Nondestructive Residual-stress Measurement in a Wide-flanged Rolled Beam by Acoustoelasticity

Acoustoelasticity stress analysis is applied to measure residual-stress distribution in a wide-flanged rolled beam and the results are compared with those obtained by the conventional destructive method

by H. Fukuoka, H. Toda and H. Naka

ABSTRACT—X-ray stress analysis is a standard nondestructive stress-measurement technique, but its use is limited in the sense that only a surface layer is surveyed. Recently, acoustoelasticity has emerged as a technique for nondestructive stress analysis. Acoustoelasticity makes use of stress-induced acoustic-birefringent effects. It gives stress distributions averaged through the thickness of a specimen. This technique is attractive because it does not require a transparent plastic model as photoelasticity does. However, much should be done before this method is established as a standard nondestructive technique of stress analysis. The most important among them is to separate stress-induced birefringence from that introduced by texture structure. For special cases, such as axisymmetric stress distributions and when a stress-free region is known *a priori*, residual-stress distributions can be evaluated nondestructively. In this paper, we measured residual-stress distribution in a wide-flanged rolled beam by using a recently developed T-type transducer. The results were compared to those obtained from conventional destructive methods.

Introduction

Ultrasonic elastic waves transmitted through a material can be used to interrogate the internal condition of the material. Acoustoelasticity uses elastic waves to gain information on internal stress distributions in much the same way as photoelasticity does with polarized light waves. Unlike its forerunner, acoustoelasticity does not require transparent models and is applicable directly to structural elements. When used correctly it not only offers information on material properties but, since it is sensitive to small structural changes, it can, in principle, be used to make nondestructive residual-stress measurements. This latter capability has particularly attractive practical possibilities.

Because of birefringent effects, the difference of propagation velocities in acoustic shear waves polarized in principal-stress directions is proportional to the principal-stress difference in plane-stress states. In addition to this stress-induced birefringence, a preferred grain orientation or the texture structure of metallic materials also causes acoustic birefringence. The separation of these two effects is crucial for nondestructive residual-stress measurement. Unfortunately, a general solution to this problem has not yet been found. Consequently the separation of the two effects should be performed individually for each problem by symmetry and other considerations. For example, in a patch-welded circular disk,[1] residual stress was separated by the assumption that the stress distribution was axisymmetric. The results coincided fairly well with those obtained from the conventional destructive methods.

In this paper the residual-stress distribution in a wide-flanged rolled beam was evaluated by separating the birefringent effect due to stress state (stress anisotropy) from that due to texture structure (texture anisotropy) by assuming that: (1) the residual stress was longitudinal; (2) both end sections of the beam were stress free; and (3) only texture anisotropy existed at the stress-free ends. The measurements were made using the sing-around method with a T-type transducer and gated amplifier. The results obtained were compared with those from conventional destructive methods.

Method of Acoustoelasticity

For an isotropic material under plane stress, the law of acoustoelasticity relates the difference of propagation speeds V_{T_1} and V_{T_2} of the shear waves polarized in principal directions and the principal-stress difference $\sigma_1 - \sigma_2$ as[2]

$$\frac{V_{T_1} - V_{T_2}}{V_{T_0}} = C_A(\sigma_1 - \sigma_2) \tag{1}$$

$$C_A = \frac{1}{2\mu}\left(1 + \frac{\nu_3}{\mu}\right) \tag{2}$$

where

V_{T_0} = the shear-wave speed in stress-free materials
μ, ν_3 = second- and third-order elasticity constants
C_A = the 'acoustoelastic constant' which is evaluated from a sample specimen of the isotropic material in a conventionally standardized material test.

The acoustoelastic constant, thus obtained, remains unchanged if the material is not exposed to plastic deformation or heat treatment any further. Then, the principal-stress difference for such material is obtained from eq (1) by measuring the propagation velocity difference of two shear waves. The separation of σ_1 from σ_2 is possible in principle. (See Appendix.)

H. Fukuoka is Professor and H. Toda is Associate Professor, Faculty of Engineering Science, Osaka University, Toyonaka, Osaka, 560 Japan. H. Naka is Research Fellow, Matsushita Electric Company, Kadoma, Osaka, 571 Japan.

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Polycrystalline material possesses intrinsic anisotropy because of a texture structure or preferred grain orientation originated by the process of plastic deformation and/or heat treatment. There will, therefore, always be some acoustic anisotropy even under stress-free conditions. We call this texture anisotropy. In the presence of stresses the total acoustic anisotropy is therefore composed of texture anisotropy plus stress anisotropy. When the material possesses orthotropic symmetry, which represents the type of symmetry of a cold-rolled metal plate, eq (1) should be replaced by the following equation which takes the texture anisotropy into account.[3]

$$\frac{V_{T_1} - V_{T_2}}{V_{T_0}} = \sqrt{\alpha^2 + 2\alpha C_A(\sigma_1 - \sigma_2)\cos 2\theta + \{C_A(\sigma_1 - \sigma_2)\}^2} \tag{3}$$

where θ is the angle between one principal stress direction and one orthotropic symmetry direction, and α is the coefficient of texture anisotropy given by

$$\alpha = \frac{C_{55} - C_{44}}{2\mu} \tag{4}$$

in which C_{44} and C_{55} are the elastic stiffnesses by Voigt notation. The polarization directions of the shear waves is given by

$$\tan 2\phi = \frac{C_A(\sigma_1 - \sigma_2) \sin 2\theta}{\alpha + C_A(\sigma_1 - \sigma_2) \cos 2\theta} \tag{5}$$

where ϕ is the angle between one of the polarization directions and one of the orthotropic symmetry directions. When the principal-stress direction coincides with the direction of orthotropic symmetry, θ becomes zero and eqs (3) and (5) become

$$\frac{V_{T_1} - V_{T_2}}{V_{T_0}} = \alpha + C_A(\sigma_1 - \sigma_2) \tag{6}$$

and

$$\phi = 0 \tag{7}$$

If the extent of texture anisotropy is known beforehand, the measurements of the acoustic anisotropy $(V_{T_1} - V_{T_2})/V_{T_0}$ and of ϕ give us principal-stress differences $\sigma_1 - \sigma_2$ and principal-stress directions θ. Otherwise, stress anisotropy cannot be separated from eq (3) or (6).

