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Searching for residual stress measurement methods for structural steel components

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ABSTRACT: Many of engineering graduates' generic skills can only be developed by experiential learning. The main opportunity for acquiring these skills is the final thesis and this article focuses on some work carried out by students. In real metallic structures, residual stresses can reach or even exceed a material's yield point. Many difficulties arise when assessing the residual stresses in a real structure. The main objective of this student work was to find the best non-destructive control method for residual stress from among the following methods: magnetic metal memory, ultrasonic wave propagation, X-Ray diffraction, neutron diffraction and hole drilling technique. Comparison of residual stress measurement methods allows the most suitable method for construction assembling sites to be determined. This experiential learning project has proven successful in its aims associated with practical skills and the use of modern measuring equipment, and proved to be an effective motivator for research-based projects.

INTRODUCTION

Employers require graduates from engineering study programmes to be able to demonstrate that they have the skills necessary to practice in a real environment. Most industrial steel structures, such as bridges, tanks, pressure vessels, piping and other are joined by welds. Residual welding stresses are close to or even exceed a material yield point. According to the recommendations of industrial construction standards, when welded objects are thicker than 35 mm, such residual stresses should be thermally relieved. However, the practical problem arises when there is a need to assess the change in residual stresses in a real structure after stress relief.

Accurate residual stress measurement methods, such as X-rays or neutron diffraction, can show the distribution of stresses only under laboratory conditions and when applied to limited size products. Therefore, many difficulties arise when assessing the residual stresses in a large structural member or structures. By doing this engineering work, the students are equipped with valuable manual skills, the ability to use measuring equipment and interact and communicate with the technical staff who maintain the equipment.

THE MEASUREMENT OF RESIDUAL STRESS

Residual stress measurement techniques of different materials can be classified into three types: destructive method, semi-destructive method and non-destructive methods [1]. In the destructive method, a portion of the residually-stressed body is cut away and the resulting deformation of the body is carefully measured. The disadvantages of this technique are that the method is tedious and painstaking, theoretical analysis is difficult and the method is unable to detect residual micro-stresses [1].

The semi-destructive hole-drilling method involves drilling a hole on the surface of the object being examined, and measurement of strain redistribution that takes place on the surface as a result of the hole [2][3]. Non-destructive methods are of three basic types: *X-ray diffraction method, neutron diffraction method* and *ultrasonic method*.

The *X-ray diffraction method* is the most common non-destructive method for evaluating residual stresses. It is based on lattice strains and changes in the spacing between crystallographic lattice planes, which are caused by stress [4].

The neutron diffraction method relies on elastic deformations within a polycrystalline material that cause changes in the spacing of the lattice planes from their stress free value. Measurements are carried out in much the same way as with X-ray diffraction. The greatest advantage that neutrons have over X-rays is the large penetration depths that neutrons can obtain, which makes them capable of measuring at near surface depths of around 0.2 mm down to through-thickness measurements of up to 30 mm in steel.

The ultrasonic method is based upon the changes in the velocities of ultrasonic waves due to stress. The disadvantage of this method is that higher order elastic constants are generally required in order to relate ultrasonic velocities to residual stress. This method has a limited capability for detecting sharp stress gradients [5][6].

MATERIALS AND RESEARCH METHODS

The specimens were produced from low carbon hot-rolled steel plate. The specimen size was selected according to limitation of the used measurement technique. Several series of specimens were prepared: the series contained *no treatment after welding*, heat *treatment performed after welding*, *vibratory stress relief (VSR) treatment applied during welding, VSR applied after welding*.

Vibrational conditioning relaxation process uses a sinusoidal vibration waveform. A force inducer induces energy to create vibration amplitude that is below the harmonic amplitude. A dwell time and working frequency depending on the component's strength, elastic modulus, and size, is maintained to allow internal stresses to redistribute and balance themselves. The change in residual stresses was measured using the following methods: ultrasonic wave propagation UT (ultrasonic testing), high resolution X-ray diffraction, neutron diffraction (ND), hole drilling HD/DSPI (HD digital speckle pattern interferometry) and numerical FEM (final element method).

ANALYSIS OF RESIDUAL STRESS MEASUREMENTS

Ultrasonic wave propagation analysis (UT). The ultrasonic wave propagation method of stress measurement is based on the acoustic-elasticity effect, when the velocity of elastic wave propagation in solids is dependent on mechanical stresses. This technique takes into account the effect of the microstructure through the application of coefficients of corrections to the measurements carried out in the melted zone and parent metal. During the tensile test the interdependency of the speed of surface ultrasonic longitudinal wave propagation and stresses was identified, i.e. constants of structural steel acoustic elasticity were determined: for a basic metal *KPM* = -1.377 × 10-5 MPa-1, for a weld metal *KSZ* = -1.616 × 10-5 MPa-1.

