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DETERMINATION OF STRESSES IN PLATES USING ULTRASONIC SHEAR WAVES

Authors:
Auteliano Antunes dos Santos Júnior
Departamento de Projeto Mecanico\FEM\UNICAMP
Caixa Postal 6122 - Campinas (SP) - Brasil - 13100-970
E.mail: aute@fem.unicamp.br

Jagan M R Kypa
8335 Waldorf Lane Apt # A - Indianapolis IN 46268.
E.mail: jagankypa@aol.com

Don E. Bray
Department of Mechanical Engineering - Texas A&M University
College Station - TX - USA - ZIP 77843-3123
E.mail: dbray@mengr.tamu.edu

Abstract. *Fabrication processes or events in service may cause residual stresses. Most of the methods for determination of residual stresses inside metallic solids are destructive and it is undesirable that the specimen be destroyed after testing for stress analysis. The ultrasonic technique provides an useful nondestructive tool in the evaluation of stresses. In bodies under traction this technique can be used to prevent catastrophic failure in pressure vessels and bridges or railroad wheels. This work presents the application of shear waves in the determination of the stress state in a frame made of steel plates. Two fixtures are used in the research: an arrangement composed of two plates fitted together and a bar stressed by a hydraulic system simulating the tensile stress. A finite element model was used to calculate stress distribution in the former and manual calculations in the later. The comparison between the theoretic and experimental results shows that it is possible to identify the tensile and compressive regions inside the plates using this system, and to provide a valuable nondestructive way to evaluate stresses in mechanical components.*

Keywords: *Ultrasonic techniques, nondestructive stress measurements, shear waves.*

1. INTRODUCTION

The study of the stress distribution in mechanical parts has been one of the challenges for mechanical engineering around the world. Building more reliable and at the same time economically feasible mechanical systems is the goal of this science. Knowing the life expectancy of the parts is crucial in developing a good design. However, the life of a part depends on the loads to which it is subject. These loads can overstress the parts and cause unexpected failures. An overload can change the internal stresses in the parts also. It can expose the parts to a resultant stress different from the one for which it was designed. Some of the most catastrophic disasters happen because the stress distribution was different from the original. The stresses in pressure vessels, nuclear reactor parts and railroad wheels are some of many examples of situations where the periodical verification of the internal stresses is of fundamental importance.

1.1. Residual Stresses

Residual stresses, also called internal stresses, refer to a system of self-equilibrating stresses that exist in a body free of any restraints or external forces. Residual stresses may be induced by processes like thermal expansion or contraction, diffusion, phase changes, rolling, drawing, forging, welding etc. They may be imposed over the external or the applied stress. Residual stresses have always posed a problem for designers. While compressive residual stresses countering tensile applied stresses can increase the load bearing capacity of a component, tensile residual stresses severely decrease this capacity. Manufacturing techniques like autofretting, shrinking, shot penning and surface rolling are typically used to produce residual stress patterns that oppose the applied stress. Common detrimental effects of residual stresses include warping of machined parts, cracking of drawn products, quenching cracks, permanent failure caused by fatigue, and stress corrosion cracking. In the absence of information about the residual stress, the safe assumption is that the residual stresses may be as high as the yield strength of the material. Uncertainties in knowing the residual stress field have caused significant over-design in many engineering structures. Therefore the knowledge of the residual stresses would be beneficial to engineering design.

1.2. Stress Determination Techniques

Various techniques are available for the measurement of residual stress. Residual stress is never measured directly, but indirectly through the strain induced by the residual stress. Mechanical methods involve physically releasing stresses by some means and then measuring the amount of stress relieved. The stresses are typically released by material removal operations. The stress relieved is measured by using strain gages. The major drawback of the mechanical methods is that a certain degree of destruction is necessary and the machining operations may introduce additional residual stresses. The X-ray diffraction technique has become a widely used non-destructive technique to measure residual stresses. Many researchers have studied this technique extensively (Prevey, 1991). However, X-ray diffraction is suitable for measuring only surface stresses and also the equipment is bulky. Neutron diffraction method uses a neutron beam instead of an X-ray beam. The advantage of the neutron diffraction method is better penetration. However the equipment is bulky as well as expensive. Commonly used magneto elastic methods include the use of Barkhausen noise. This method requires very exact calibration. The stress gradient also is difficult to obtain with this method. Ultrasonic techniques rely on the variations in the time-of-flight difference of ultrasonic waves. It requires non-expensive instrumentation and can be used in the field with small and simplified fixtures. There are a number of commercial enterprises that sells products related to ultrasonic instrumentation and the cost of these is becoming lower along the last two decades.

