Finite Element Analysis and Ultrasonic Evaluation of Stresses in Q345 Plates

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Abstract. This paper investigates and demonstrates the nondestructive capability of ultrasonic waves and magnetic Barkhausen noise (MBN) in stress evaluation of Q345 plates. A 10mm thick Q345 specimen was subject to a concentrated load by a stressing jack, known as a three-point bending test. A finite element model of Q345 plate was established to verify the experimental results. The stresses have been measured by three nondestructive evaluation methods including ultrasonic techniques, magnetic Barkhausen noise method and strain gauge method. This paper gives the details of development of ultrasonic longitudinal critically refracted (LCR) wave based technique for stress measurement. The results show great agreement between finite element and three stress measurements which are accomplished nondestructively.

1. Introduction

The stress plays a significant role in the strength and service life of structures. It is quite important to quantify the levels of residual stress in critical components such as those high-level vessels in petrochemical plants, since they can deeply impact in-service performance.

Stress evaluation is a significant tool of condition monitoring. The measurement of stresses can be achieved by destructive methods (e.g., the contour method), semi-destructive methods (e.g., hole-drilling) or nondestructive methods (e.g., ultrasonic techniques [1, 2, 3], X-Ray diffraction, magnetic Barkhausen noise [4, 5]). The high industry request for stress measurement techniques expects development of nondestructive methods. Since the strain gages method is standardized by ASTM E251, it is often used as a verification tool for other stress measurement methods. Ultrasonic stress measurement is based on the linear relation between the ultrasonic wave velocity and the stress, known as the acoustoelastic effect. The longitudinal critically refracted (LCR) wave which travels near to the surface, shows the most strain sensitivity among all other types of ultrasonic waves when the wave travels parallel to the stress [1]. As for MBN method, magnetic Barkhausen Noise is a pulsed electromagnetic signal generated by discontinuous jumps of magnetic domains when the ferromagnetic material is dynamically magnetized [4]. The jump of magnetic domains introduced by stress during magnetization influences the emission of the magnetic Barkhausen noise signal. Studies have shown that tensile stress would increase the energy released by the magnetic Barkhausen noise signal, while the compressive stress brings the reversed result [5].

In this study, three methods mentioned above were employed to measure the stress in the three-point bending test.
2. Theoretical backgrounds
Within the elastic limit, the ultrasonic stress evaluation technique relies on the acoustoelastic law. Figure 1 shows elements of a bar under tension where the ultrasonic wave propagates in two perpendicular directions. In figure 1a the wave propagates parallel to the load and \( V_{L1} \) represents the velocity of the particles in the same direction (longitudinal wave), while in figure 1b, the \( V_{L2} \) velocity is for longitudinal waves propagating perpendicular to the stress direction.

\[
\rho_0 V_{L1}^2 = \lambda + 2\mu + \sigma \left[ \frac{\lambda + \mu}{\mu} \left(4\lambda + 10\mu + 4m\right) + \lambda + 2l \right] (3\lambda + 2\mu)^{-1}
\]  

(1)

\[
\rho_0 V_{L2}^2 = \lambda + 2\mu + \sigma \left[ 2l - \frac{2\lambda}{\mu} (\lambda + 2\mu + m) \right] (3\lambda + 2\mu)^{-1}
\]  

(2)

Where \( \rho_0 \) is the initial density; \( V_{L1} \) is the velocity of waves travelling parallel to load; \( V_{L2} \) is the velocity of waves travelling perpendicular to load. \( \lambda, \mu \) are the second order elastic constants (Lame’s constants); \( l, m, n \) are the third order elastic constants. Since waves travelling parallel to load are more sensitivity to the strain than those travelling perpendicular to load, we focus on the former wave in this study. The relative sensitivity is the variation of the velocity with the strain and can be calculated by equation (3) (\( V_L \), instead of \( V_{L1} \)).

\[
V_L^2 = V_{L0}^2 (1 + k\sigma)
\]  

(3)

where:

\[
k = \frac{\lambda + \mu}{\mu} \left(4\lambda + 10\mu + 4m\right) + \lambda + 2l \right] (3\lambda + 2\mu)^{-1}
\]  

(4)

The LCR technique uses a special longitudinal bulk wave mode, as shown in figure 2. When the ultrasonic longitudinal wave reaches an interface between two media at the first critical angle, wave mode conversion occurs, and the LCR wave is produced (\( \beta_L = 90^\circ \)), which travels parallel to the surface, particularly propagating below the surface at a certain depth, about twice of the wavelength.

In this study, the structural Q345 material is assumed to be isotropic and homogeneous. Moreover, it is assumed to be in its elastic range. After a derivation from equation (3), the relationship between the measured wave time-of-flight (TOF) and corresponding uniaxial stress can be written as follows. In equation (7), \( K \) is the dimensionless acoustoelastic constant for LCR waves.

\[
dV_L = - \frac{L}{t^2} dt
\]  

(5)
\[
\frac{dt}{d\sigma} = -\frac{kV_{L_0}t^2}{2L} \equiv -\frac{k_0}{2} = K
\]

where:

\[
K = -t_0 \left[ \lambda + \mu \left( 4\lambda + 10\mu + 4m \right) + \lambda + 2l \right] \left[ 2(\lambda + 2\mu)(3\lambda + 2\mu) \right]^{-1}
\]

3. Experimental procedures

3.1 Sample description and finite element simulation

A 10mm thick Q345 experimental sample was shown in figure 3. This specimen would be used for acoustoelastic constant evaluation and three-point bending test. Also, the annealing process was done at 600°C in vacuum to give the specimen a uniform fine-grained structure and a stress-free state.

