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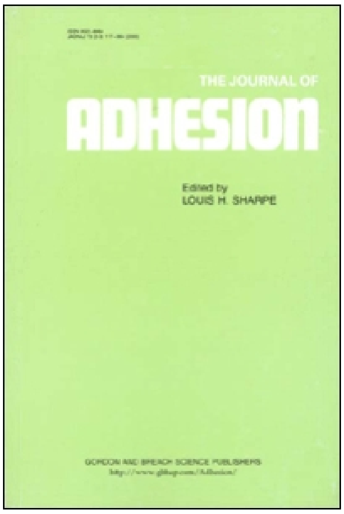

The Journal of Adhesion

Publication details, including instructions for authors and subscription information:
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To cite this Article Romanko, John and Knauss, W. G.(1980) 'On the Time Dependence of the Poisson's Ratio of a Commercial Adhesive Material', The Journal of Adhesion, 10: 4, 269 — 277

To link to this Article: DOI: 10.1080/0021846808544633

URL: http://dx.doi.org/10.1080/0021846808544633

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J. Adhesion, 1980, Vol. 10, pp. 269–277
0021-8464/80/1004-0269 $04.50/0
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Printed in Great Britain

On the Time Dependence of the Poisson's Ratio of a Commercial Adhesive Material

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(*Received February 5, 1979; in final form August 30, 1979*)

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In order to provide quantitative information for the viscoelastic stress analysis of polymer-bonded structural joints, the time or rate sensitivity of Poisson's ratio for a structural adhesive FM-73M is examined. The experimental method is based on holographic interferometry. It is found that for times in the glassy-to-rubbery range, Poisson's ratio remains constant even though measurable creep occurs in the same time domain.

INTRODUCTION

The subject of this communication is the examination of the time dependence of the Poisson function by a holographic technique. The mechanical behavior of an isotropic, linearly viscoelastic solid can be prescribed by two functions of time which individually describe the time dependence in shear and dilation; or in uniaxial extension and Poisson contraction. Any one of these modes of deformation can be characterized in a relaxation or creep test. From the viewpoint of viscoelastic stress analysis it is important to assess basically the rigidity of a material in shear and in volume (bulk) deformation. However, the direct determination of the property associated with bulk deformation is experimentally very difficult, so that it becomes attractive to measure the experimentally more readily accessible Poisson contraction. While this measurement in conjunction with a property determined in homogeneous and uniaxial extension or shear provides, in principle, all the information necessary for isothermal volume deformation, it is in practical terms usually too inaccurate to allow a definitive calculation of the volume bulk modulus. Nevertheless, if one can establish the variation of Poisson's ratio over the time range in which the structure under consideration is to be used, that information is useful in preparing a structural stress analysis. In particular, if it should turn out that (within experimental error) the Poisson contraction is time or deformation-rate insensitive in the time (and temperature) range of interest then the structural stress analysis becomes considerably simplified. It is with these considerations in mind that we examine the viscoelastic behavior of a potentially important material function.

This investigation is part of a study of time dependent behavior and fatigue of adhesively bonded joints. We have already documented in reports the significant creep behavior of two commercially used adhesives, FM-73M and FM-400.[1] Further measurements are to be reported separately later; here we report only on the results obtained for FM-73M.

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EXPERIMENTAL CONSIDERATIONS

The commercially available adhesive FM-73M† is supplied in 8 to 10 mil-thick films containing a carrier in a Dacron mat form. Moreover FM-73M is apparently a rubber-modified epoxy so that the material is, strictly speaking, neither homogeneous nor isotropic. However, because the carrier is a random mat, we assume that specimens laminated from these films are sufficiently isotropic in the bondline specimen plane so that the characterization techniques developed for isotropic solids are sufficiently accurate. Results on the time-dependence (or independence) are not markedly violated by this assumption.

The most common way to determine Poisson's ratio is to measure the contraction of a uniaxially stressed tensile or compression coupon either by means of a displacement transducer (LVDT) or by electrical strain gages.

The use of the latter may be questioned because the gage material is much stiffer than the viscoelastic base to which it is glued. However, Brinson *et al.*[2] have successfully used this method on sufficiently thick specimens of the adhesive Metlbond 1113. The various properties measured by these investigators, including Poisson's ratio, were obtained at relatively high strain levels such that crazing or phase-separation become prevalent phenomena.