For the wide-flanged rolled beam, investigated in this paper, the thermal gradients were predominant in the transverse section during the cooling process after hot rolling. The resulting residual stresses were almost fully longitudinal. Texture anisotropy was also likely to be constant along a particular rolling line. Since the residual stresses were released at both end sections, the acoustic anisotropy there coincides with the texture anisotropy. In this way we can evaluate the value of α in eq (6), and thus obtain residual stresses by measuring the shear-wave velocity differences.

Experimental Method

A block diagram of the measuring system is shown in Fig. 1. An electronic pulse of 30 V and 0.1 microsecond width generated from an oscillator excites the transmitter transducer which launches elastic shear waves of 5 MHz into the specimen. The pulse that travels through the specimen is received by the receiving transducer. This signal is amplified to a preselected level. A new trigger signal is generated and returned to the oscillator, via a multiple delay circuit, to retrigger it. Thus the signal circulates in a closed loop. One period of this loop is called a sing-around period. In this experiment, an average period was measured for 10,000 repetitions of the loop by an electronic counter having reference frequency of 10 MHz. Thus the average period is measured with the sensitivity of 10^{-11} s. The gated amplifier admitted a particular echo pulse selectively out of the series of echoes. As the reflection method was adopted, only a part of one surface of the material on which the transducer was attached was polished while the other surface was left with rusty state. This makes the application of the acoustoelasticity method to structural components much easier

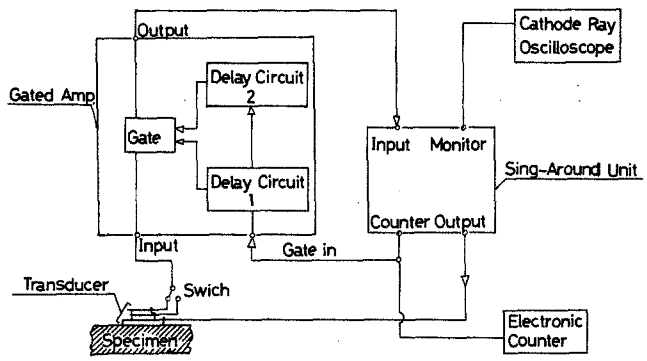


Fig. 1—Block diagram of measuring system

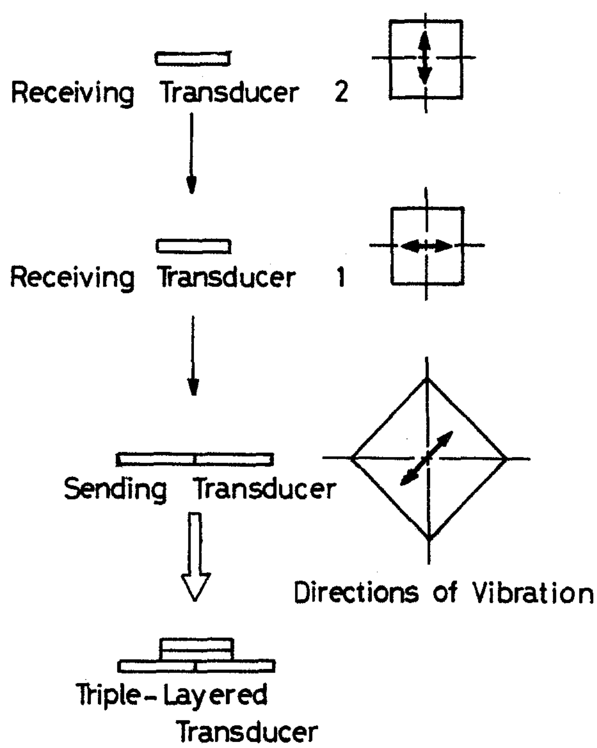


Fig. 2—T-type transducer

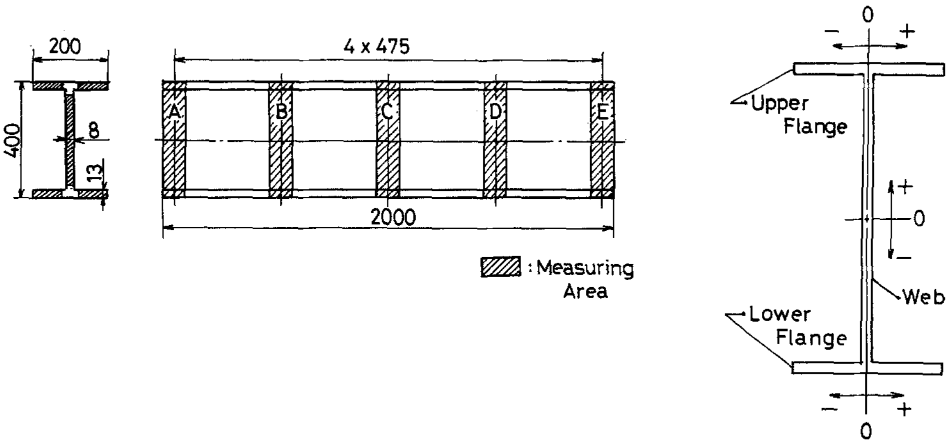


Fig. 3—Measuring area of flange and web of the beam

than the transmitting method for which both surfaces should be polished.

