The Application of Coherent Optics to the Study of Adhesive Joints II. Holographic Interferometry

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Synopsis

The technique of holographic interferometry is complementary to the technique of speckle photography described previously. It allows the out-of-plane motion to be visualized with a sensitivity of about 0.3 μm. This technique has been applied to the study of the behavior of model glass-glass joints bonded by different adhesives under shear stress. Its high sensitivity allowed the presence of stress concentrations at the ends of the joints to be shown in the case of high-modulus adhesives and the existence of additional torsion and/or cleavage stresses to be demonstrated in the case of lower modulus adhesives. Work in progress should lead to more quantitative data.

INTRODUCTION

In the first part of this study[1] of the behavior of glass-glass adhesive joints under shear-stress, the technique of speckle photography has been outlined. The method used here, double-exposure holographic interferometry, is a complementary technique to speckle photography for the following reasons: its higher sensitivity and the possibility of detecting the out-of-plane motions of the assembly under stress.

PRINCIPLE OF DOUBLE-EXPOSURE HOLOGRAPHIC INTERFEROMETRY

This technique[2,3] is based on the superposition of two holograms, that is, three-dimensional images of the same object in two different states of stress. Each hologram is obtained by interference of the light diffused by the object with the light of the reference beam, both originating from the same laser. The photographic plate containing these two holograms is then illuminated by the reference beam and reconstructed, the reconstructed wave is modulated by a fringe pattern. These fringes describe the phase differences resulting from the motion of the different points of the object between the two states of stress.

The localization in space of the fringes and their structure (shape and visibility) are characteristic of the motions (displacement and deformation)

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of the object. In the case of a complex movement, the quantitative interpretation is extremely difficult since the fringes result from motion in the three dimensions. However, the qualitative analysis of the shape and the localization of the fringes can lead to fruitful information. In double-exposure holographic interferometry, the fringes can be localized either on the surface of the object or in the space behind or in front of the object surface. In the case of a pure motion (in one direction only), it has been verified[4–6] that the shape and localization of the fringes are well defined. When the motions are complex, the fringes may be anywhere in space depending on the respective amplitude of each elementary motion component.

One of the great advantage of holographic interferometry is its high sensitivity, of the order of one-half wavelength of the light, that is, 0.316 μm in the case of the helium neon laser used here. This sensitivity is about one order of magnitude as high as that given by speckle photography.

EXPERIMENTAL

Optical Arrangement

The helium neon laser (Spectra Physics model 124B, 15 mW) is divided into two parts by means of a beam-splitting plate: a reference wave 1 and an object beam 2 (Figure 1). A polarizer is placed in the path of the reference beam, which allows its intensity to be adjusted. The adjustment is made so that the average intensity of the reference beam on the photographic plate (Agfa Gevaert 10E75) is roughly equal to that of the light diffused by the object. Note that, as in the speckle photography technique,[1] the object (assembly) is illuminated on the edge as illustrated in Figure 1.

In order to produce interference, the optical path difference between the two beams must be inferior to the coherence length of the laser (0.5 m).

As for speckle photography, the photographic plate is exposed twice, each exposure corresponding to a different state of stress. This shows that the object under stress can be analyzed by both techniques simultaneously. After processing, the virtual image of the object is observed in the first-order diffraction by illuminating the plate only with the reference beam

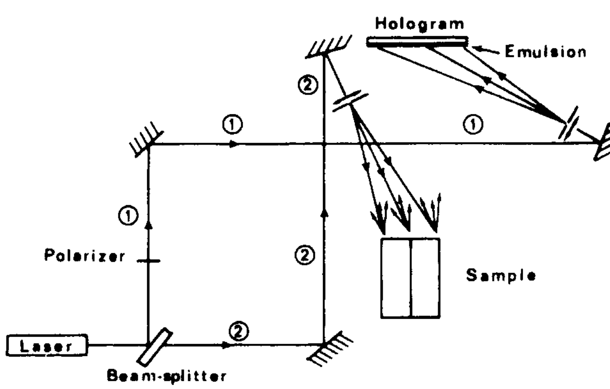


Fig. 1. Experimental setup: holographic interferometry.

at its maximum intensity, as shown in Figure 2. This image is modulated by the interference fringes indicating the modification of the object between the two exposures.

