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SURFACE STRESS MEASUREMENT USING LONGITUDINAL CRITICALLY REFRACTED (L_{CR}) WAVES

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Abstract. *Longitudinal waves generated by ultrasonic probe travel in the surface of the material when the angle of incidence is approximately equal to the first critical angle. For steel with a Plexiglas wedge, this angle is 28^o. A longitudinal wave traveling in the direction of the stress field is the one most sensitive to stress variations. This work shows the determination of stresses in the surface of plates using L_{CR} waves. An estimate of magnitude of the stresses was determined by the finite element method. The probe is built in a rigid structure and comprised of two sensors mounted in a Plexiglas support and posted at a fixed distance one from each other. The electronic system is able to sample at 100 MHz and the interpolation of the result permits the standard deviation for travel time in each measure to be lower than 3 nanoseconds. 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 calculate the magnitudes. Further developments of the method provide a valuable nondestructive way to evaluate stresses in mechanical components.*

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

1. INTRODUCTION

A stress state, which exists in the bulk of a material without the application of an external load, including gravity or other sources of stress such as a thermal gradient, is called a residual or internal stress (James and Lu, 1996). All residual stresses are self-equilibrating; the resultant force and the moment that they produce must be zero. Plastic deformation or forming, including rolling, drawing, extruding, bending, forging, pressing, spinning, shot-peening and laser shock, can cause residual stresses. They can also be produced by certain manufacturing processes such as welding, brazing sprayed coated, cladding, electrodeposition, CVD, PVD, machining and grinding. Further, they can be produced during heat or thermochemical treatment including quenching, laser and plasma heat treatment, carburizing, nitriding, case hardening, ion plating and a combination of these treatments, casting and cooling of a multiphase material, such as a metal composite.

Residual stress is imposed on the applied stress or the external stress. Thus, it can be beneficial or detrimental to the life of the component, depending on its design or final use. Residual stress can be beneficial if it acts opposite to the applied stress. Manufacturing techniques like autofretting, shrinking, shot peening, and surface rolling produces residual stress patterns that oppose the applied stress. Common detrimental effects of residual stresses include warping of machined parts, cracking of drawn products, quench cracks, permanent failure caused by fatigue, and stress corrosion cracking. It has always posed a problem for designers. While compressive residual stresses countering applied tensile stresses can increase the load bearing capacity of a component, residual tensile stresses severely decrease this capacity. 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.

1.1 Measurement 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. Over the last few decades, various quantitative and qualitative techniques have been developed. They can be generally classified into two distinct classes, destructive and nondestructive techniques.

The destructive techniques are based on the destruction of the state of equilibrium of the residual stresses in a mechanical component. In this way, residual stresses can be measured by the relaxation technique. However, it is possible only to measure the consequences of the stress relaxation (displacement, fracture, and strain) and not the relaxation itself. In most of the cases, strain change is selected as the parameter to be studied. Relaxation techniques consist of creation of a new stress state by machining or layer removal and detection of the local change in the stress by measuring the strain or displacement. Finally, the residual stress is calculated as a function of strain measured using the elasticity theory.

The nondestructive methods are based on the relationship between physical or the crystallographic parameters and the residual stress. X-ray diffraction and the neutron methods are based on the measurement of lattice strains by studying the variations in the interplanar spacing of the polycrystalline material. The X-ray diffraction technique measures the residual strain on the surface of the material, while the neutron diffraction method measures the residual strain within a volume of the sample. Magnetic stress measuring methods rely on the interaction between the magnetization and the elastic strain in ferromagnetic materials. Ultrasonic techniques rely on the variations in the time of flight difference of ultrasonic waves, which can be related to the residual stress state through third order elastic constant of the material.