The T-type transducer used in this experiment is made of three 5-MHz shear type PZT transducer elements piled on and cemented in three layers (Fig. 2). The first element is a transmitting transducer and the second and third are receiving transducers. The polarization directions of the two receiving elements are set perpendicular to each other and at 45-deg to that of the transmitting element. The T-type transducer was set on the specimen such that the polarization direction of the transmitting element was at 45 deg with a principal acoustic direction. A pulse excited by this element was then decomposed in the material into two shear waves polarized in the principal acoustic directions. These two waves propagated independently into the specimen and two kinds of echoes were received separately by the two receiving elements. These echoes were fed to the gated amplifier alternately by a change-over switch. By combining this type of transducer with a sing-around circuit and a gated amplifier, the difference of propagation speeds of two shear waves, polarized in the directions of principal acoustic anisotropy, can be measured without rotating the transducer as was done by the ordinary type of transducer. By the ordinary method,[1] the receiving transducer was first set so that the polarization direction was in one of the principal acoustic directions and the transit time of the shear wave was measured. Then, the transducer was rotated 90 deg and the measurement was done again. This means the measurement for one point was done for two different transducer-specimen coupling conditions and the environmental temperature changed sensibly during the measurement. These gave rise to the errors in measurement of the transit time. But the present method of using T-type transducer avoids these disadvantages and the error in measurement of transit time is found to be within 0.5×10^{-9} s from the experiments. Thus for a specimen of 20-mm thickness, the acoustic anisotropy can be evaluated to within 0.004 percent. The couplant is Canada balsam diluted with castor oil.

The wide-flanged rolled beam that was used in this experiment is shown in Fig. 3. It measured $8/13 \times 400 \times 200 \times 2000$ mm and had an unknown manufacturing history. The measurements of acoustic anisotropy were done for shaded regions A to E shown in Fig. 3.

As mentioned previously, we assumed that the acoustic anisotropy along each rolling line of end sections A and E represented texture anisotropy only. By averaging values at A and E, texture anisotropy for each rolling line was obtained. Stress anisotropy for regions B, C and D was then obtained by subtracting the texture anisotropy from sections A and E from the total acoustic anisotropy through the use of eq (6). The residual-stress distributions obtained by this procedure represent a nondestructive acoustoelasticity measurement. To check the accuracy of the acoustoelastic technique the residual stresses of the beam was measured by a conventional destructive method.

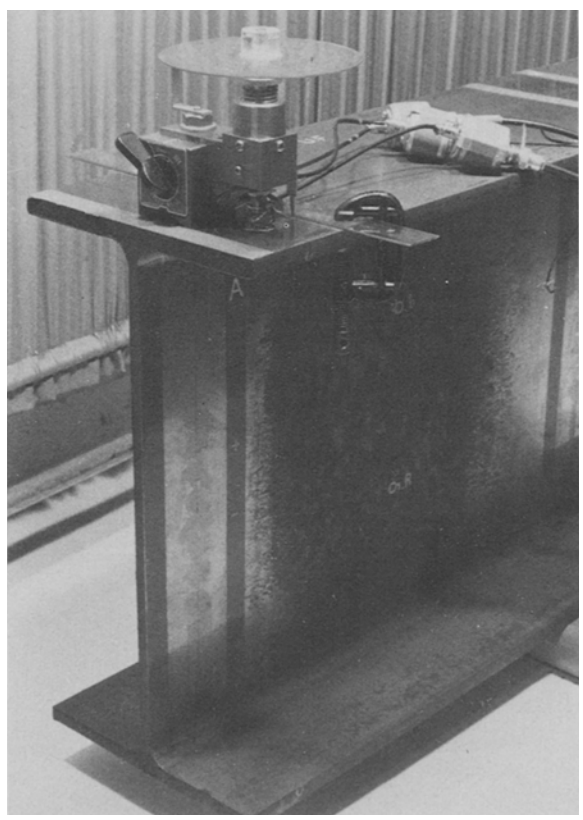


Fig. 4—T-type transducer with a setting block on the flange of the beam

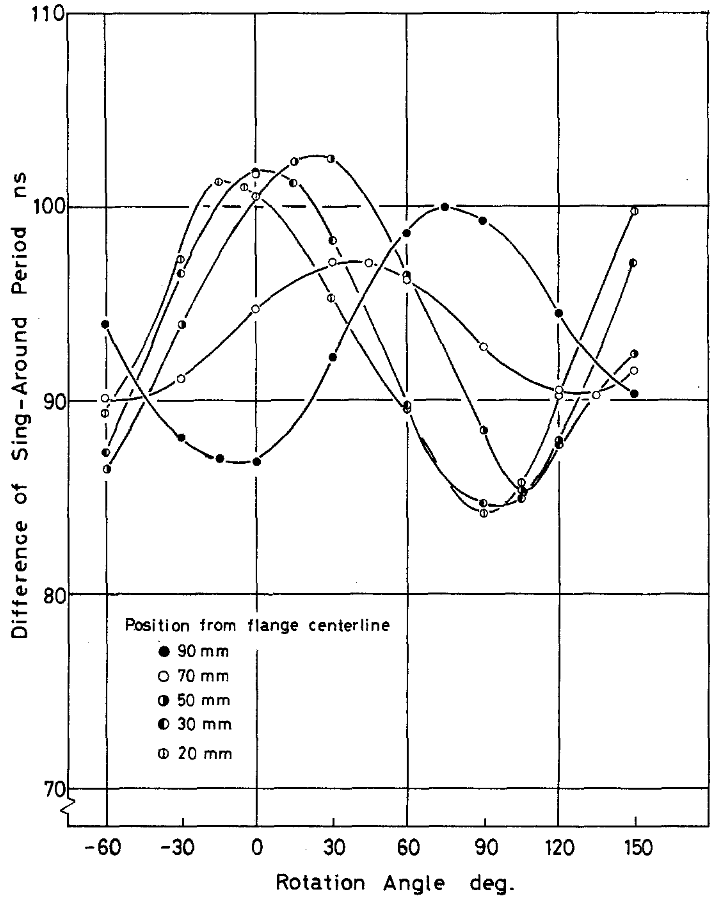


Fig. 5—Transit time difference of sing-around period for region *C* of the flange

To do this, regions A to E were cut out as pieces having a longitudinal length of 100 mm. Gage length was measured before and after the sectioning by a contact strain gage which is widely used in iron and steel industries.