1.3. Objective

This work presents the application of shear waves in the determination of the stress state in the plates. Two fixtures are used in the research: an arrangement composed of two plates fitted together and a bar stressed by a hydraulic system simulating the tensile stress. A finite element model was used to calculate stress distribution in the former and manual calculations in the later. The comparison between the theoretic and experimental results shows that is possible to identify the tensile and compressive regions inside the plates using this system and provide a valuable nondestructive way to evaluate stresses in mechanical components.

2. ACOUSTOELASTIC THEORY

Ultrasonic methods for residual stress measurement are based on the dependency of the velocity of the acoustic waves on the state of elastic strain in the material, also known as the acoustoelastic effect. The nature and the magnitude of the acoustoelastic response are dependent upon the material and the type of wave being propagated. Different techniques have been developed making use of different ultrasonic waves.

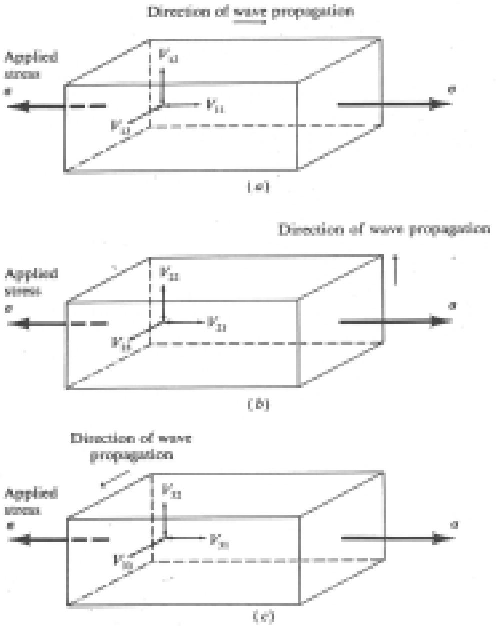

Figure 1 *Velocity of plane waves and stress field in orthogonal coordinate system. Adapted from Bray and Stanley (1997).*

Egle and Bray (1978) showed that it was possible to generate ultrasonic waves with different orientations between the directions of the plane wave travel, particle displacement, and the applied stress in a uniaxial stress field. While any of these combinations may be used in stress measurement, the most sensitive and convenient wave should be chosen. The different combinations possible are illustrated schematically on an orthogonal coordinate system in Fig 1, where V is the wave speed.

The acoustic birefringence method is an ultrasonic technique that makes use of shear waves to measure residual stresses. Shear waves propagate perpendicular to the stress field but can be polarized parallel and perpendicular to it (Schramn et al., 1991; Allen et al., 1982; Egle and Bray, 1976; Pao et al., 1984). Figure 1b shows this effect. The velocities V_{22} and V_{23} represents two differently polarized shear waves, which the first 2 subscript indicating wave propagation in the 2 direction, and the second 2 and 3 subscript indicating motion in the parallel and perpendicular directions to the stress field, respectively. The stress can be estimated based on the fact that the velocities are different for shear waves polarized parallel and perpendicular to the stress field. However, anisotropy and the texture in the material affect shear waves.

For the acoustic birefringence technique, the relation between the wave speed and stress is based on the Birefringence (B), that is the wave velocity difference in two orthogonal directions. It can be expressed by (Schramm et al., 1995):

$$\sigma_{\theta} - \sigma_{R} = \frac{B - B_{O}}{C_{A}} \tag{1}$$

Where: σ_θ = Stress in the direction θ, in the orthogonal system R X θ
σ_R = Stress in the direction R, in the orthogonal system R X θ
C_A = Acoustoelastic constant for the material
B_O = Birefringence, unstressed state

The birefringence can be calculated by:

$$B = 2.\frac{t_R - t_\theta}{t_R + t_\theta} \tag{2}$$

Where: t_θ = time-of-flight in the direction θ
t_R = time-of-flight in the direction R

Bray and Stanley (1997) showed that the stresses could also be calculated by eq. 3. The acoustoelastic constant used in this equation (L_{23}) differs from the C_A because the first is non-dimensional and the later includes the Young's module.

$$\sigma_{R} - \sigma_{\theta} = \frac{E}{L_{23}.t_{O}}.(t - t_{O}) \tag{3}$$

Where: t = time-of-flight in the direction of the stress
t_O = time-of-flight in a standard in unstressed state
L_{23} = Acoustoelastic constant for the material

3. DESCRIPTION OF THE SYSTEMS

Two experimental set-ups were used to test the application of the birefringence technique to stress determination. One ste-up is a frame with a plate in compression through an interference fit and the other is a fixture with a bar submitted to tensile using external force.

