Application of an Acoustoelastic Stress Measurement System Using Grazing SH-wave to Angle Steel Construction

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(Received 13 January 2012; received in revised form 13 April 2012; accepted 26 April 2012)

Abstract
As for the structures built at rapid economic growth, obsolescence is progressing, and the accidents by damage are occurring frequently. As a cause for collapse of a structure, the load stress more than assumption is considered. The aim of this study is to apply a grazing SH-wave acoustoelastic method to the stress measurement in actual angle steel used in power transmission steel towers. A new-type grazing SH-wave sensor was developed in order to measure the wave velocity of angle steel in a high accuracy. The search of optimal measurement area in stress evaluation and the grinding method for making a smooth measuring plane were also discussed. As a result, stress measurement for the angle steel was enabled, because the part which the influence of the bending is little was able to be found out.

Key words
Grazing SH-wave, Acoustoelastic, Residual Stress, Angle Steel, Grinding Method

1. Introduction
By the influence in the East Japan great earthquake that collapsed Fukushima nuclear power plant, the concern in the durability of structures is increasing more and more. In order to use such large-sized structures safely, suitable non-destructive testing and repairing are necessary to be carried out periodically. As a cause for collapse of a structure, the load stress more than assumption is considered [1]. Therefore, stress evaluation of a structure attracts attention as a means evaluating the unbalance of force in the structure, and the method that can measure the residual stress of it in use is desired strongly [2]. However, a practical measurement method for the residual stress in material has not been developed yet.

Acoustoelasticity is a phenomenon that the velocity of ultrasonic wave propagating in a solid varies according to a stress condition in the medium [3, 4]. The acoustic birefringent of shear wave is linearly related to the principal stress difference of medium under a plane stress. Birefringent acoustoelasticity [5] and horizontally polarized SH-wave acoustoelasticity [6] have been studied as useful methods for nondestructive measurement of the residual stress. However, the residual stress measurement with the acoustoelasticity has not been practically used. The reason for this is that in the birefringent acoustoelasticity method the measured acoustical anisotropy includes not only stress anisotropy but also material anisotropy produced in manufacturing processes.

A method for separating them has not been developed yet. On the other hand, residual stress could be evaluated by using horizontally polarized SH-wave with a V path technique in two incident angles, but the measurement accuracy is greatly affected by the roughness of the bottom surface of material. A grazing SH-wave acoustoelasticity has been devised as one method for separating stress anisotropy and material anisotropy [7-9]. By this method, it became possible to measure the residual stress of the surface region of material, without the influence of the material anisotropy. However, in the grazing SH-wave acoustoelasticity method it was very difficult to measure the residual stress with high accuracy because the measurements are strongly affected by the contact condition and the roughness of the surface of material.

A Grazing SH-wave sensor in which highly precise stress measurement is theoretically possible has been studied [10]. In this study, applying a new grazing SH-wave sensor to the stress measurement of angle steels used in power transmission steel towers as actual constructions was investigated. The search of optimal measurement area in stress evaluation and the grinding method for making a smooth measuring plane were also discussed.

2. Grazing SH-wave
2.1 Grazing SH-wave acoustoelasticity
Grazing SH-wave is an elastic wave which propagates near the surface of solid. When a grazing SH-wave is propagated along each principal stress axis which is perpendicular to each other as shown in Fig. 1 and the wave velocity of each direction in material is measured, the acoustical anisotropy is expressed by the following equations [3].

\[ \Phi = \frac{V(0\degree) - V(90\degree)}{(V(0\degree) + V(90\degree))/2} = C_s(\sigma_1 - \sigma_2) \]  \hspace{1cm} (1)

\[ C_s = -\frac{1}{2\mu} \]  \hspace{1cm} (2)