The mechanical stress relaxation methods (hole drilling, deflection and sectioning) can generally be used to evaluate 1st order residual stresses, but they can't be used for nondestructive controls (Lu et al., 1996). The hole drilling method usually has a precision of ± 20MPa. The deflection method has a precision of precision of ± 30MPa and the sectioning method, ± 10MPa. The neutron diffraction method requires a source of neutrons, which is very expensive. The nuclear reactor is the most common source of neutrons. This is not portable, and is expensive as well. It would be very difficult to apply this method to industrial problems, except for the development of manufacturing processes or the control of industrial parts with a very high added value. It has a precision of ± 30MPa. X-ray diffraction cannot be used to measure the residual stresses nondestructively through the thickness of the part. The residual stress distribution can only be obtained by the removal of successive layers, which makes this technique destructive. It has a precision of ± 20MPa. Magnetic methods can only measure surface stresses and are highly sensitive to microstructure. Their precision is ± 10-20 MPa. Ultrasonic methods do not have many of the disadvantages that the other techniques have. They usually have a precision of ± 20 MPa. Ultrasonic methods are highly sensitive to the microstructure (texture, work hardening and grain size). However, the L_{CR} technique appears to show the most promise for residual stress measurement since it is largely unaffected by microstructure.

1.2 Acoustoelastic Effect

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. 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 acoustoelastic effect is greater on the propagation of the longitudinal waves than for shear waves. Thus, a longitudinal wave traveling in the same direction of the stress field is the one most sensitive to the stress. The longitudinal wave can be critically refracted in order to travel parallel to the surface. This requires access to only one surface of the component.

2. MATERIALS AND METHODS

The determination of the stress distribution in plates has many applications in engineering. Especially in pressure vessels and in the nuclear engineering, the need of a nondestructive method to evaluate the safety of the system is clear. One set was used to test the application of the birefringence technique to stress determination. Two fixed plates fitted by interference compose it.

2.1 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 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 1. The small rectangles in the center represents the position of six strain-gages originally placed in one side of the plate. The sensors were placed before assembly so that the strain due the deformation could be measured.

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 development of uniaxial stress state is very important since most of the known acoustoelastic constants, which could be used for comparison, have been developed for the uniaxial stress state.

As shown in Fig. 1, the assembly contains only two components: an outer frame and a shrink fitted, center plate. 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. However, they are considered as macrostresses within the standard. 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.

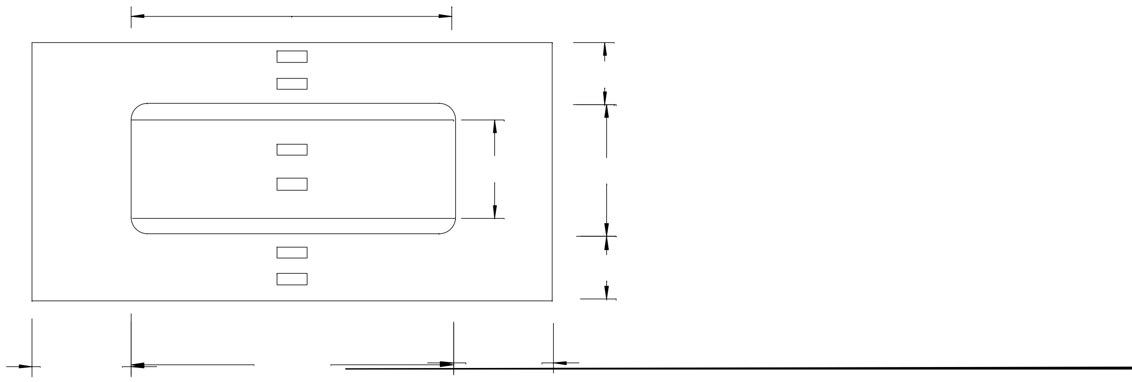

Figure 1 - Standard Reference dimensions – [mm] (Kypa, 1999)