Two different data acquisition systems are used. Although both are based on computer boards, the system used with the plates is able to average a number of waves up to 256 and record the result in a file. The system used with the bar is able to acquire data in a higher frequency. The data acquisition rate used in all measurements was 100 MHz

3.1. Standard Reference

Junghans (in Kypa, 1999) performed initial work on the development of a reference standard to be used for residual stresses. Kypa (1999) presented the study about new developments in the area of ultrasonic applications of longitudinal critically refracted waves, and he used the same reference standard built with two pieces of plate fixed together using interference. The dimensions of the plates are presented in the Fig 2. The plates are 0,75-in (19,05-mm) thick. The small rectangles in the plates represent the position of six strain-gages originally placed in one side of the plate. The sensors were placed before the assembly, so the strain due the deformation could be measured. The legs and the center plate were marked in 1/2 inch (12,7-mm) from the borders. So there were 21 marks in one of the sides. The two sensors in the legs are equally spaced (position 2, 4, 18 and 20) and the sensors in the internal plate were placed in the positions 8 and 14.

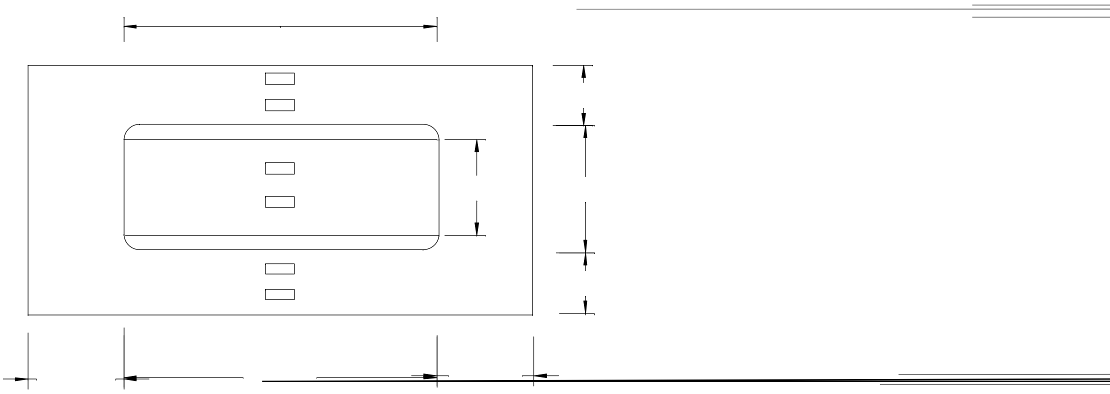

Figure 2 - *Standard Reference dimensions [mm] (Kypa, 1999)*

The residual stress standard was designed with two specific goals in mind: first, that large areas of uniform stress should be produced and, second, that these areas should be in a uniaxial stress state. Large areas of uniform stress are desirable so that probes of different sizes and shapes can be easily tested and calibrated. If stress gradients did exist in the standard, the required corrections and the need for exact position would add considerable difficulty and uncertainty to the results.

The internal frame (center plate) was cooled and fixed internally the outer frame. It was positioned by wood pieces. When the temperature returned to equilibrium, the interference rose between the frames. The frame and the center plate were manufactured to have interference fit, which was measured to be 0.406 mm (0.016 inches). It is this interference fit that creates the residual stresses throughout the standard. The stresses maybe considered assembly reaction stresses since the reaction forces between the frame and the center plate produce them. They may also be called residual stresses since an external load did not produce them, but exist after the assembly of the final component. This design should create large areas of uniaxial tensile stresses in the thin side of the frame and a single, large area of compressive stresses in the center plate.

3.2. Tensile Stress Fixture

The Tensile Stress Fixture was built with the same objective of the Standard Reference, but only tensile stresses could be generated. It is basically a tensile stress machine, which can be operated using a hydraulic manual pump. Two cylinders apply the force to stretch the bar under test. The force can be calculated using the hydraulic pressure and the effective area of the cylinders, $A = 1\text{-in}^2$ ($645{,}16\text{-mm}^2$). The bar under test is 63,0-mm wide and its thickness is 12,6-mm. Figure 3 show a scheme of the fixture. There are also two bars that are used to assure that the bar under test does not bend. These bars are parallel to the bar under test and they are not showed in the figure.

