In-Situ Measurement Of The Stiffness Of The Foam Layer In Foam-Adhesive Bonded Structures

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ABSTRACT

Foam-adhesive bonding is a common fabrication process in the aerospace, the automobile and the electronic industry. During service, the change with time in the behaviour of components fabricated by this process is often caused by degradation of the foam layer within. As it is impractical, and at times impracticable, to dismantle the component for the purpose of testing and examining the foam layer, the need arises to develop methods of assessing the properties of the foam layer *in situ*. Many foam-adhesive bonded components comprise segments of strips bonded along their lengths to a rigid support. Additionally, these strips are secured with mechanical fasteners to prevent detachment from the support should the bonding fail. In this paper, a method is proposed which permits estimating the stiffness of the foam layer when the adherend (ie, the strip) is subjected to point loads representing the forces exerted by the fasteners. The surface of the adherend is of mirror-like finish, as is found in the disk-drives industry. From the Moiré fringe pattern generated with the use of the mirror-image method, the deflection of the adherend due to the point loads is deduced. Treating the foam layer as of the Winkler type, the magnitude of its stiffness is iterated using the theory of beams on elastic foundation.

Keywords: Moiré, foam adhesive, foundation modulus, stiffness, elastic foundation, nondestructive evaluation

1. INTRODUCTION

The use of foam-adhesives in joining components is gaining grounds in many engineering applications. The mechanical properties, in particular the stiffness, of the foam layer that are available to designers are generally tested by the manufacturer of these adhesives. Whilst these data are appropriate for use at the design stage, degradation of the foam material during service will alter the stiffness, and subsequently the serviceability of the joint. It is therefore important to evaluate *in-situ* the stiffness of the foam layer within the component. Reflection will show that the current stiffness of the foam layer cannot be determined directly from the usual test methods, such as the uniaxial tension or compression test, but must be deduced from the response of the component when subjected to a prescribed load.

In this investigation, a simple structure is used which represents a segment of many common foam-adhesive bonded components, Fig. 1. A metallic strip (the adherend) with a mirror-like surface finish is bonded along its entire length to a rigid support with a commercial foam-adhesive. Point loads are subsequently applied on the adherend, simulating the forces exerted by mechanical fasteners that are used customarily to prevent detachment of the adherend from the support should the bonding fail. In practice, an array of fasteners is used, but for simplicity, the use of only one and two fasteners will be considered in this investigation. The deflection of the adherend, for a given load exerted by the fastener, is governed primarily by the stiffness of the foam layer. An indirect method is proposed to determine the stiffness of the foam layer from the Moiré fringe pattern generated from the use of the mirror-image method which measures the deflection of the adherend.

SPIE Vol. 2921 • 0277-786X/97/$10.00

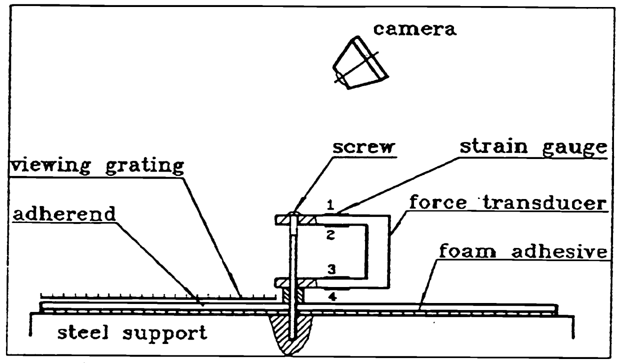

Fig. 1 General arrangement for testing the stiffness of the adhesive layer of a specimen

Fig. 2 shows a schematic layout of the mirror-image method (Chiang, 1969) for generating Moiré fringes on a slightly undulated, mirror-like surface. A viewing grating of pitch p is placed very close to the test surface so that, upon illuminating the system with normal diffused light, the mirror image of the grating is formed behind the test surface. Interference of the viewing and image gratings generates a Moiré fringe pattern representing the topography of the adherend. It has been shown (Chiang, 1969) that if the eye or a charge-coupled device (CCD) camera is located at the position (x_c, z_c) so that x_c is large compared to p, the fringe pattern manifests as lines of constant elevation of the measured surface, the distance between two adjacent fringes being $\left(\frac{p z_c}{x_c \tan\theta}\right)$ with $\theta = 2\delta$. The relative height h of two points on the test surface corresponding to the locations of the two adjacent fringes is thus $\left(\frac{p z_c}{x_c \tan(2\delta)}\delta\right)$. For a small angle, $\tan(2\delta) \approx 2\delta$, resulting in the following expression.

$$h = \frac{p z_c}{2 x_c} \qquad (1)$$

where h denotes the relative height of two points on the test surface corresponding to the locations of any two adjacent fringes; and x_c and z_c denote the coordinates along the reference x- and z-axis of the observation point where the eye or the CCD camera is placed.