The reference standard was constructed of ASTM A-516 steel plate (Grade 70) which has a reported composition of 0.25% C, 1.01% Mn, 0.007% P, 0.017% S, 0.26% Si and 0.048% Al. The yield and the tensile strengths were tested by the manufacturer to be 359 MPa (52 Ksi) and 538 MPa (78 Ksi), respectively. Junghans (in Kypa, 1999) studied residual stresses in similar kind of material. A 19.05 mm (0.75 in) thick, hot rolled material was selected for the following reasons. The thickness of the plate greatly reduces the chance of center plate buckling. A hot rolled plate was chosen since the levels of residual stress and microstructural texture produced in its manufacture is much less than in the cold rolled plates. Excellent correlation between theoretical and experimental results has been obtained when the L_{CR} technique was applied to the hot rolled steel plate (Bray & Junghans, 1995; Leon-Salamanca & Bray, 1996).

The components of the reference standard were stress relief annealed before assembly. This was done as a precautionary step to remove any residual stresses that may have been created in the plate’s manufacture and its subsequent machining. The stress relief anneal consisted of slowly heating the components to 607°C (1125°F) and holding them at this temperature for one hour in an Argon bath. The Argon gas environment was used to reduce surface scaling. It was maintained until the plates cooled to 450°C (850°F). The components were furnace cooled for 19 ½ hours to 175°C (350°F). This was a rather cautious application of a typical stress relief treatment (Masubuchi, 1980). Strain gages were then mounted on both legs of the frame and the center plate along a centerline.

The components were then assembled, by cooling the center plate in a bath of the liquid nitrogen until it contracted enough to slide into the outer frame. This cooling approach to the shrink-fit was taken to prevent any changes in texture or residual stress that might have occurred if the frame had been heated. To overcome the interference fit between the frame and the center plate, a temperature differential greater than 95°C (202°F) was required. The center plate was exactly positioned within the outer frame by using wooden positioning blocks.

2.2 Instrumentation

Strain gages were mounted during the manufacture of the reference standard. The following description is extracted from Junghans (in Kypa, 1999). They were mounted on both sides of the outer frame and the center plate along the centerline. All of the strain gages, strain indicator (Model P-350A) and switch and balance unit (Model SB-1) were obtained from Measurement Group, Inc. WK-06-125BT-350. Single element strain gages were used on the center plate since the components had to subject to cryogenic temperatures. EA-06-125AC-350 single element strain gages were used on the outer frame. A single WA-06-120WR-120 stacked rosette strain gage was also mounted on the thin side of the frame. The ultrasonic data acquisition system is composed by on computer Pentium 200; a Sonix 8100 internal board (100 MHz); a pulse-receiver Panametrics 5052UA and a LabView 5.0, witch is a program in graphical language to be used to control the whole system. Figure 2 shows the scheme of the data acquisition system.

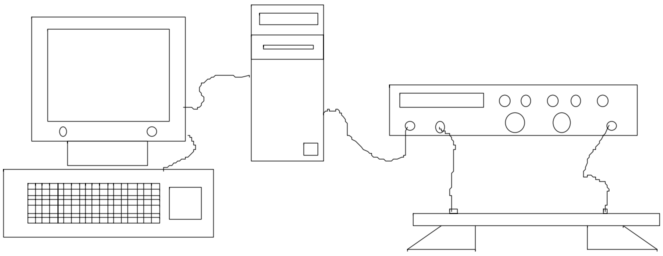

Figure 2 - Data Acquisition system used in the tests with Lcr probes. Computer/ Internal board Sonix 8100/ Lcr Probe/ Panametrics 5052UA.

LabView virtual instrument (str8100.vi) was used to display the initial signal. Channel 1 display was turned on. The sampling rate was set at 100 MHz. The voltage level was set at 250 mV. The voltage offset and the vernier gain were set at 0. The memory map was set to CC00 and the base port to 250. The input polarity was set to positive and the signal type was set to RF. A zero post-trigger delay was used. The data collection length was set to 4800. The number of waves to save was set to 20. For the present work, 20 waves were averaged. A large number of waves had to be sampled so that the average of the sample would be closer to the true average of the population. The virtual instrument had the capability of using the average of 256 waveforms. However, since the averaging is done by software as opposed to being done by hardware like in oscilloscopes, a large number of waveforms implies storing very large files and longer times for data storage.