A less common method, though well documented (e.g., Ref. 3 and 4), relies on the anticlastic curvature developed by the surface of a plate or beam

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† Produced by American Cyanamid Company, Bloomingdale Aerospace Products, Havre de Grace, MD 21078.

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in bending. The substitution of laser holography for the light interference method recorded in Ref. 3 has introduced an additional degree of freedom into the measurements because they can now be made without contacting the test body. This is important when measurements are to be made in various environments (temperature, humidity, corrosive gases or liquids) which can affect the more conventional instrumentation adversely. Investigations along this line have been made by several researchers.[5-9]

Heflinger's arrangement[6] required plane wavefront illumination and viewing of a diffusely reflecting specimen from a carefully monitored direction normal to the specimen. This was effected by including a corner cube in the scene beam during holographic recording and by using a telecentric system to establish readout in this normal incidence direction by maximizing the intensity of the reconstructed image through alignment of the corner cube. Jones[8-10] also used a normal plane wave illumination and viewing technique to measure Poisson's ratio of relatively rigid materials, such as (mild) steel. The use of a beam-splitting cube to provide the collimated scene beam and reference beam achieves the same results as Heflinger's. Jones and Leendertz[11] and Jones[9] apply speckle pattern interferometry methods to the determination of Poisson's ratio. In the latter work[9] the four-point bending loading technique is used. In the former work,[11] tensile loading of the specimen is used and the authors claim that the speckle technique is especially promising in measuring Poisson's ratio for the more compliant polymeric materials which "materials are not sufficiently stiff to permit the interferometric four-point bending measurement to be made". This implies that exposure times are not compatible with the creep characteristics of the compliant polymeric materials to permit recording of fringes in double exposure holographs using his original technique. Although we shall not employ this method here, it is of interest to point out that an alleged limitation to his original holographic interferometry was readily overcome in our study. Because low-powered lasers require extended exposures, it is potentially difficult to record fringes while viscoelastic creep occurs. However, if the specimen is coated with retro-reflective paint,† the intensity of the reflected beam is increased by three orders of magnitude. In the following developments we make use of this technique.

THEORETICAL BACKGROUND

Let us assume that the prescription of loads in the subsequent experiments corresponds to a pure bending moment in the central section of the specimen. This assumption is not valid, of course, near the application of the loads if

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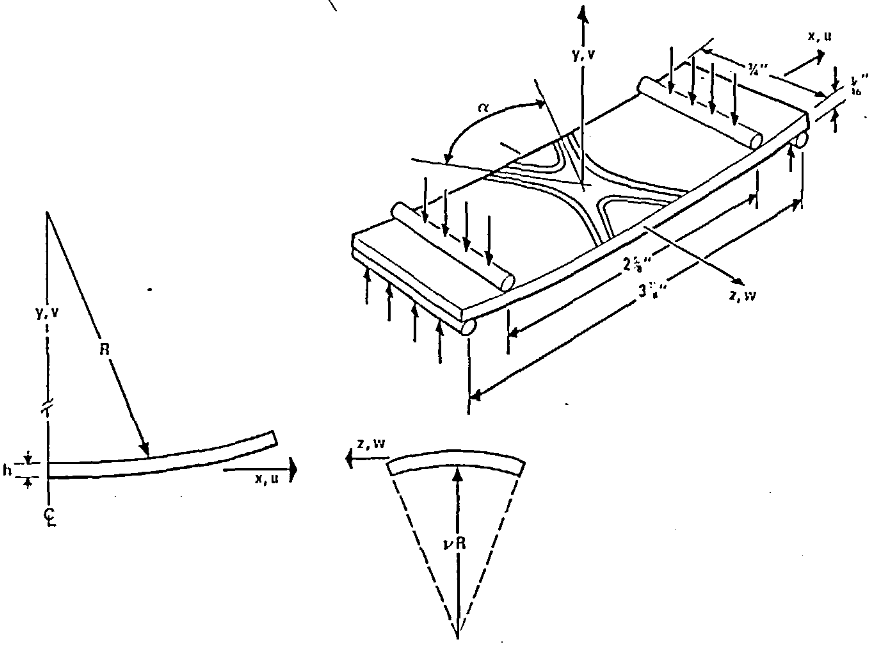
† Codit® Reflective Liquid (7216 White), 3M Co., 3M Center St. Paul, MN 55101.

they are supplied by round bars or knife edges spanning the breadth of the specimen (cf. Figure 1). Jones and Bijl have shown experimentally[10] that the dimensions in Figure 1 were adequate for the present purpose. The anticlastic curvature in the central portion of the specimen should not be affected strongly. We may then formulate a simple viscoelastic boundary value problem in which only tractions are applied to the specimen surfaces.