3.3. Description of the Sensor

The transducer was built with four sensors placed in a closed stainless steel case. The sensors are aligned in pairs in two perpendicular directions. It was borrowed from the National Institute of Standards and Technology (NIST), in Boulder, CO, and it was constructed by the company QMI. Only the sensors 1 and 2 were used in the tests described in this work. All the sensors are 2,25 MHz natural frequency. During the tests they are exited by a Panametrics 5052 A pulse-receiver. A graphical program (VI of the LabView V) was used in both tests.

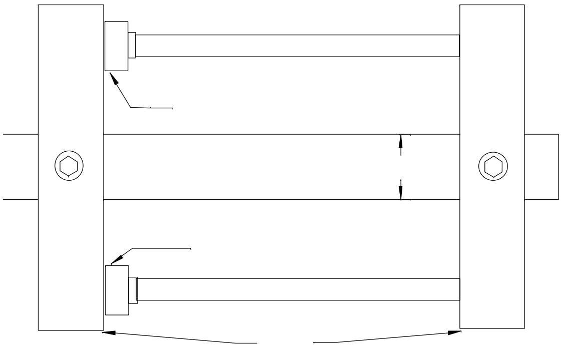

Figure 3- ***Fixture of the Tensile Stress Machine***

4. RESULTS AND DISCUSSION

4.1. Standard Reference Results

The time-of-flight for shear wave in the Standard Reference was measured in five points in one of the fixture large sides (side B). This side was selected because it has a smooth surface. The couplant used was commercial honey. The stresses were measured in 7 marks: positions 2, 4, 7, 12, 15, 18 and 20. Where the strain gage interfered with the measurement, the sensor was placed in the same longitudinal line, so that no significant difference between the real and measured stress is expected. The results obtained with the strain gages were used for comparison to ultrasonic longitudinal waves and were presented by Kypa (Kypa et al., 1999). The data for the travel time, the birefringence and the stresses are presented in Table 1. Figure 4 shows the value of the stresses along a central line in the plate. The numbers represent the marks as discussed before. The influence of the birefringence in the unstressed state in hot-rolled steel is small so it was neglected in this analysis.

The Standard Reference should generate tensile stress in the legs and compressive stresses in the center plate. The crossed section of both legs has the same areas and each one is half of the center plate cross section. If the effects of the bending are not considered, the stresses in both members should have the same magnitude. In the center plate (compressive stress) the assumption of uniform stresses far away from the load point is consistent with the geometry of the problem. Modeling the center plate by a column where a displacement of half of the interference is applied leads to a compressive stress of 118 MPa. However the stresses in the legs have a strong influence of the bending and should be calculated. The Finite Element Method was used to find these stresses (Mechanica program) and the results are showed in the Figure 5. As is reasonable, the average tensile stress along the section has approximately the same value as the compressive uniform stress calculated before.

Table 1- ***Data measured in the Standard Reference***

Position	*Travel time D1*	*Travel time D2*	*B*	*Stress (MPa)*
2	11829,5	11848,8	-0,001630191	58,0
4	11838,8	11854,8	-0,001346358	93,9
7	11810,4	11848,7	-0,003241888	-146,1
12	11787,8	11822,8	-0,00296477	-111,0
15	11851,7	11864,4	-0,001073812	128,4
18	11832,1	11858,4	-0,002216083	-16,2
20	11839,1	11842,6	-0,000292772	227,2

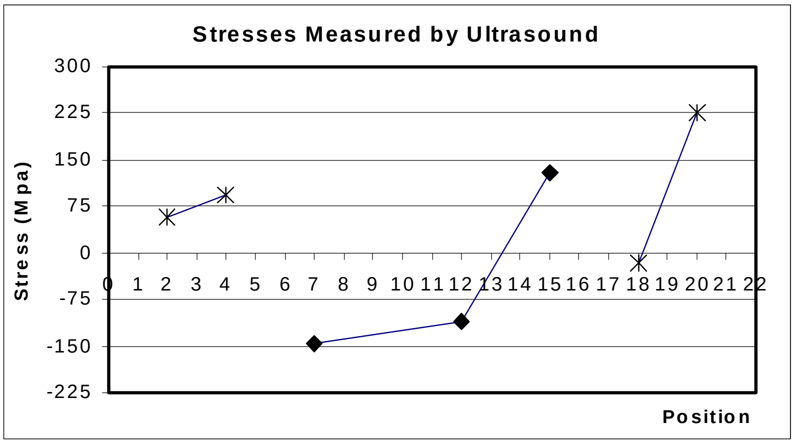

Figure 5- ***Stresses calculated using ultrasonic data***

Figure 4- ***Stresses in the legs calculated by Finite Element Method***

Table 1 and the Figure 4 show that the stresses are not uniform, neither in the center plate or in the legs. Careful examination of the causes of this unexpected non-uniformity shows that the Standard Reference was bent in two axes: perpendicular to the plane of the Figure 2 and in the axle from bottom to top of the same figure. So the bend in the first axix cause the change in the sign of the stresses in the points 15 and 18. The additional influence of the bending in the second direction should also modify the results in both positions.