For nondestructive acoustoelasticity measurement of residual stress, we assumed that the texture anisotropy was mean values of acoustoelasticity measurements at both free ends. To confirm this assumption, acoustoelasticity measurement was done for every piece A to E which was free from residual stress by sectioning. Thus, actual texture anisotropies were measured for every region A to E. These values are subtracted from acoustic anisotropy of the corresponding point obtained before releasing the residual stress. The residual stresses thus obtained are called those of destructive acoustoelasticity measurements.

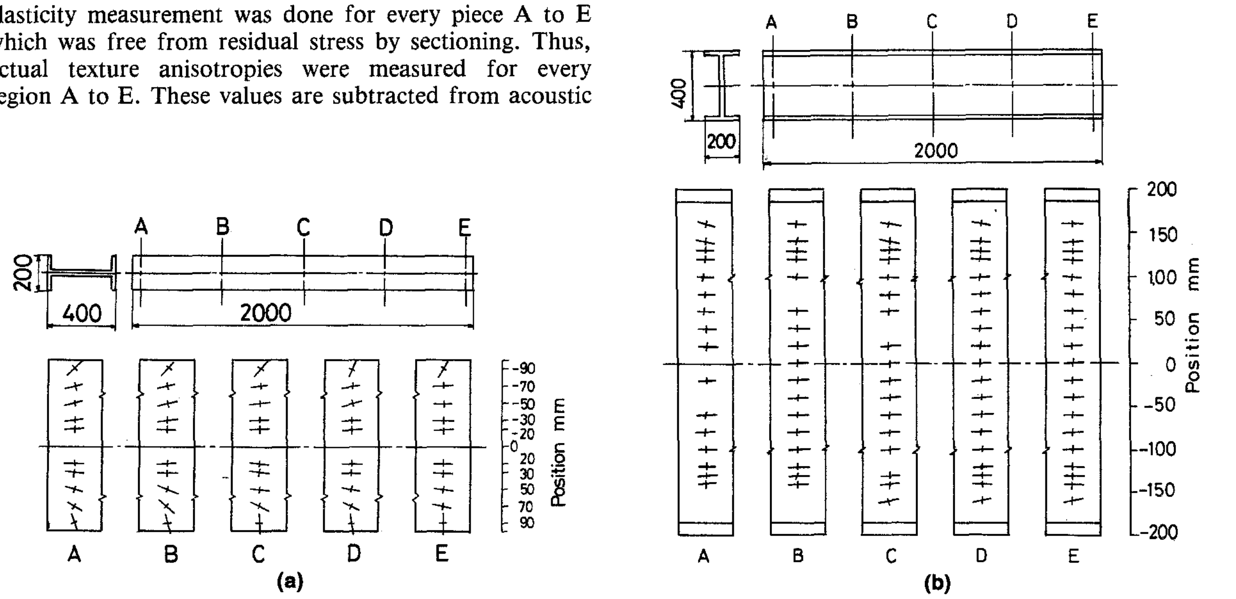
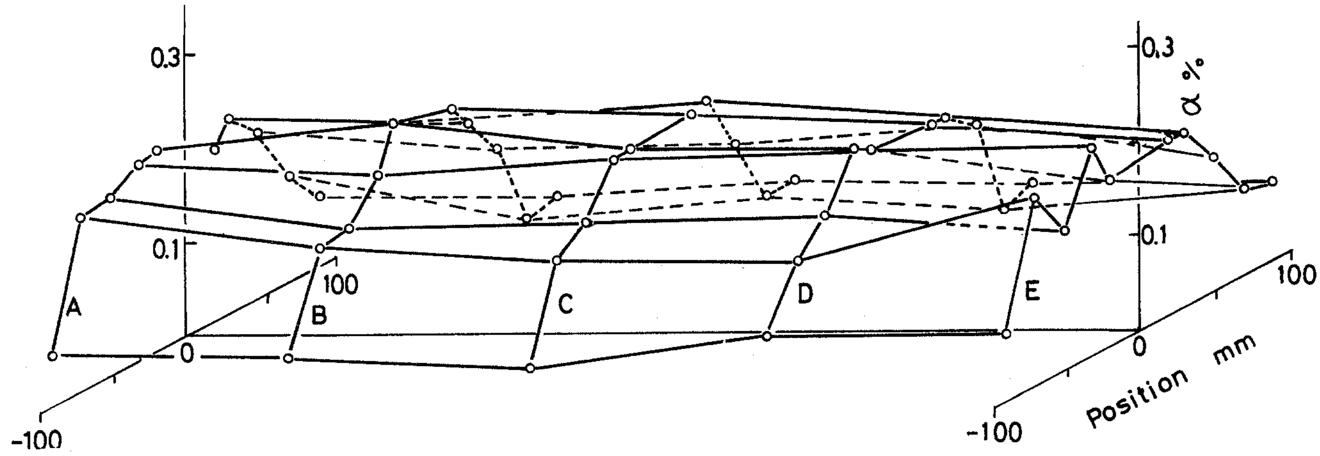
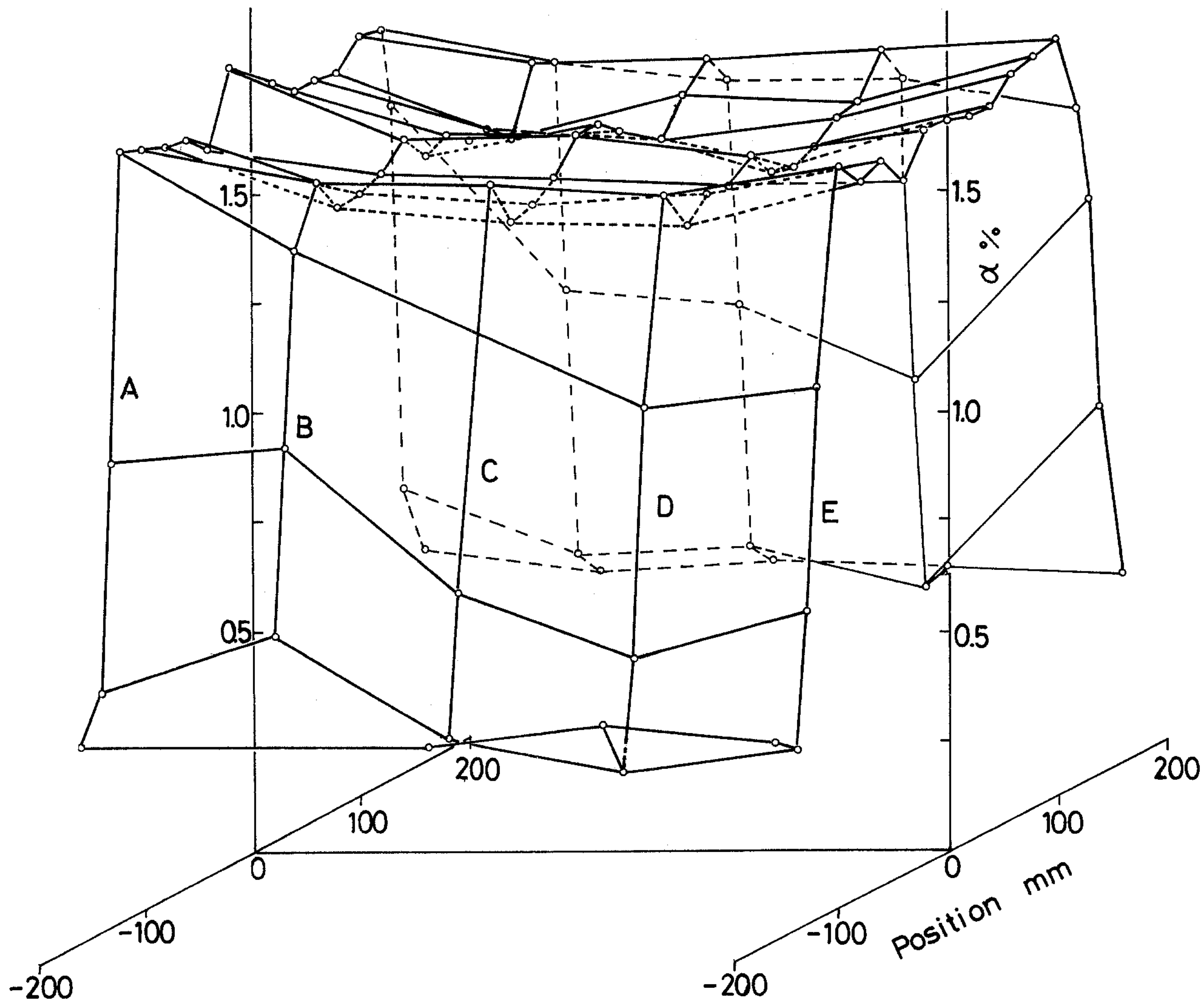