Poisson's ratio $\nu = \tan^2 \alpha/2$

FIGURE 1 Test geometry and reference frame.

Certainly the viscoelastic correspondence principle applies. Then the Laplace-transformed displacements are given by expressions for the corresponding elastic problem with elastic moduli replaced by p-multiplied Laplace transforms‡ of the relaxation moduli in shear and bulk. Since Poisson's ratio is a ratio of combinations of shear and bulk moduli, its Laplace transform is not multiplied by p whenever it appears in the solution.

Using the notation in Figure 1 and following developments in Refs. 3 and 4, the transformed solution for the displacement, v, normal to specimen midplane is calculated. Let M_0 denote the magnitude of the bending moment applied as a time-step function at time $t = 0$. Then the displacement, v, is—

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‡ p is the Laplace transform parameter.

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apart from an additive rigid body displacement of the specimen center—

$$\bar{v}(x, y, z, p) = \bar{D}(p)\frac{M_0}{2I}[x^2+\bar{\nu}(y^2-z^2)] \tag{1}$$

The corresponding viscoelastic solution is

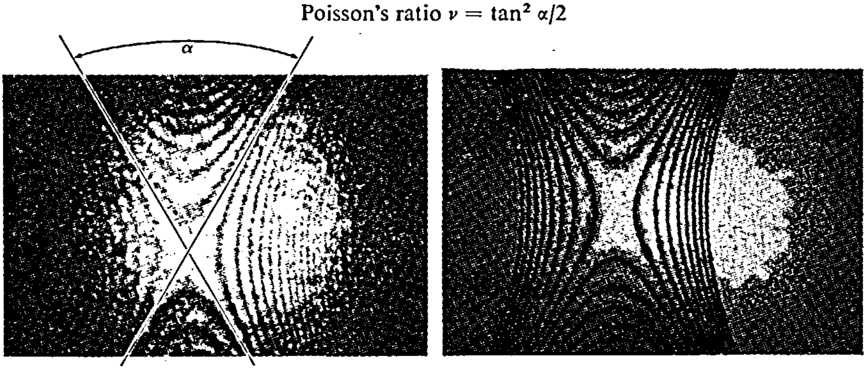
$$v(x, y, z, t) = D(t)\frac{M_0}{2I}x^2+(y^2-z^2)\frac{M_0}{2I}\int_0^t D(\tau)\nu(t-\tau)\,\mathrm{d}\tau \tag{2}$$

Note that the coefficient of x^2 is the curvature in the x direction, while the coefficient (y^2-z^2) in the second term is the curvature in the z-direction. According to Eq. (2) the ratio of the two curvatures would change with time unless Poisson's ratio is constant and equal to ν_0. In that case Eq. (1) renders on the surface, $y = \pm\frac{1}{2}h$

$$v(x, \tfrac{1}{2}h, z, t) = D(t)\nu_0\frac{M_0h^2}{8I}+D(t)\frac{M_0}{2I}(x^2-\nu_0 z^2) \tag{3}$$

One sees that the displacement increases monotonically with $D(t)$ but that the ratio of the curvature in the x and z directions now remains constant. In order to examine to what extent Poisson's ratio remains constant (or varies) we need to examine, therefore, how the curvature ratio changes, if at all.

To do this we make a holographic record of the displacement at time t. After a time lapse of Δt, a second holographic image is recorded during which time the displacement has grown in accordance with $D(t+\Delta t)$. The interference of the two holograms produces a stepped-time average of the surface curvature during the short time interval Δt. By performing this double



(a) (b)

(a) Holographic fringes for 2024 T6 Al with asymptotic tangent construction.
(b) Holographic fringes for FM-73M (dry) with calculated fringe fit conjugate hyperbolas for $\nu = 0.320$.

FIGURE 2 Holographic fringes for rigid and compliant materials.