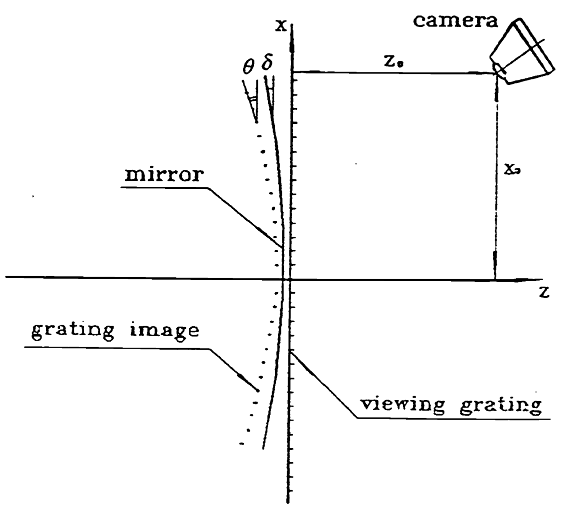

Fig. 2 Schematic layout of the mirror-image method

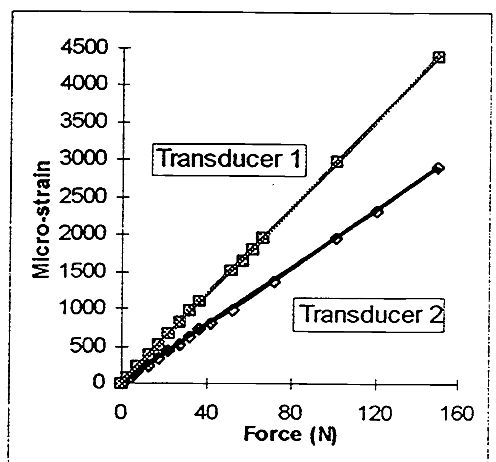

Fig.3 Calibration charts of the force transducers used, Transducer 1 being located at point O_1, and Transducer 2 being located at point O_2

2. EXPERIMENTAL TECHNIQUES

Fig. 1 shows the adhesive-bonded structure prepared by bonding a brass strip (the adherend) of 250 mm-length, 10 mm-width and 1.72 mm-thickness to a rigid steel support with a commercially available double-coated acrylic adhesive foam tape of 1.1 mm-nominal thickness. The brass strip, of elastic constants $\nu = 0.3$ and $E = 97$ GPa, is prepared by first shearing from a large sheet in the as-received condition to the approximate size, followed by milling to the correct size.

To simulate the additional load exerted by the mechanical fastener, a screw-assembly that forms a strain gauge-based force transducer is used (Fig. 1). The strain gauges are connected using the full-bridge configuration with Gauge 1 and Gauge 4 connected to the opposite arms of the circuit. Turning the M2-screw slowly and continuously with a screw-driver, a point load is exerted on the adherend via the sleeve of outer diameter of 5.0mm that is placed between the brass strip and the force transducer. The use of the calibration chart (Fig. 3) gives the magnitude of the applied force from the reading of the strainmeter.

The pitch p of the viewing grating is 25.4 μm, which is equivalent to a density of 1000 lines per inch. As the strip is warped during shearing and milling, a Moiré pattern, which represents the initial flatness of the adherend after being bonded to the rigid structure, is observed and recorded using a CCD camera placed at (x_c, z_c). With the point load F_1 exerted by the screw-assembly, the adherend is deflected, generating another Moiré pattern that is also recorded by the CCD camera. Subtracting the first fringe pattern from the second, the actual deflection of the adherend is deduced.

Tests on three types of structures are made, as shown in Fig. 4. Type 1 structure involves the use of an adherend containing only one hole of 2.5 mm-diameter at O_1, for the application of point load F_1 . It is noted that Fig. 1 depicts testing of Type 1 structure. Type 2 structure requires the adherend to have two holes of 2.5 mm-diameter each at O_1 and O_2 and spaced at $d = 15$ mm apart so that a point load F_1 is applied at O_1 followed by F_2 at O_2. Type 3 structure involves the application of an additional point load $\Delta F'$ at O_2 after F_1 and F_2 are applied at O_1 and O_2, respectively. It is also noted that testing of Type 2 and Type 3 structures requires the use of two force transducers at O_1 and O_2 whose calibration curves are shown in Fig. 3.