Fig. 6—Distribution of acoustic-anisotropy direction, (a) upper flange, (b) web



(a)



(b)

Fig. 7—Distribution of texture anisotropy, (a) upper flange, (b) web

Experimental Results

The positions of the measuring sites are designated from the center lines of the flange and the web as shown in Fig. 3. The magnitudes and directions of acoustic anisotropy were obtained by rotating the orientation angles of the T-type transducer continuously and plotting, for each orientation angle, the difference in the transit times of the two perpendicularly polarized shear waves. The directions of acoustic anisotropy are mutually perpendicular and correspond to the directions which give maximum and minimum values when the transducer is rotated. The magnitude of the acoustic anisotropy is half of the difference between the maximum and minimum values. Fig. 4 shows the T-type transducer supported by a setting block measuring acoustic anisotropy on the flange of the beam. And Fig. 5 shows the results of the measurement for the region C of flange. The zero of rotation angle corresponds to the rolling direction, i.e., the axial direction. Hereafter we call the direction which gives the maximum value the 'direction of acoustic anisotropy.' For the flange, the directions of acoustic anisotropy along the edge (90 mm) have rotated nearly 90 deg with respect to those near the center line (20 mm).

The directions of acoustic anisotropy for the flange and the web, before sectioning, are shown in Figs. 6(a) and (b), respectively. The distributions of acoustic anisotropy after sectioning, i.e., the distributions of texture anisotropy, are shown in Figs. 7(a) and (b).

From these figures, it is shown that the distribution of texture anisotropy in the flange is fairly constant along the longitudinal direction, although it fluctuates widthwise. And the magnitude of texture anisotropy is on the same order as that of stress anisotropy for flange. On the other hand, the distribution of texture anisotropy in the web fluctuates along the longitudinal direction as well as the transverse direction. This, together with the fact that the magnitude of texture anisotropy is seven to eight times larger than that of stress anisotropy in the web makes the evaluation of nondestructive-acoustoelasticity measurement of residual stress in a web very poor as will be seen in Fig. 10(c). The texture anisotropy at sections A and E were essentially the same before and after sectioning the beam.

To obtain the acoustoelastic constant C_A and the coefficient of texture anisotropy α of this beam material for eq (6), we cut out sample specimens from the positions shown in Table 1. The size of the specimen was 60 mm × 60 mm. The compression test was done for the specimen as shown in Fig. 8. An example of the results is shown in Fig. 9, where the slope of the plotted line gives the acoustoelastic constant C_A and the acoustic anisotropy at zero stress gives the texture anisotropy α.

The residual-stress distribution obtained by nondestructive-acoustoelasticity measurement is shown as solid circles in Figs. 10(a), (b) and (c) for region C in the upper flange, lower flange and web, respectively. The open circles in the same figures represent the results obtained from the conventional sectioning method. For this method, the gage length was selected as 60 mm along the longitudinal direction and 20 mm along the transverse direction. The gage positions were marked accurately by the gage punch [Fig. 11(a)], and the hardened-steel ball of 1.6-mm diameter was indented at the gage position by the hammer punch as shown in Figs. 11(b) and (c). Then, each region A to E was cut out as a piece having 100 mm length in longitudinal direction (Fig. 13). The cutting was done by a contour machine with water cooling to prevent the temperature rise. The gage length changed by releasing the residual stress due to sectioning was measured by the contact strain gage as shown in Fig. 12. The dial gage with the mechanical-lever ratio of five times gives the measuring sensitivity of 0.001 mm. The residual stress by the conventional destructive method is thus obtained from the gage lengths before and after the sectioning.