\( \Phi \) is acoustic anisotropy, \( C_s \) is Grazing SH-wave acoustoelasticity coefficient [11], \( \sigma_1 \) and \( \sigma_2 \) are each principal stress, \( V(0\degree) \) and \( V(90\degree) \) are velocity of grazing SH-wave in direction of principal stress, respectively. \( 0\degree \) and \( 90\degree \) show the parallel and the perpendicular direction to the rolling direction, respectively. As shown in Eq. (1),
in grazing SH-wave acoustoelasticity the acoustical anisotropy is dependent only on stress anisotropy. Grazing SH-wave acoustoelasticity coefficient is a half of the reciprocal of shear modulus \( \mu \) and is fixed for the material. The coefficient does not vary in the same material even if processing and heat treatment are carried out. Since in a grazing SH-wave acoustoelastic method the acoustical anisotropy which is defined by \( V(0^\circ) \) and \( V(90^\circ) \) has proportionality relation to the principal stress difference, a principal stress difference can be calculated by measuring each acoustic velocity. In this method, it is possible to measure the averaged principal stress difference in the surface region of material. The depth of the measured depends on the directivity of radiated ultrasonic wave, and almost corresponds to the wavelength.

2.2 T-type grazing SH-wave sensor

In the grazing SH-wave acoustoelasticity method, propagation time have to be measured with very high accuracy. Therefore, the measurement error by the coupling medium was not able to be disregarded. The thickness of the coupling medium varies by time progress and the contact condition between the sensor and the tested material. Then, in order to measure grazing SH-wave acoustoelasticity with less error, we have developed a new grazing SH-wave sensor. The sensor consisted of two transmitters and four receivers as shown in Fig. 2. The sensor propagated a grazing SH-wave into two pathways. The sensor was named T-type grazing SH-wave sensor. The detailed measurement principle for acoustoelasticity using this sensor is explained below.

In Fig. 2, the measured propagation time \( T'_{A-a_2} \) from the transmitter-A to the receiver-a is expressed by

\[
T'_{A-a_2} = T_{A-a_2} + t_\alpha + t_\beta, \tag{3}
\]

Where \( T_{A-a_2} \) is the real propagation time, \( t_\alpha \) and \( t_\beta \) are the error due to the contact condition at the contact surface of P and at the contact surface of the transmitter-A, respectively. Similarly, the measured propagation time

\[
T'_{A-a_2} \text{ from the transmitter-A to the receiver-a is expressed by}
T'_{A-a_2} = T_{A-a_2} + t_\beta + t_\gamma. \tag{4}
\]

where \( T_{A-a_2} \) is the real propagation time by the receiver-a, and \( t_\beta \) is the error by the contact condition at the contact surface at Q. The propagation time \( \Delta T_A \) between P and Q corresponds to the time difference between the \( T'_{A-a_1} \) and \( T'_{A-a_2} \). Therefore, the \( \Delta T_A \) is given by

\[
\Delta T_A = T'_{A-a_2} - T'_{A-a_1} = T_{A-a_2} + t_\beta - (T_{A-a_1} + t_\alpha). \tag{5}
\]

In the same way, using the transmitter-B, the propagation time \( \Delta T_B \) between P and Q is given by

\[
\Delta T_B = T'_{B-b_2} - T'_{B-b_1} = T_{B-b_2} + t_\beta - (T_{B-b_1} + t_\alpha). \tag{6}
\]

where \( T'_{B-b_2} \) and \( T'_{B-b_2} \) are the measured propagation time from the transmitter-B to the receiver-b and to the receiver-b, \( T_{B-b_1} \) and \( T_{B-b_1} \) are the real propagation time of the \( T'_{B-b_1} \) and \( T'_{B-b_2} \), respectively. Then, by averaging \( \Delta T_A \) and \( \Delta T_B \), we can obtain the propagation time as

\[
\Delta T = \frac{\Delta T_A + \Delta T_B}{2} = \frac{T_{A-a_2} - T_{A-a_1} + T_{B-b_2} - T_{B-b_1}}{2}. \tag{7}
\]
ΔT does not include the error by the contact condition.

2.3 Fabrication of T-type SH-wave sensor
In order to propagate grazing SH-wave in angle steel, shear wave was transmitted and received through wedges. The wedges were made of Polystyrene. Shear wave piezoelectric element made of PZT was applied to the transmitters and the receivers. The resonant frequency of each element was 5MHz. The element size of the transmitter and the receiver were 10.0mm x 2.2mm and 8.0mm x 1.6mm, respectively. On the surface of each element was adhered to the wedges using epoxy glue. The other surface was fixed to aluminum plate by using the glue and a synthetic rubber. In order to generate a grazing SH-wave into the angle steel, the incident angle from the wedge to the angle steel was set to 20.7º, which corresponds to the critical angle between Polystyrene and the angle steel. The distance between P and Q in Fig. 2 was 12mm. Therefore, the averaged principal stress difference in the area of 12mm square could be measured by this sensor.