3. THEORETICAL CONSIDERATIONS

The test structure may be treated as a beam, which is the adherend, supported on an elastic foundation, which is the foam layer between the adherend and the rigid support. Previous investigations (Qin et al., 1996; Shang et al.,1995) have also shown that the foam material may be taken as a Winkler type in which the intensity f of the reaction forces at any point is proportional to the deflection z of the adherend at that point, that is,

$$f = b\kappa_o z \qquad (2)$$

where b is the width of the adherend which, in this investigation, is 10 mm; κ_o is a constant of proportionality known as the foundation modulus and having the dimension [FL^{-3}]. Assuming the length of the adherend as infinite, and for the reference axes shown in Fig. 4, the deflection z of the adherend for Type 1 structure under the point load F_1 at O_1 is given by the following expression (Hetényi, 1946).

$$z = \frac{F_1 \mu}{2\, b\kappa_o} e^{-\mu|y|} \left(\cos \mu|y| + \sin \mu|y|\right) \qquad (3)$$

where $|y|$ represents the numerical value of y; μ, related to the flexural stiffness (EI) of the adherend and defined as $\sqrt[4]{\frac{b\kappa_o}{4EI}}$, is sometimes called the damping factor.

In the case of Type 2 structure where the point load F_1 is applied on the adherend via the screw-assembly at O_1 (ie, at $y = 0$), followed by the point load F_2 applied via the screw-assembly at O_2 (ie, at $y = -d$), the stiffness of the screw in the screw-assembly causes the force F_1 at O_1 be changed to $(F_1+\Delta F_1)$ which is measured by the force transducer at O_1. With reference to Eq. (3), the use of the principle of superposition gives the following expression for the final deflection of the adherend.

$$z = \frac{F_2 \mu}{2\, b\kappa_o} e^{-\mu|(y+d)|}\left[\cos \mu|(y+d)| + \sin \mu|(y+d)|\right] + \frac{(F_1 + \Delta F_1)\mu}{2b\kappa_o} e^{-\mu|y|}\left(\cos \mu|y| + \sin \mu|y|\right) \qquad (4)$$

In the case of Type 3 structure, an additional point load of magnitude $\Delta F'$ is applied at O_2 after F_1 and F_2 are applied at O_1 and O_2 on the adherend in that sequence. The final deflection of the adherend is also expressed by Eq. (4) except that F_2 is replaced by $(F_2+\Delta F')$ whose magnitude is measured by the force transducer at O_2, and $(F_1+\Delta F_1)$ becomes $(F_1+\Delta F_1+\Delta F_2)$ whose magnitude is measured by the force transducer at O_1.

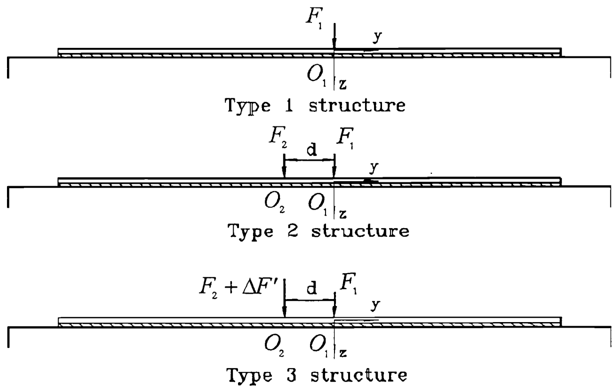

Fig. 4 Methods of loading the test specimens

4. RESULTS AND DISCUSSION

Figs. 5(a) and 5(b) show the typical Moiré fringe patterns and the surface contours of Type 1 structure before and after F_1 = 60 N at O_1 is applied – the experimental data points have been fitted with a sixth-order polynomial equation which gives excellent correlation of $R^2 = 1$. The difference of the two empirical equations, which is plotted in Fig. 6, subsequently gives the experimental deflection of the adherend due to the applied load. The stiffness of the adhesive layer is thus the iterated value of κ_o which corresponds to the minimum least-square error between the experimental deflection curve and the theoretical curve generated using Eq. 3. Fig. 6 also shows a typical comparison between theoretical and experimental deflection curves for Type 1 structures.