TABLE 1—POSITION OF SAMPLE SPECIMEN TO OBTAIN ACOUSTOELASTIC CONSTANT AND COEFFICIENT OF TEXTURE ANISOTROPY

Position of sample specimen	α[%]	C [1/MPa]
Flange 20 mm	0.23	0.69×10^{-5}
Flange 90 mm	0.06	0.65×10^{-5}
Web 0 mm	1.58	1.31×10^{-5}
Web 160 mm	0.41	1.00×10^{-5}

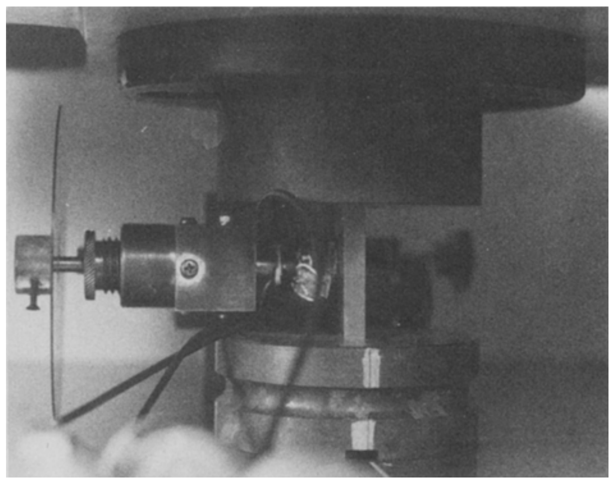


Fig. 8—Compression test to obtain acoustoelastic constant

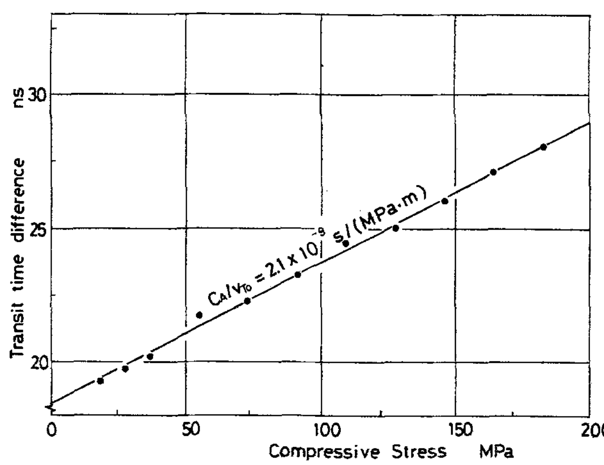


Fig. 9—Acoustoelastic constant by compression test

Good agreements for the nondestructive-acoustoelasticity measurement and the conventional sectioning method for both upper and lower flanges are shown in Figs. 10(a) and (b), but it is not the case for the web [Fig. 10(c)]. This discrepancy was discussed before when Fig. 7(b) was referred to.

Figure 14 shows the comparison of the results between destructive acoustoelasticity measurement and the conventional sectioning method. For destructive-acoustoelasticity measurement, as the texture anisotropy α is evaluated actually for every measuring point, both results show good agreement for web as well as for flange. We thus confirm the validity of eq (6).

Conclusions

For metallic materials which have a texture structure, the acoustic anisotropy consists of texture anisotropy and stress anisotropy and the additive law for both contributions is confirmed for a wide-flanged rolled beam.

In cases where the distribution of texture anisotropy is conjectured by geometry and forming process, the acoustoelasticity technique can be applied to measure residual stress nondestructively.

Directions of texture anisotropy are parallel to rolling directions for center regions both for flange and web, but they will deviate as the edge regions are approached.

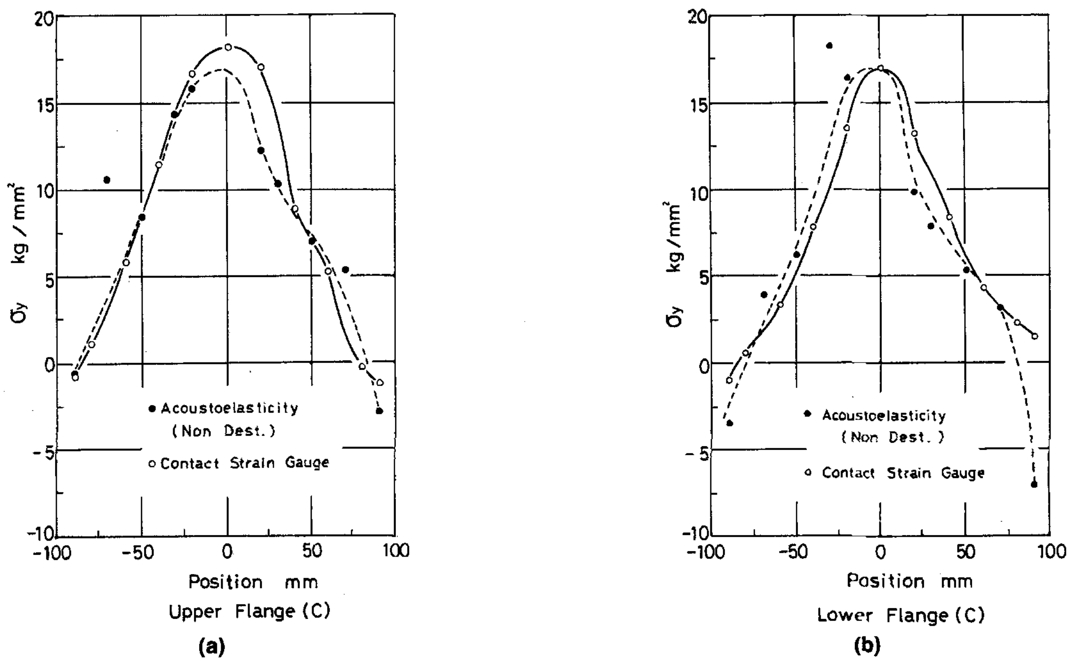
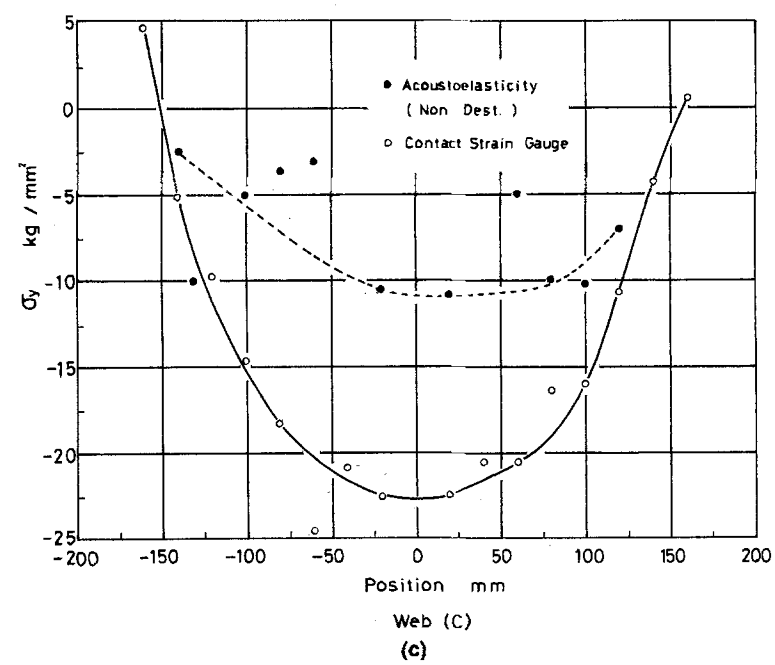