The surface longitudinal wave method is sensitive to sensor pressing. The analysis of ultrasonic wave propagation speed has shown that the maximum tensile stresses at the centre of a joint in specimens without application of any treatment were 324 MPa (Figure 1). The maximum compressive stresses in the same series of specimen reached 123 MPa. During the application of the VSR treatment the peak of longitudinal residual stresses in specimen was reduced by approximately 65%. The VSR treatment after welding reduced the peak of residual stresses on average by approximately 47%. The thermal treatment reduced residual stresses of the specimens by approximately 71%.

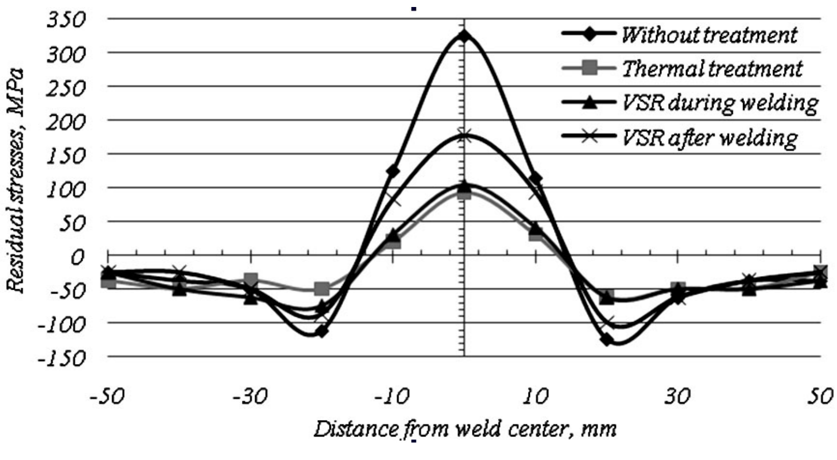

Figure 1: Distribution of longitudinal residual stresses in specimens measured by ultrasonic technique.

The ultrasonic surface longitudinal wave propagation speed method for the measurement of residual stresses (up to a depth of 3 mm) is practical and easily applicable at the production or assembly sites. Structural steel acoustoelastic constants identified during the research can be used in the ultrasonic analysis of residual stresses for the same steel group.

Hole drilling method analysis. Under laboratory conditions a HD/DSPI device was practical and easy to use. The time necessary to measure residual stresses is about ten times faster than what is required when strain gauges rosettes are used. Almost no surface preparation is required. The acquisition and processing time is very short. However, some experience and measurement skills are necessary at the current development stage to measure residual stresses successfully (Figure 2).

Diffraction analysis. X-ray diffraction measurements were conducted with a portable X-ray device *PROTO iXRD*. Cr-Ka radiation and (BCC, hkl-211) reflections were used to study residual stress distribution in weld region. The research shows that the X-ray diffraction analysis allows for identification of surface residual stresses only in a depth of 50-100 μm. This method is sensitive to the quality of the material surface treatment and mobility of the required installations is limited. For these reasons, its application on the production or assembly sites is difficult; however, the measurement process is contactless, reliable and fully automatic.

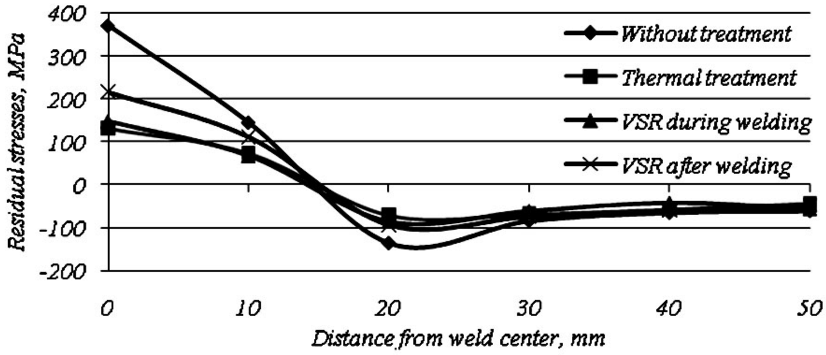

Figure 2: Distribution of longitudinal residual stresses in specimens measured by hole drilling method.