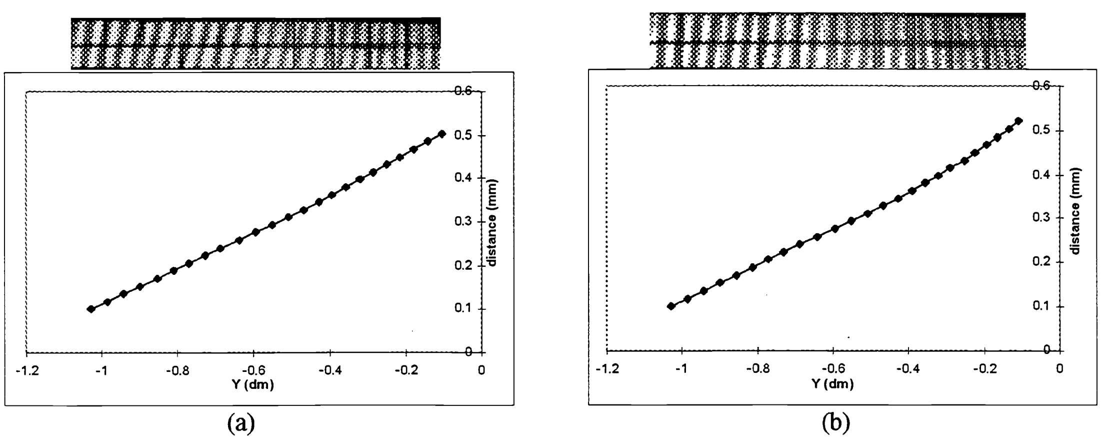

Fig. 5 Typical Moiré patterns and surface contours of a Type 1 structure

The values of κ_o determined from the test results for three different loads F_1 are tabulated in Table 1, the average stiffness being 6.0 N mm^{-3}. The values of κ_o tend to suggest that the stiffness decreases gradually with F_1, this

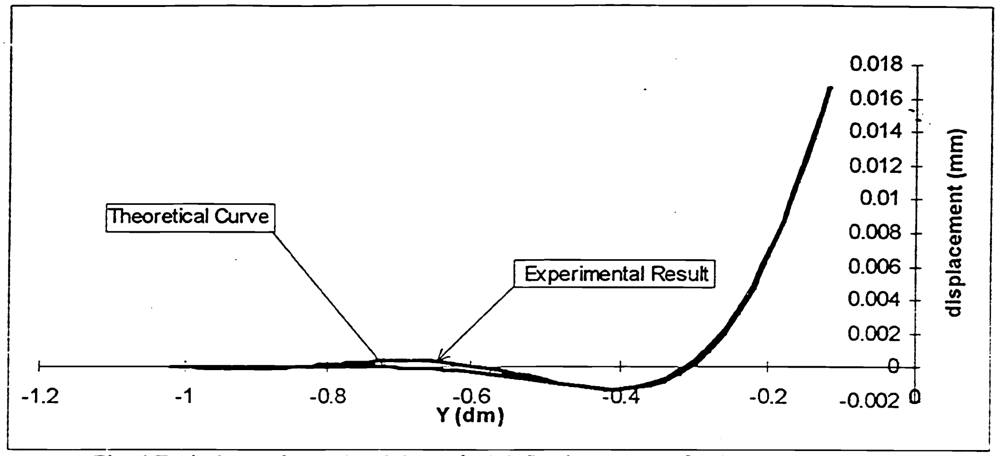

Fig. 6 Typical experimental and theoretical deflection curves of a Type 1 structure

may be attributed to the collapse of the cells in the foam layer when subjected to compressive loads (Gibson and Ashby, 1988).

Table 1. Values of κ_o of the foam layer tested on Type 1 structure.

Initial F_1 (N)	Final F_1 (N)	κ_o, (N mm^{-3})
0	40.0	6.2
0	60.0	6.1
0	74.8	5.7
	Average:	6.0

The iterated values of κ_o for the Type 2 and Type 3 structures are shown in Tables 2 and 3, and typical comparison between the experimental and theoretical deflection curves generated using these values are shown in Figs. 7 and 8.

Table 2. Values of κ_o of the foam layer tested on Type 2 structure.