Fig. 10—Distribution of residual stress by nondestructive acoustoelasticity and contact strain-gage measurements, (a) region *C* of upper flange, (b) region *C* of lower flange, (c) region *C* of web



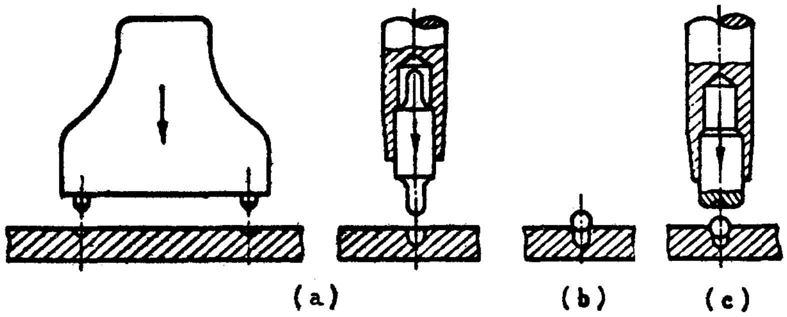


Fig. 11—Process of establishing gage points

For web, magnitude of texture anisotropy is not uniform along a particular rolling line. This fact together with the large values of texture anisotropy there makes the evaluation of the residual stress by nondestructive-acoustoelasticity method poor for the web of the beam used in this experiment.

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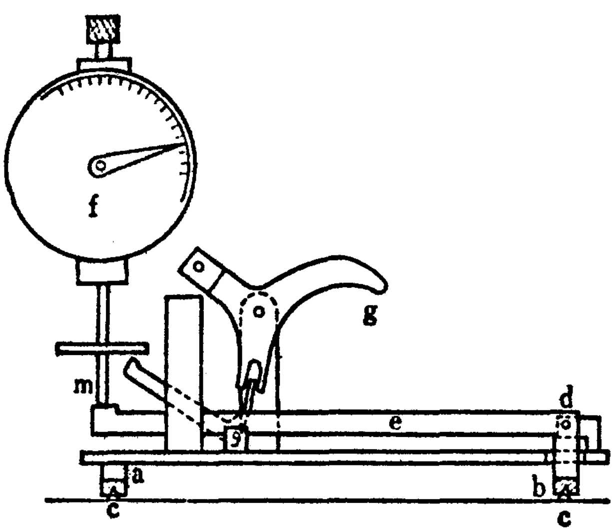


Fig. 12—Contact strain gage

APPENDIX

Propagation velocities of waves in material under stress were analyzed by Tokuoka and Iwashimizu[2] by using the theory of small motion superimposed on finite-static deformation. The strain energy ϵ of the isotropic elastic material is given by

$$\epsilon = \frac{1}{2}(\lambda + 2\mu)\mathrm{I}^2 - 2\mu\mathrm{II} + \frac{1}{6}(\nu_1 + 6\nu_2 + 8\nu_3)\mathrm{I}^3 - 2(\nu_2 + 2\nu_3)\mathrm{I}\cdot\mathrm{II} + 4\nu_3\mathrm{III} \quad \text{(A1)}$$

where

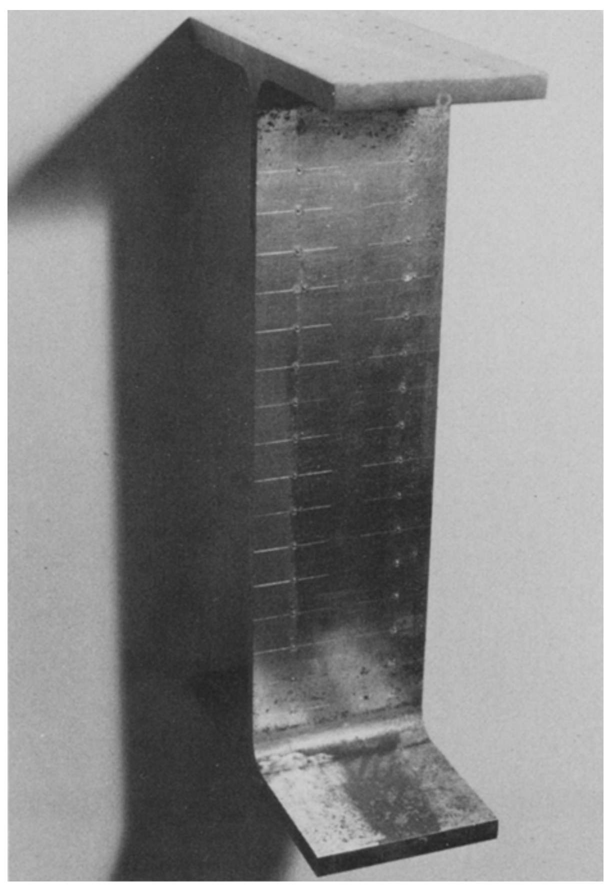


Fig. 13—Beam piece after sectioning

I, II, III = basic invariants of Green's strain tensor
λ, μ = Lame's constants
ν_1, ν_2, ν_3 = third-order elastic constants