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exposure at different times, t, after the initial loading is applied, we record any possible changes in the double curvature and thus in Poisson's ratio.

The double exposure photographs produce lines of constant displacement which, by Eq. (3), are sets of conjugate hyperbolas with common asymptotes as shown, for example, in Figure 2(a) for an aluminum specimen. Poisson's ratio may be extracted by matching a set of conjugate hyperbolas to the fringes, thus determining ν with the best fit of the fringe field as in Figure 2(b). Alternatively, we may estimate the asymptotes of the hyperbolas and determine Poisson's ratio from the relation

$$\tan^2 \tfrac{1}{2}\alpha = \nu \tag{4}$$

where α is the acute angle between the common asymptotes marked in Figure 2(a).

CURRENT STUDY

From a practical point of view it is important to choose the time interval, Δt, large enough that interference fringes occur between a first and a second exposure, but small enough that not too many appear to make identification difficult. Two hours were found to be a convenient time interval. As we have indicated at the end of the section on experimental considerations, one must have the ability to record interference fringe patterns sufficiently fast to prevent blurring or smearing of the image, yet to achieve enough reflectance of the light if only a low-power laser is available. This may be achieved through the use of retro-reflective paint which increases reflected light intensity by a factor of 1600 over matte white paint at normal incidence.[12]

The light retro-reflected from such a surface retains its original polarization so that the reflected and diffracted image light fields are still in the same plane of polarization. Therefore, the interference fringes of the resulting hologram possess a high contrast with a correspondingly high image diffraction efficiency. Retro-reflective paint also produces a large-sized speckle which somewhat reduces the high degree of stability normally required in holography and permits use of more coarse-grained holographic film than is usually necessary.

The laser-optical configuration used in our study is shown schematically in Figure 3. Here L is a 15 mW HeNe laser, its output being passed through a beam expander-collimator, BEC, and 50/50 beam-splitting cube, BSC. The plane front-surface mirror, M, reflects the split beam through a polarizing filter, F, to the holographic recording plane, H.

The adhesive strip specimen was loaded in a four-point bending fixture under constant load as shown in Figure 1. The polarizing filter, F, can be adjusted to give a suitable relative intensity of object, O, and reference, R, beams for maximum fringe contrast upon reconstruction.

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Because the measured deformations are small, one might wonder whether experimental misalignment or other uncontrolled deformations influence the measurements such as could result from uneven loading or from thickness variations in the specimen. While we have taken care to prevent geometric and load asymmetries, it should be pointed out that if they were present they would have no significant effect on our measurements because in the vicinity of the recorded fringe pattern they would be equivalent to rigid body motions of the specimen. In fact, rigid body translation and rotation do not affect the asymptotic behavior of the conjugate hyperbolic fringe pattern. This follows from the observation that in the central section of the specimen the out-of-plane displacement is described by arcs of constant curvature in the *xy*- and the *yz*-planes. Rotation about the *x* and *z* axes (or a combination thereof) can only translate the fringe pattern, while a rigid body displacement in the *y*-direction will move the fringes closer to, or farther away from, the origin of the pattern leaving the asymptotic behavior and the pattern unaltered.

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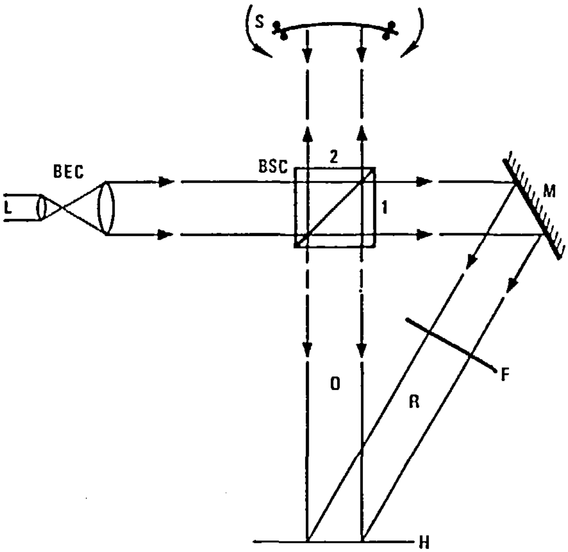

FIGURE 3 Laser/optical configuration for measurement of Poisson's ratio of compliant materials.