2.4 Setup of a measurement system for grazing SH-wave acoustoelasticity
The block diagram of a measurement system for the grazing SH-wave acoustoelasticity is shown in Fig. 3. A sing-around technique was adopted to measure wave velocity. The sing-around unit (Ultrasonic Engineering Co., Ltd., UVM-2) drove the transmitters by a pulse. The signals from four receivers were automatically changed by a switching unit (Thamway Co., Ltd., T121-205AC) and sent to the sing-around unit. The sing-around unit measured the propagation time with the time resolution of 10ps through adding up propagation time 10,000 times.

2.5 Influence of contact condition on measurement
It is thought that the thickness of the coupling medium differs at every measurement. The reason for this is the contact condition between the ultrasonic sensor and the test piece differs at every measurement. Then, we investigated the measurement error by contact conditions in plural propagation time measurements. A flat steel plate made of SS400 was used as a test piece. A coupling medium (Nichigou Acetylene Co., Ltd., SONI COAT SHN-A5) was used on the contact surface of the test piece and the sensor. In order to compare with the previous method, the measurement by only one receiver was also carried out. The ultrasonic sensor was removed from the test piece whenever the measurements finished, and the coupling medium was newly applied. Ultrasonic wave was radiated to the test piece from the transmitter-A, and the propagation time $T'_{A-a_1}$ was measured only by the receiver-$a_1$. The variation of the $T'_{A-a_1}$ in measurements of 10 times is shown in Fig. 4(a). On the other hand, the propagation time $ΔT$ was measured by all the transmitters and the receivers of T-type grazing SH-wave sensor. Figure 4(b) shows the variation of the $ΔT$. From these figures, it has been found that the measurement error by the T-type SH-wave sensor was little in comparison with the other methods.

![Fig. 3 Block diagram of a measurement system for the grazing SH-wave acoustoelasticity](image)

![Fig. 4 Comparison of the variation in the measured propagation time](image)
of transmitter and receiver, the distance between the transmitter and the receiver was variable. In this experiment, the distance was 13 mm. The propagation time was measured for 10 minutes after installing each ultrasonic sensor. As the result, the measured propagation time by the earlier sensor varied with lapsed time as shown in Fig. 5(a). On the other hand, the measured propagation time by the T-type grazing SH-wave sensor almost did not varied with lapsed time as shown in Fig. 5(b). Therefore, it was demonstrated that the T-type grazing SH-wave sensor was able to measure the propagation time immediately after installing the sensor. From the above-mentioned results, it has become clear that the T-type SH-wave sensor could measure the stress without the influence of the coupling medium. And in a flat test piece, this sensor was able to measure stably wave velocity in the accuracy of less than 0.1 m/s. Therefore, we can measure grazing SH-wave acoustoelasticity accurately using T-type SH-wave sensor.

3. Stress Measurement of Angle Steel

3.1 Estimation of the optimal measurement part

Generally, angle steels, used for power transmission steel towers etc., are made through a bending [13]. For the stress evaluation of angle steel (see, Fig. 6) of 10.75mm thickness, the low residual stress part of the angle steel was searched in this study. This is because if stress remains in the short axis (width) direction in an angle steel, wrong estimation might be carried out in the long axis direction. When stress measurements are carried out using T-type grazing SH-wave sensor, smooth surfaces must be made by grinding at first. After grinding galvanizing of the central part of angle steel by machine process, a surface processing was carried out using ♯2000 sanding sheet. Measuring points were 30 points in the grinding area shown in Fig. 7. \( V(0') \) and \( V(90') \) were measured 7 times, respectively and the principal stress difference was calculated from the average for 5 times except those minimum and maximum values.