If we take x_3-coordinate axis in the direction of wave propagation, then the propagation velocities of longitudinal and shear waves are given by

$$V_L = V_{L_0}\left[1 + \frac{1}{2(\lambda+2\mu)}\{(\lambda+\nu_1+2\nu_2)e + 2(2\lambda+5\mu+2\nu_2+4\nu_3)e_3\}\right] \quad (A2)$$

$$V_{T\Gamma} = V_{T_0}\left[1 + \frac{1}{2\mu}\{(\lambda+\nu_2)e + 2(2\mu+\nu_3)e_3 + 2(\mu+\nu_3)e_\Gamma\}\right] \quad (A3)$$

respectively, in which shear waves $V_{T\Gamma}$ ($\Gamma = 1, 2$) are polarized in principal directions, V_{L_0} and V_{T_0} are those values for stress-free state, e_Γ ($\Gamma = 1, 2$) and e_3 are principal strains and $e = e_{RR}$ is the cubical dilatation.

For plane-stress state $\sigma_3 = 0$, we have

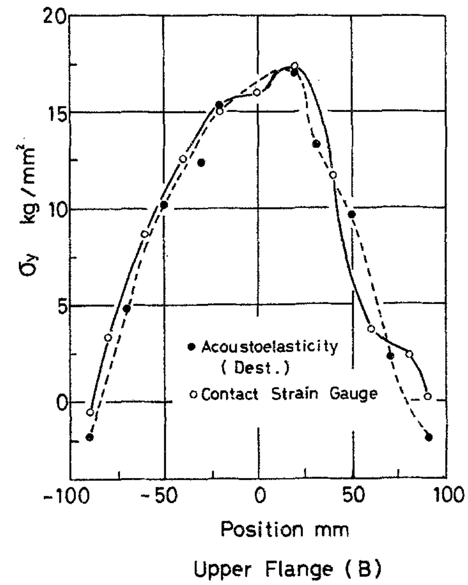
$$e_3 = -\frac{\lambda}{2\mu}e = -\frac{\lambda}{2\mu(3\lambda+2\mu)}(\sigma_1+\sigma_2) \quad (A4)$$

Substituting eq (A4) into eq (A2), we obtain

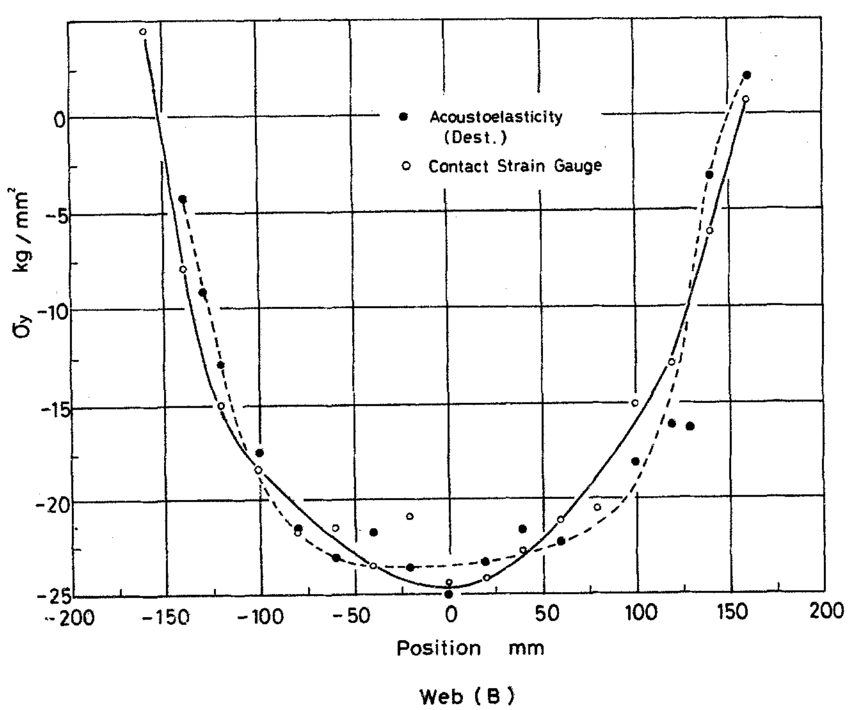
$$\frac{V_L - V_{L_0}}{V_{L_0}} = \frac{-2\lambda(\lambda+2\mu) + \mu\nu_1 - 2(\lambda-\mu)\nu_2 - 4\lambda\nu_3}{2\mu(\lambda+2\mu)(3\lambda+2\mu)}(\sigma_1+\sigma_2) \quad (A5)$$

for the fractional velocity change of the longitudinal wave.

Therefore, if we measure the longitudinal velocity change as well as the difference of velocities of shear waves polarized in principal directions, we can separate σ_1 from σ_2 by eqs (A5) and (1). From our experience, however, the order of error in thickness measurement of the specimen is much larger than that of transit time measurement so that the resulting error is too large for the acoustoelastic analysis to be of practical value.



(a)



(b)

Fig. 14—Distribution of residual stress by destructive acoustoelastic and contact strain-gage measurement, (a) region *B* of upper flange, (b) region *B* of web