Neutron diffraction measurements were made using a (211) reflection, at the detector angle, 2θ, of approximately 156°. The depth of the measurements was 5-8 mm on the specimen surface. Neutron diffraction analysis shows that volumetric residual welding stresses in the depth of 5-8 mm are approximately 12% lower than those at the surface of the weldment. The measurement method is characterised by its high precision, and it does not require surface preparation, but is very time consuming and can be carried out only under laboratory conditions.

The depth of residual stress measurement reached 1.5-2.0 mm when using the combined HD/DSPI method. The measurement of one point took one-fifth of the time of measuring with the X-ray diffraction method, but yielded equivalent measurement precision level and depth of residual stresses. Due to the sensitivity to environmental vibrations, the application of this method at the production or assembly site is limited.

The distribution of residual stresses in the specimen section determined using the numerical method (FEM) (Figure 3) correlates with the results of experimental methods (UT, XRD, ND, HD/DSPI).

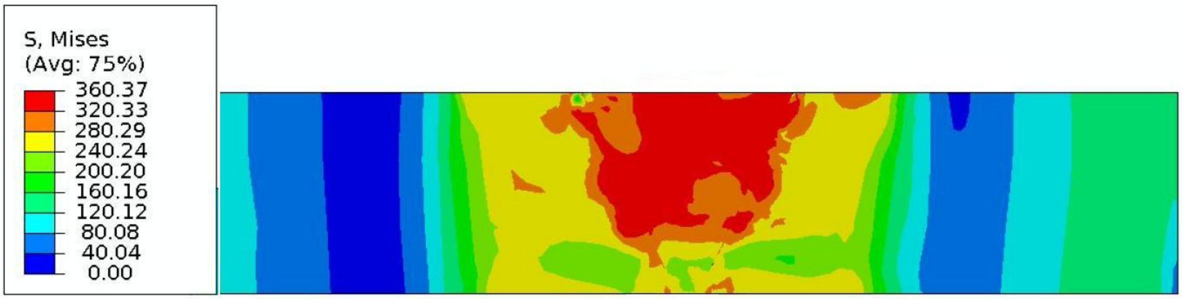

Figure 3: Distribution of *von Mises* stresses, MPa.

Comparison of residual stress measurement methods. Based on the assessment of the change of residual stresses, the measuring techniques and tools used, the most suitable method for residual stress measurements at production and assembly sides is the *ultrasonic method* (Figure 4).

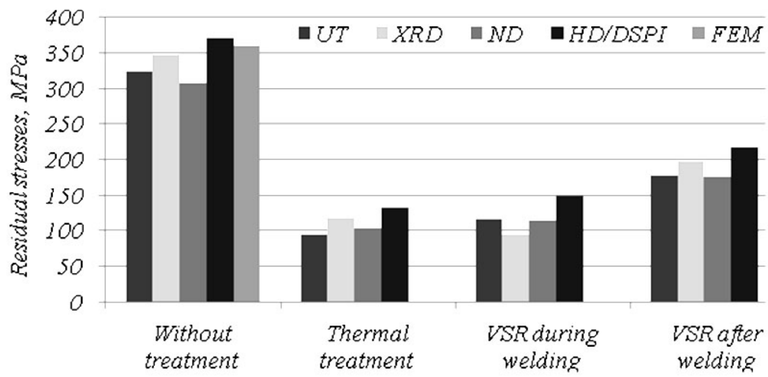

Figure 4: Longitudinal residual stresses in welded specimens, using different measurement techniques.

CONCLUSIONS

On completion of the project, the following conclusions were drawn:

- Professional engineers seldom spend their time at work with expensive measurement equipment, but they do need to know how measurements are carried out and how the received measurement results can be applied to real structures.
- The current problem-based project allowed students to draw out the following conclusions:

  - The X-ray diffraction analysis allows for identification of surface residual stresses only to depths of 50-100 μm. This method is sensitive to the quality of the material surface treatment and mobility of the required installations is limited. For these reasons, its application on production or assembly sites is difficult.
  - Neutron diffraction analysis shows that volumetric residual welding stresses in the range of 5-8 mm are approximately 12% lower than those at the surface of the weldment. The measurement method that is characterised by a high precision level, does not require surface preparation, but is time consuming and can be carried out under laboratory conditions only.
  - The combined HD/DSPI method shows the residual stress in the range 1.5-2.0 mm. The measurement of one point took one-fifth of the time of measuring with the X-ray diffraction method. Due to the sensitivity to environmental vibrations, the application of this method at the production or assembly site is limited.
  - The most suitable method for residual stress measurement at production or assembly sites is the ultrasonic method.

- The true problem-based project has proved to be an effective vehicle for stimulating students' thinking, developing problem-solving skills and raising their curiosity.

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