3.2 Measurement device

The ultrasonic measurement device includes an Ultrasonic Instrument with integrated pulser, receiver and computer and two transducers assembled on a united wedge. The frequency of transducers was 5 MHz and the diameter of the piezoelectric elements was 6mm. The Ultrasonic Instrument is a 100 MHz ultrasonic testing device which allows precise measurements of the time of flight, even better than 2ns after data process. For the united wedge, the LCR wave travels about 25mm on the specimen.
The MBN measurement device used in this experiment was developed by China Special Equipment Inspection and Research Institute. The excitation frequency for the transducer is 5Hz ~ 500Hz, with the adjustable excitation strength 0.1T ~ 2.0T.

3.3 Acoustoelastic constant evaluation
To evaluate the acoustoelastic constant, the calibration samples were taken from a Q345 plate with exactly the same thickness and chemical composition of the experimental plate. The acoustoelastic constant is deduced experimentally from a uniaxial tensile test associated with an ultrasonic measurement (figure 8).

Acoustoelastic constant represents the slope of the relative variation curve of the time-of-flight and the applied stress, as shown in figure 9. The key of acoustoelastic constant evaluation is to make sure the thickness of the couplant is fixed, which means a thick gel couplant will get a better result than a liquid one. The installation of wedge could make it works stably as well.

After several tensile tests, the acoustoelastic constant within the elastic limit were got. To be noticed that the acoustoelastic constant might be slightly changed on different specimens, even on the same specimen. The constant cannot be the exactly same since the couplant’s thickness varies. In this study, we have done four times of tensile tests on the single specimen, and took the average value. Furthermore, later in the paper, the three-point bend test experiment was made on exactly the same specimen.

![Figure 8. The acoustoelastic constant evaluation.](image)

![Figure 9. Result of tensile test to evaluate acoustoelastic constant.](image)

![Figure 10. Result of tensile test to evaluate MBN constant.](image)
For the MBN method, the same tensile tests shown in figure 8 were done to get MBN constant. The result in figure 10 shows the nonlinear relationship between strain and RMS.

4. Results and discussion

Three-point bend test of Q345 beam was carried out by using FEM simulation. Load was applied at the bottom of material at a concentrated point. In order to install the ultrasonic wedge (46mm in length) on the sample, half of the strain gauges had to be taken off, and stresses on only three positions were measured by ultrasonic method. For MBN method, the effective size of the transducer is about 8mm$^2$, and therefore the transducer can be placed very closely to the stress gauges.

![Figure 11. Measurement in three-point bending test.](image)

Measurement results in figure 12 have shown that all measurement techniques give the same tendency, the further the position was from the force, the smaller the stress measured was. It’s easy to find out that stresses measured by MBN method, LCR technique and strain gauge method are bigger than those by FEM. Since FEM is a simulation proposed as an ideal tool for assessment, the result of strain gauges was taken as a basis.

![Figure 12. Result of three-point bending test.](image)

Normally, LCR waves propagate underneath the surface at a depth about 2.5mm (twice of the wavelength), while MBN method and strain gauge method reveals the strain of the surface about several μm. Thus, in this particular study, it is can be seen an agreement among those methods rather than a comparison of values.

To be noticed that, since the stressing jack cannot keep the strain stable, the strain gauges have to be bonded all the time. Moreover, the ultrasonic result has been corrected. LCR waves give information on the strain that is the average of the through-path with length of 25 mm, where information of strain gauges and MBN are from the single point with size of about 8mm$^2$. Therefore, it shows greater agreement between strain gauge technique and MBN method.

However, in the case of ultrasonic measurement, the result is much bigger than that measured by strain gauges. The measured stresses are about 100Mpa more than those measured by MBN method or strain gauges. The reason probably is the thickness of couplant varied. From figure 9 it is known that,
if TOF changes 4ns, the stress will varies 100Mpa. If the thickness of couplant modifies about 5μm (assuming the velocity of ultrasound in the couplant is 2mm/μm), the result would change about 125Mpa, which is actually introduced by the couplant instead of strain.

In the left area of the loading point, the stress measured by MBN method are about 60Mpa higher than those measured by strain gauges, while it shows great agreement between them in the right area, only 20Mpa higher. It is possible that the beam was loading at the left part once before (within the elastic limit), which means it may not relieved of all the stress. Moreover, since it is regarded as 0Mpa at the very left point when using the strain gauges, the stresses loaded were measured instead of all the strain in the beam. From this point of view, the stresses measured by MBN method might be more precise.

5. Conclusions
It has been concluded that LCR based technique and MBN method could provide a great opportunity for stress evaluation of Q345.

For ultrasonic LCR wave technique, the result reveals the average stress of the propagation path. Even those two transducers are closer, it cannot be used to measure the stress at one single position. To get a more precise result, the most essential thing is to make sure the thickness of couplant is constant.

For the MBN method, once the quantitative relationships between MBN parameters and the stress are established, MBN method can be employed efficiently and effectively for evaluating the stress state of components during fabrication or service.

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