPa, in a simple, single-phase glassy material. On the other hand, if the calculated shear modulus values are not correct, there are several possible explanations. First, the assumptions involved in deriving the equations may contribute to the problem. Although the theories are to some extent limiting cases for the geometries tested here, the fact remains that neither theory claims to be applicable in this central range. This possibility suggests that it would be useful to conduct experiments where the geometry parameters and the adherend modulus are varied over a wide range. Unfortunately, many of these geometries may no longer fit in standard viscoelastic test equipment so the possibility for easy automation of viscoelastic measurements will be lost. In addition, a finite element analysis could be formulated using the exact geometries tested here so no assumptions about specimen dimensions would be needed. This model could then be compared with the experimental results obtained here. A second factor that could contribute to the problem is defects in the specimen. Features like a flaw or voids in the adhesive, an uneven bond thickness, or a debond region, might effect the measured stiffness. Since only one specimen was tested for each geometry, such defects are certainly a possibility. For this to be a viable explanation, however, the defects must alter the stiffness in the glassy region but not affect the stiffness in the rubbery range since the same specimens were used for both tests. Moreover, the defects must affect all 5 specimens in about the same way since the calculated values for G_a are similar for all geometries. Again, these issues could be examined with a FEA study.

5. Conclusions

Techniques to characterize the mechanical properties of adhesives in a bonded geometry are important because these properties reflect that state of the adhesive, and how it changes with time. Although there are numerous tests available, the simplicity of the sandwich beam specimen makes it attractive. The sample is easy to make and test. Moreover, standard viscoelastic test equipment can automate the measurement process and extend it to the viscoelastic range. A number of equations are available to analyze the behavior in the elastic range, but there is no analysis currently available when the behavior is viscoelastic. The experiments conducted here suggest that the sandwich test has potential to characterize the viscoelastic shear modulus of an adhesive if an appropriate analysis is developed. The range of properties that can be examined were shown to depend on the sample geometry. With the geometries used here, the tests show promise for soft adhesives but suggest problems with glassy systems. Clearly, additional studies are needed to see how much of this technique's potential can actually be realized in a reliable test method.

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Note

[1] Certain commercial materials and equipment are identified in this paper in order to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply necessarily that the items are the best available for the purpose.

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