The probe was built with two clear acrylic blocks. They were machined to an angle of 28°, which was slightly greater than the calculated critical angle of 27.56°, in order to generate a critically refracted longitudinal wave. The transducer design consists of a sender and two receiver transducers. All the three transducers were fixed to a special frame to hold them as a set. Two receivers are effectively used in varying temperature environments. For the present study, only one receiver was used since the reference standard was maintained at a constant temperature. The probe schematic with one sender and one receiver is shown in Figure 3. The probe used for these tests had two receivers, but only one was used.

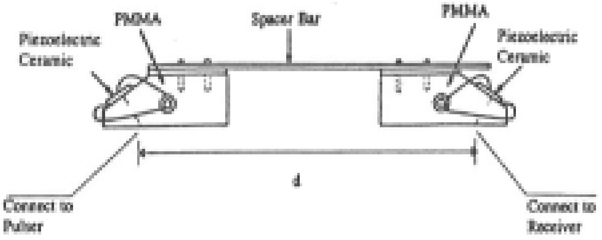

Figure 3 - L_{CR} Probe (Kypa, 1999)

2.3 Finite Element Model

The outside plate of the standard reference was modeled using the finite element model. It was done to verify the hypothesis of uniform tensile in the outside legs. Only half of the standard reference was necessary. By the theoretical analysis, the internal potion of the leg should have higher tensile.

The hypothesis of central symmetry is coherent with the Standard Reference geometry. Displacements were considered applied loads and were applied at the contact between both plates. Uniform pressure was supposed in the whole area between the parts. The displacements were restrained at the symmetry plane.

Finite Element Method can be used when the loads and the geometry are well known. In this case, the visual observation of the plates shows that a poor fitting is obtained. FEM can cause a misinterpretation of the results in situations like that.

3. RESULTS AND DISCUSSION

Three methods for determination of the stresses inside the Standard Reference were used. The measurements were take with strain gages and calculated by FEM. Both were compared with the value of travel time obtained with the L_{CR} system. The results for all methods and the discussion are shown below.

3.1 Strain Gage Results

Figure 4 shows the results for the strain measured in the surface of the plate. They are shown in the table 1 also. Numbers 1, 4, 18 and 20 represent the legs, subjected to tensile stress. Number 8 represents the strain gage in the internal plate. The data shows tensile stress in the legs and compressive stresses in the center, as expected. The internal face of the legs has higher tensile stress than the outside face. There is only one strain gage in the center because the other fails during the fitting process.

Table 1 - Strain Measured by Strain Gage in the Surface of the Standard Reference

Position on reference standard	*Strain (microstrains)*
2	300
4	450
8	-450
18	500
20	300

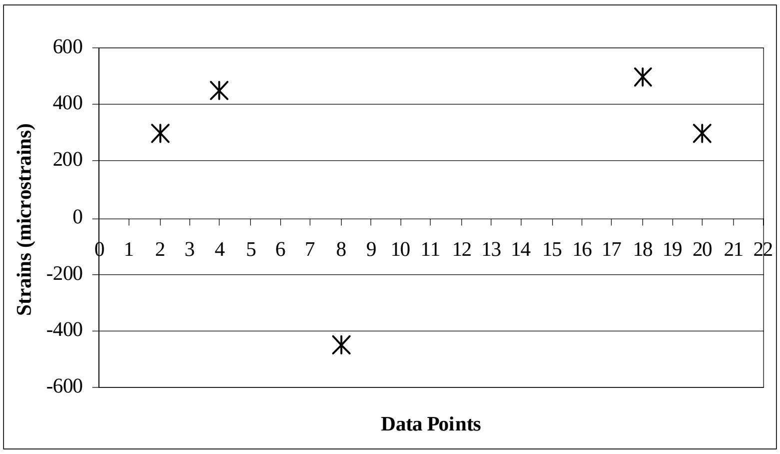

Figure 4 - Strain Gage Results for Measurements in the Reference Standard

3.2 Finite Element Results

Figure 5 shows the results for the finite element method modeling. The model considers only one quadrant of the plates because there is symmetry in the central planes. Only one symmetry axle was used. The format of the stress distribution showed agrees with the strain gage data. The compressive area was not modeled because the strain is easy to be estimated.