In order to test our experimental arrangement and/or confidence in the data reduction method, we measured Poisson's ratio of 2024 T6 Aluminum. The fringe pattern for this test is shown in Figure 2(a), and yielded a value of $\nu_M = 0.333 \pm 0.015$. This compared well with the value of $\nu_{Al} = 0.33$ as recorded in Ref. 13 for the same alloy.

The error estimate is a sole measure of our ability to interpret the fringe pattern. We tried two methods described before, namely, the evaluation of the angle between the asymptotes (illustrated in Figure 2(a)) and by fitting a field of hyperbolas to the fringes as depicted in Figure 2(b). Both methods were applied repeatedly for the aluminum specimen (as well as later for the FM-73M sample), Poisson's ratio being varied. The error bounds represent those values of Poisson's ratio for which the asymptotes or the field of hyperbolas yielded marginal fits in a purely visual evaluation. Improvements should be expected only if densitometric evaluation of the fringes is effected. We found that both methods yielded about equal precision.

MEASUREMENT OF THE TIME VARIATION OF POISSON'S RATIO

Before moving on to record measurements on Poisson's ratio of the adhesive one needs to raise the question whether it is reasonable to expect a time variation in the Poisson number if the polymer is deformed in essentially the glassy state. At room temperature the creep (or relaxation) behavior is readily noticeable as demonstrated in Figure 4 where creep over about thirty days is depicted. When that material is deformed in deformation histories involving similarly long time scales, one might expect that Poisson's ratio would also change. The question that remains then is only how much time variation to expect and in which time scale such variation might occur.

The present tests were designed to answer that initial question. A more detailed experimental analysis would require longer time scales and/or different temperatures to possibly exploit a time-temperature superposition

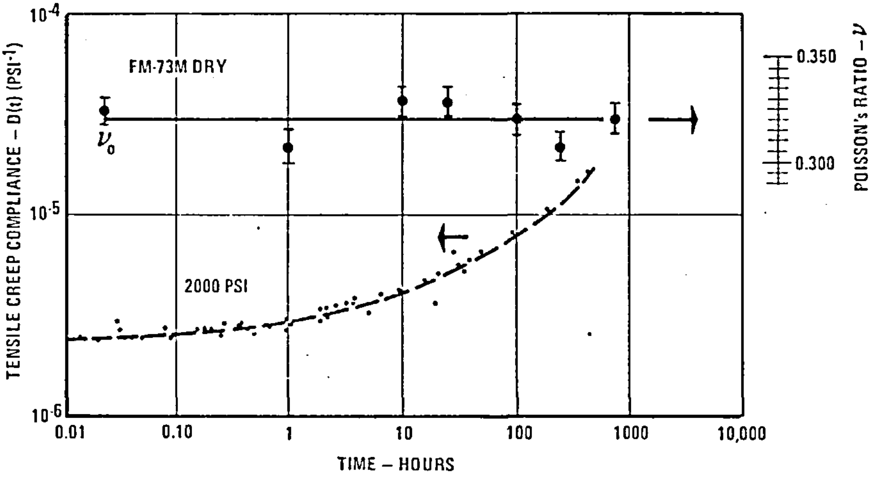

FIGURE 4 Comparison of time dependence in creep compliance at 25°C with time invariance of Poisson's ratio for Neat FM-73M.

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response. At this time the temperature-control equipment for the holographic setup is not complete.

Figure 4 shows also the values of Poisson's ratio of FM-73M determined by the two methods described above. It is clear that Poisson's ratio is essentially a constant during the time scale of investigation. In light of the results of Brinson *et al.*,[2] this result is perhaps not surprising; yet it seems important to determine this quantity well in order to provide proper input into a stress analysis. The importance of our findings is that viscoelastic stress analyses involving this material are significantly simplified in the time range of these measurements; for under these conditions the total material response may be represented fully by a single relaxation or creep function (and a constant Poisson's ratio).

Acknowledgments

This work was sponsored by Air Force Systems Command, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F33615-76-C-5220, "Fatigue Behavior of Adhesively Bonded Joints". The authors especially wish to acknowledge the interest and guidance of Dr. Wm. B. Jones, Jr., AFML/MBC Project Engineer on this program.

Mr. R. S. Chambers of the Stress Analysis Group, Materials and Structures Technology of General Dynamics' Fort Worth Division, performed the computer curve fits of the fringe data.

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