The stresses in the legs that contain the point (marks) 1 to 5 is also influenced by the bending. The average stress in the three regions is showed in the Table 2. The comparison of this table to the results calculated for the plates show that it is possible to identify the regions of compression and tensile in the plates using shear wave probes. Also, the similar magnitudes of the results indicate that there is a reasonably good perspective in the application of this technique to determination of the stresses. Nevertheless, the results are not the same and it indicates the need of a new Standard Reference. These findings stimulate the development of the Tensile Stress Fixture.

Table 2- ***Average Stresses in the Sections of the Standard Reference***

Data Points (Marks)	1-6	7-16	17-21
Average Stresses (Mpa)	76,0	-42,9	105,5

4.2. Tensile Stress Fixture Results

The results for the tensile stress fixture are shown in Table 3. The couplant used was bought from Panametrics and it is commercially available. The first and second columns show the applied pressure in the hydraulic cylinders; the third is the stress calculated using the force applied by the cylinders and the fourth is the stresses calculated using equation 3. The value L_{23}=0,9 means the acoustoelastic constant proposed by Bray and Stanley (1997). This value is for railroad rails and it is one of the few obtained in the literature.

Ultrasonic measurements are highly influenced by the material under test. The table 3 shows that there is a strong relation between the measured and the applied stress, but the values don't mach well. In fact, the best fit is obtained when using L_{23} = 0,79. The stresses calculated using the later is showed in the last column of the table and it is plotted in the Figure 6.

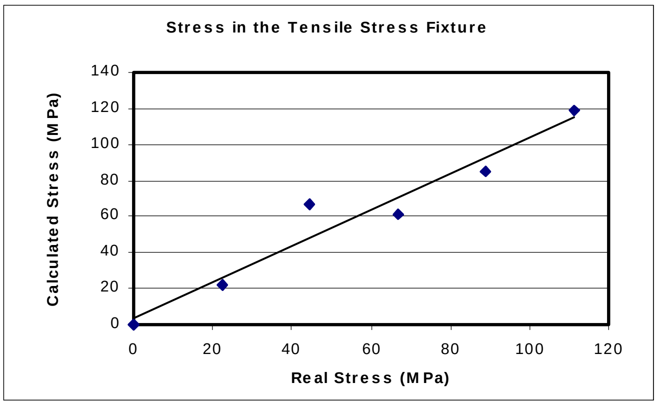

Figure 6- ***Stress calculated for the bar in Tensile Stress Fixture (L_{23} = 0,79)***

Table 3- ***Stresses calculated for the Tensile Stress Fixture***

Hid. Pressure (10^3 lb.)	Hid. Pressure (bar)	Applied Stress (MPa)	Calculated Stress (MPa) L_{23}= 0,9	Calculated Stress (MPa) L_{23}= 0,79
0	0	0	0	0
2	140,6	22,2	28,7	21,8
4	281,2	44,5	88,2	67,0
6	421,9	66,7	81,3	61,7
8	562,5	89,0	112,1	85,1
10	703,1	111,2	156,8	119,1

The results show that it is possible to determine a good approximation of the stress value using the shear wave probes, but the real value only can be determined after tests describing the behavior of the waves in the material under load. It is fundamental to know the value of the acoustoelastic constant to measure the real stress in the part.

5. CONCLUSIONS

This work shows that the ultrasonic technique can be used to determine stresses in plates and bars. A shear wave probe was used and the time-of-flight was measured in different two fixtures. One simulates the effect of residual stresses in the material using two plates fit together by interference and the another is a fixture to apply tensile stresses in a bar. Two different methods to calculate the stress were tested. Also two different couplants and two different data acquisition systems were used.

The need of the construction of a standard reference for each kind of application is emphasized because the behavior of the velocity of the wave in materials under unstressed state must be known. Both methods presented can be used but special cares should be taken in the application of each one.

The results presented an excellent correlation to the expected ones. Even knowing that the values present some dispersion the method is maybe the most powerful and economically feasible way to determine dangerous stresses non-destructively. Particularly in systems where it is important to know when stresses change from compressive to tensile, the ultrasonic shear wave technique is a valuable tool.

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