Measured result of residual stress distribution is shown in Fig.8. These values show residual stress values on only the short axis direction because the residual stress on the
long axis direction is released. It was found from Fig. 8 that the value of residual stress in 20 mm position from the corner of the angle steel was small and that its dispersion was also little regardless of the long axis direction. But its dispersion became large as the measurement position was away from the corner. As this reason, it was thought that the influence of the reform by bending process near the corner was small and that the stress remained in order to hold the shape of the angle steel in the position which was away from the corner. From the above mention, it was determined that the position near the corner was optimal measurement part for the stress evaluation of angle steels.

3.2 Stress measurement of long axis direction

Next, in order to judge whether the measurement part determined to be optimal is right, the residual stress of three areas in the long axis direction was measured (see Fig. 9(a)). Measurement positions in each area were shown in Fig. 9(b). The result is shown in Fig. 10. In the measurement of stress distribution on long axis direction, the stress values were all within ±20MPa. From the result, it was confirmed that the stress measurement near the corner of angle steel is optimal in actual constructions. It is considered as one of the causes for the dispersion of measured stress that surface preparation of the measured area was inadequate. It is necessary to perform a tension test in the future and to verify the availability of this method.

4. Examination of Grinding Method for Angle Steel

4.1 Portable grinder using a small drilling machine

By the past study, it is found that the surface roughness of a measuring plane has influenced measurement accuracy. Generally, on the surface of angle steel used to construction parts, galvanizing is carried out to prevent the corrosion. In this study, the method making a measuring plane flat and smooth by precision grinding by a small grinder after rough grinding by a commercial belt sander was adopted. We developed newly a portable grinder as shown in Fig. 11 using a small drilling machine. This grinder eccentrically moves a grinding stone. In this grinder, contact force to measuring surface can be controlled and the roughness of grinding stone can be also changed.

4.2 Availability of proposed grinding method for angle steel

As an experiment assumed measurement in a field, it was verified whether finally stress measurement would be possible with sufficient accuracy for an angle steel to which galvanizing was given. When grinding measurement surface by the portable grinder was carried out, we used grinding stones of #80, #170, #600, #1000. After the grinding, the stress of the part was measured using T-type grazing SH-wave sensor. $V(0')$ and $V(90')$ were measured 7 times, respectively and the principal stress difference was calculated from the average for 5 times except those
minimum and maximum values. Point 1 and Point 2 shown in Fig. 12 are the measuring parts.

Measured result is shown in Table 1. The variability of measured wave velocity at two points was within 0.22 m/s and stress calculated was -10.35 MPa at Point 1 and -17.6 MPa at Point 2, respectively. On the other hand, the sensitivity of received waveform during measurements was sufficient magnitude which can be observed with an oscilloscope. That is, the problems in the remove of galvanizing and in the smoothing have been overcome. However, grinding time takes 20 minutes in the present study. Therefore, the remedying is needed in the future.

Table 1 Wave velocity and stress of angle steel after the grinding

<table>
<thead>
<tr>
<th>Angle [°]</th>
<th>Average [m/s]</th>
<th>Max-Min [m/s]</th>
<th>Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3296.94</td>
<td>0.12</td>
<td>-10.35</td>
</tr>
<tr>
<td>90</td>
<td>3296.73</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3296.93</td>
<td>0.22</td>
<td>-17.61</td>
</tr>
<tr>
<td>90</td>
<td>3296.57</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusion
In this study, in order to measure grazing SH-wave acoustoelasticity with less error, a new grazing SH-wave sensor was developed. This sensor was able to measure stably wave velocity in the accuracy of less than 0.1 m/s in a flat test piece. The stress evaluation of angle steel used in power transmission steel towers was noticed, and the grinding method for making a smooth measuring plane and finding the optimal measurement part for stress evaluation were also discussed. As a result, it was found that near the corner of angle steel was the part which the influence of the bending processing in the angle steel is little. That is, it was found that residual stress at this position was small and that its dispersion was also small. Moreover, a portable grinder which can use in the field was developed. After time, the availability of the proposed stress measurement method should be demonstrated in the field.

Nomenclature
- \( C_s \): grazing SH-wave acoustoelasticity constant, 1/GPa
- \( \Phi \): acoustic anisotropy
- \( \sigma \): stress, MPa
- \( V \): sound velocity, m/s

Acknowledgement
Authors wish to thank Sakai Iron Works Co. Ltd., for the supply of angle steels.

References