The tensile stress in both legs is highest at the internal side of the frame. The reason is the bending caused by the fitting of the internal plate. This effect can be annulled using a symmetric effort in the external plate. New Standard References are in development to attain this objective. The figure shows extreme concordance with the expected format of the stresses in the real plate.

3.3 Ultrasonic Results

Figure 6 shows the travel-times recorded for 21 positions in the Reference Standard. When the material suffer tensile, the molecules increase their distance from the others and the travel-time is larger than for compressive stress. The consequence of the tensile stress is that the velocity decreases.

Figure 5 - Stresses calculated by Finite Element in the legs of the Standard Reference

Data were recorded for the two larger faces of the fixture, as shown in the figure 1. They were called side A and B. The data for the face A of the frame shows higher travel-times than for B. There is visual evidence that there was bending in the plate and that the bending occurred in more than one axle. The results for side B are shown in the figure 7. In both sides, a great variation in the travel-time was found in the data.

Several parameters were tested to find if they could affect the results. The main influence was the amount of couplant and the clamping force. There was influence of those parameters only when the effect of the variation is composed, i.e. both varies at the same time.

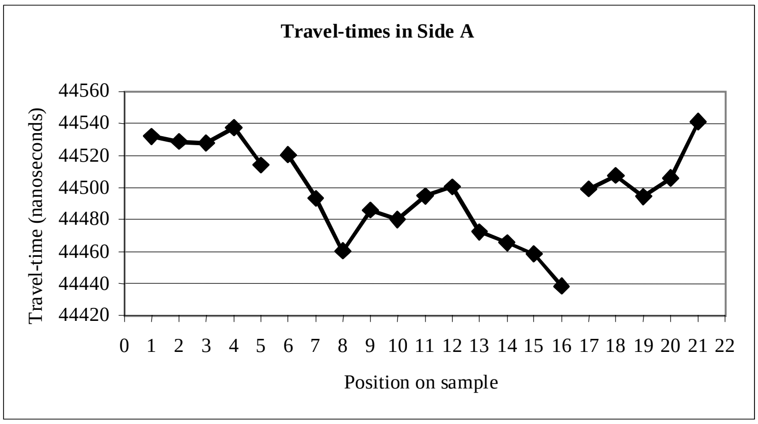

Figure 6 - Travel-time measured in the Reference Standard

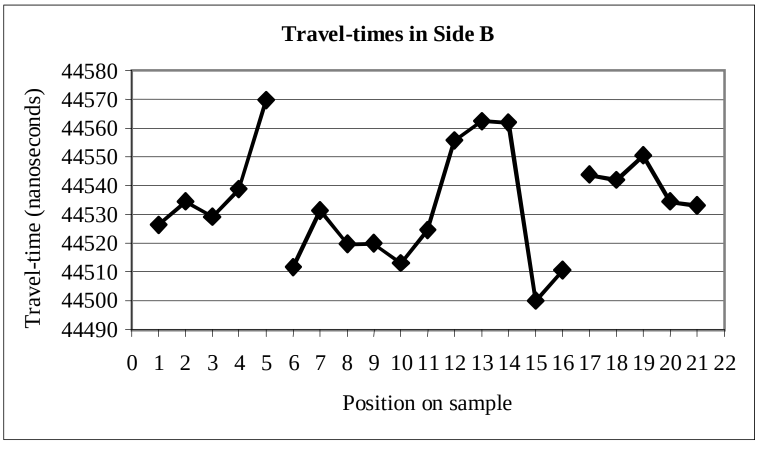

Figure 7 - Travel-time measured in the Reference Standard

3.4 Discussion

From the theoretical analysis, it is expected to observe a uniform compressive stress in the center plate of the reference standard. Also the net effect of the bending moment and the axial force would cause lower tensile force in outer part of outer frame, and a higher tensile force in the inner part of the outer frame. The finite element stress mapping only confirms the theoretical analysis.