RESULTS AND DISCUSSION

Four types of adhesives (Araldite AY 103 + HY 930; Loctite 356; NOA 65; and Sylgard 184) have been used to form the glass-glass assemblies. The characteristics of the adhesives, the geometry of the samples, and the test apparatus have been described previously.[1] The behavior under shear-stress of the four glass-glass adhesive lap joints studied in the first part[1] by speckle photography have also been examined by holographic interferometry. Due to large creep deformation of the silicone adhesive (Sylgard 184) during the exposure time, the assembly based on this adhesive could not be studied by this technique. Recall that for the high-modulus adhesives (Araldite and Loctite), no interfacial displacement was detected by the speckle photography technique in the range of forces studied (0–10 kN), whereas the low-modulus adhesive assemblies (NOA) showed an interfacial displacement on the whole range of forces.

In a first step, the behavior of bulk glass with the same dimensions as the assemblies was studied. This sample corresponds to an assembly that presents an interface with a strength equal to the cohesive strength of glass. Figure 3 shows the interferogram of this sample between two states of shear-stress the reference state corresponding to an applied force equal to 0.85 kN and the second state corresponding to 2.35 kN.

The fringes are straight and are localized at the immediate vicinity of the surface of the sample: between the two applied forces, the glass block has been subjected to a translation in the direction of the applied force together with an out-of-plane rotation. However, it can be seen that the fringes are not equidistant, which may indicate the existence of a small compression of the glass plate superimposed onto the translation and rotation. These motions are due to the mechanical imperfections of the test apparatus and to the geometric defects of the sample. This will constitute the reference behavior for the adhesive assemblies.

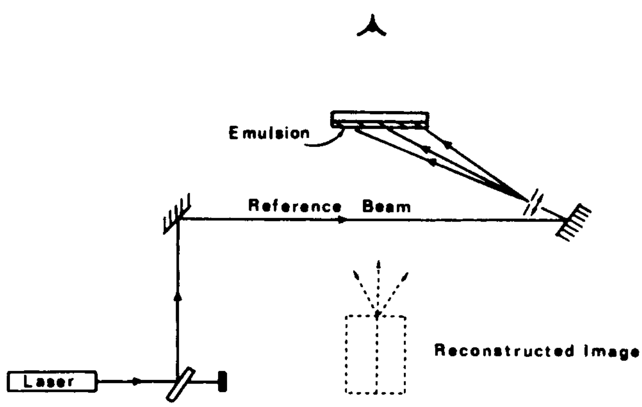
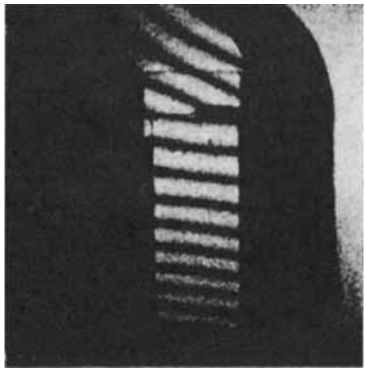


Fig. 2. Holographic reconstruction of the virtual image.



$\tau_1 = 0.34$ MPa

$\tau_2 = 0.95$ MPa

Fig. 3. Interferogram of bulk glass under shear stress (aperture f/5.6).

The interferogram presented on Figure 4 is characteristic of the epoxy-based joints. The global motion derived from the general aspect of the fringes is analogous to that of the homogeneous glass. However, the interference fringes are more inclined, which indicates that the in-plane tilt is more important. This is in agreement with what was observed by speckle photography. An important difference must be noted at the upper end of the joint near the interface: there is a nonnegligible deformation of the fringes crossing the interface, which indicates the existence of stress concentrations. Indeed, Volkersen's theory allows us to calculate that the interfacial displacement at the end of the joint is of the order of 0.3 μm when a force of 2.5 kN is applied, the thickness of the adhesive being about 20 μm and its modulus of the order of 2000 MPa. The deformation observed at the upper end of the joint in Figure 4 is in good agreement with Volkersen's theory since the sensitivity of holographic interferometry equal to the half-wavelength of the helium neon laser is 0.316 μm. These experiments, done with the high-modulus epoxy adhesive in the considered range of forces, show the limits of the holographic interferometry technique.

Figure 5 shows the same experiment applied to the Loctite-based samples; here again, the same global motion observed for the isotropic glass block

$\tau_1 = 0.20$ MPa

$\tau_2 = 1.00$ MPa

Fig. 4. Interferogram of an epoxy-based joint under shear-stress (Araldite AY 103 + HY 930).