Step 1: F_1 (N)	Step 2: F_2 (N)	κ_o, (N mm^{-3})
50.0	50.0	6.9
60.0	60.0	7.3
50.0	80.0	6.3
60.0	100.0	6.2
	Average:	6.7

Table 3. Values of κ_o of the foam layer tested on Type 3 structure.

Step 1: F_1 (N)	Step 2: F_2 (N)	Step 3: $F_2+\Delta F'$ (N)	κ_o, (N mm^{-3})
50.0	50.0	80.0	5.4
60.0	60.0	100.0	5.0
		Average:	5.2

5. CONCLUSION

The structure of foam materials is cellular which, when subjected to compressive loads, gives rise to a limited linear-elastic range due to bending of the cell walls, followed by creep under essentially constant stress due to elastic buckling, plastic yielding or brittle crushing of cell walls, and finally a non-linear rapid increase in stress with strain due to densification. Despite this non-linear behaviour, the assumption that the foam material is of the Winkler type is satisfactory in describing the deflection of the adherend when subjected to point loads. Test results have also shown that reasonably consistent values of the stiffness of the foam layer (6.0, 6.7, and 5.2 N mm^{-3}) are deduced from the deflection of the adherend caused by the application of one or two point loads, concluding that the current stiffness can be determined *in situ*.

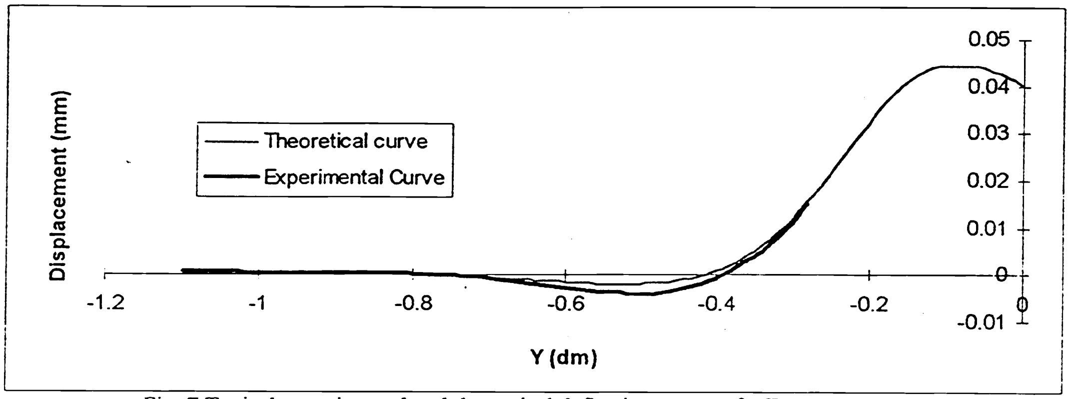

Fig. 7 Typical experimental and theoretical deflection curves of a Type 2 structure

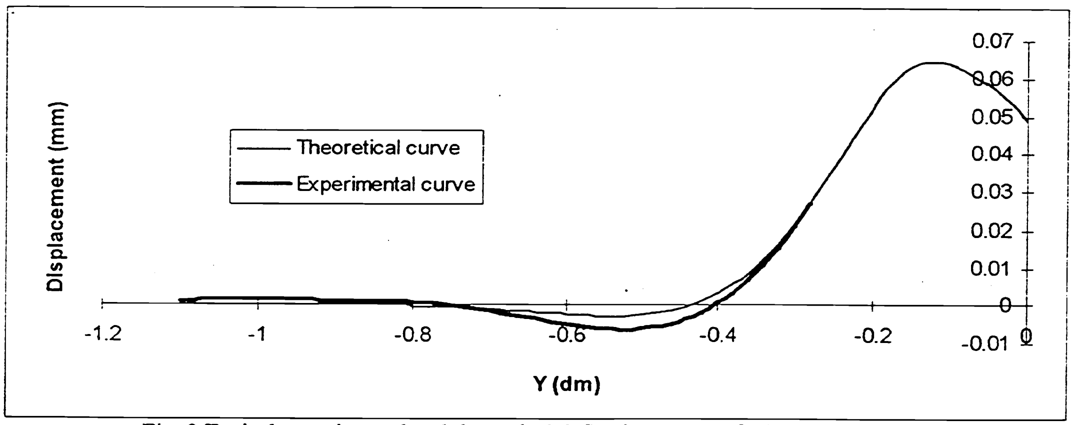

Fig. 8 Typical experimental and theoretical deflection curves of a Type 3 structure

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