Ultrasonic travel time measurements confirm the theoretical analysis. There is compressive stresses in the center plate and tensile stresses in the legs. Also the tensile is higher in the internal side of the legs, as expected. The values obtained for travel times confirms that there is a relation between the time-of-flight for ultrasonic waves and the stresses.

The unexpected difference between the travel times for different faces of the plate can possibly be explained by the fact that there was a poor assembly of the parts during the fitting process. Extreme values of travel time in the side B indicates that there is bending in more than one plane. This unexpected effect could have influenced the reading, but the pattern agrees with the theory in the side A.

The digitization of the instrumentation made it possible to detect a travel-time change of up to 0.1 nanoseconds. This translates to roughly 1.85 MPa change in stress level. Considering that ultrasound techniques typically have a precision of only 10 MPa-20 MPa, the current system has a significantly higher precision. The current ultrasonic data acquisition system had made it possible to achieve a standard deviation of about 2.5 nanoseconds in travel-time measurement. Earlier work was limited due to the poor resolution of about 26 nanoseconds. The current system made it possible to achieve highly accurate as well as precise travel-time measurements that had excellent repeatability.

4. CONCLUSIONS

This research provided a very accurate and reliable stress measurement system. It also shows the significance of the L_{CR} system in indicating the true stress state existent in the system. Although numerical techniques provide excellent approximate solutions for many engineering problems, they do not indicate the true stress state. This is because numerical techniques fail to take into account common manufacturing process defects, age hardening, creeping phenomenon etc. The L_{CR} system on the other hand has proved, through this research, the importance of actual testing of mechanical components. The current system can be readily used in fieldwork with very minor modifications. It also offers data storage and manipulation capabilities for better presentation of the travel-time data.

Exhaustive work on this system made it apparent that changes could be made to improve the results. First and foremost would be the reference standard. The design of the reference standard had aimed at generation of large areas of uniaxial tensile as well as compressive stresses. As seen from the travel-time data, a truly uniaxial stress state was not achieved. The reason being for the varying stress field was misalignment between the center plate and the outer frame of the reference standard that caused one side to be bent in concave shape and the other side in a convex shape.

A data acquisition board with higher sampling frequency can increase the resolution of the travel-time data. The driver software for the data acquisition board would be even more beneficial if it were to provide a tool for frequency analysis. The current probe had large separation between the sender and the receiver, which prevented stress mapping for whole of the reference standard. A smaller probe separation can provide for more travel-time data across the area of the specimen. Thus, enabling for the development of a c-scan display of the stress field. Higher frequency probes can be used to measure stress fields close to the surface and lower frequency probes can be used to measure stresses to a larger depth. The ultrasonic pulser-receiver had a settling time of close to thirty minutes. A newer pulser-receiver would solve this problem. The clamping pressure could be monitored if provision is available for a clamping system with a pressure gage. This would ensure that both the sender and the receiver are clamped with a uniform pressure. The pressure gages can also be used to indicate any slip between the probe and the specimen.

In this work, the longitudinal critically refracted wave was used to find the stresses in plates. A special fixture was built providing it had internal stresses. The stresses could be calculated using strength of materials concepts. The strain was measured using strain gage bonded in the surface and they were used to verify the stresses. An L_{CR} probe was used to acquire the travel time. Strong correlation between the readings, the FEM and the measured variables indicates that the acoustoelastic effect can be used to find stresses in plates.

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