$\tau_1 = 0.08$ MPa

$\tau_2 = 2.00$ MPa

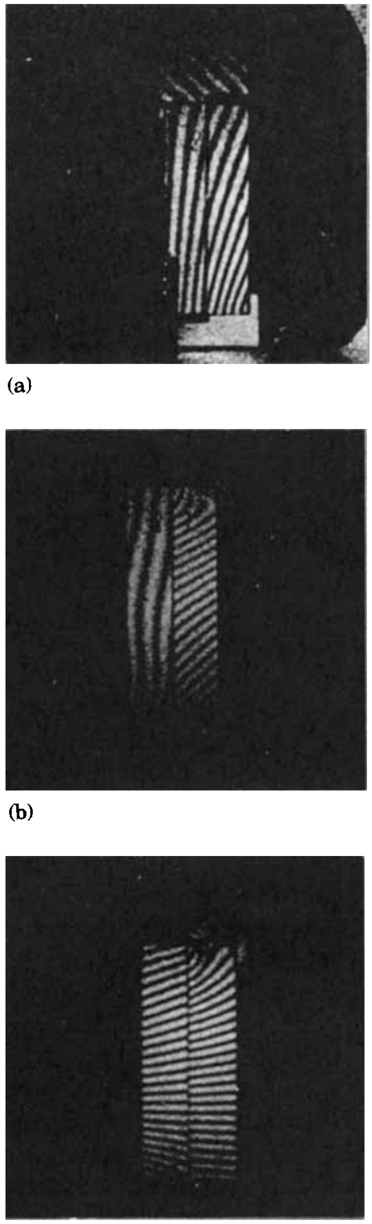
Fig. 5. Interferogram of Loctite 356-based joint under shear-stress.

can be seen. The high sensitivity of holographic interferometry allows us to visualize the interfacial displacement, which could not be observed by speckle photography. As can be seen by the degree of discontinuity of the fringes through the interface, the displacement is large at the upper end of the joint and almost negligible in the middle of the sample. Again, this is in good agreement with Volkersen's theory, which predicts a displacement of the order of 0.9 μm at the end of the joint and of 0.03 μm in the middle of the joint for an applied force of 5 kN, the thickness of the adhesive being equal to about 20 μm. The nonsymmetrical behavior of the upper and lower ends of the joints is due to the particular geometry of the test.

With the low-modulus ($E = 4.7$ MPa) adhesive (NOA65) based samples undergoing large deformations when submitted to the range of forces considered, the holographic interferometry technique shows three different types of behavior, as illustrated on the three interferograms of Figure 6. It must be noted that, this time, the global motion of the sample can be notably different from the one observed for the homogeneous glass block. The general aspect of the fringes indicates very complex compositions of motions; for instance, the rotation axis is either parallel (Figure 6a) or normal (Figure 6c) to the interface or, as shown on Figure 6b, the direction of the rotation axis can be totally different for the two glass plates. Therefore, the holographic interferometry technique reveals that a torsion and/or a cleavage stress can be added to the pure shear-stress. Moreover, a discontinuity of the fringes through the interface along the whole joint is observed, demonstrating, in agreement with the data obtained from speckle photography and Volkersen's theory, that a large shear-deformation has occurred in the adhesive layer. The particular overall motion of the sample observed is probably a result of this large interfacial displacement.

CONCLUSION

The technique of holographic interferometry described here has two advantages over the speckle photography technique: it allows the out-of-plane motions to be clearly shown and through its high sensitivity to visualize deformations of the order of 0.3 μm. Its major inconvenience is that quantitative interpretation of the interferograms is critical. This technique is



(a) $\tau_1 = 0.12$ MPa, $\tau_2 = 0.46$ MPa

(b) $\tau_1 = 0.04$ MPa, $\tau_2 = 1.70$ MPa

(c) $\tau_1 = 0.04$ MPa, $\tau_2 = 1.68$ MPa

Fig. 6. Interferograms of NOA 65-based samples under shear-stress.

therefore complementary to speckle photography, which is well adapted to in-plane motion measurements, less sensitive, and whose data are easily interpreted on a quantitative basis.

The holographic interferometry technique has been applied to study the behavior under shear of model glass-glass assemblies using adhesives of different moduli ranging from 5 to 2000 MPa. In the case of the high-modulus adhesives, stress concentrations and/or interfacial displacement at the end of the joint have been shown. In the case of the low-modulus adhesive, the existence of torsion and/or cleavage stresses superimposed on the applied shear stress has been demonstrated.

It must be stressed that both techniques are applicable to nontransparent solids. As a matter of fact, the work now in progress is devoted to glass-metal and metal-metal assemblies.

Besides, our present studies on composed elementary motions of objects by holographic interferometry should lead to a more quantitative interpretation of the data obtained by this technique.

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