Measurement Technology for Residual Stresses Locked in Structural Members

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If large compressive residual stresses are produced on the surface of a structure by shot-peening, surface heat treatment, and so on, the material will have high structural strength, and it is this characteristic that enables downsizing and lightening of the structure. On the other hand, if tensile residual stresses are produced in a welded structure during the welding process, Stress Corrosion Cracking (SCC) or fatigue failure may occur. Accurate evaluation of residual stresses is therefore very important. This paper discusses the residual stress measurement technologies that are being used in IIC.

1. Introduction

Generally, stresses produced in machine structural members are external stresses due to external forces and internal stresses that are locked inside the member itself over the course of manufacturing or operation. Typically, these internal stresses are called residual stresses. In material mechanics, stress is evaluated with a stress value obtained by adding together these internal and external stresses. Residual stresses produced inside an object often have a complex distribution, and accurate evaluation of these stresses is demanded. The existence of residual stresses may cause various kinds of failure, such as ① member deformation, ② Stress Corrosion Cracking (SCC), ③ delayed fracture, ④ reduced fatigue life, and ⑤ reduced life due to creep.

Figure 1 illustrates an example of SCC caused by residual stresses arising from the welding process. As in this example, accurately ascertaining residual stresses in the member is an important issue for quality control and lifetime evaluation. Recently, analysis techniques using the Finite Element Method (FEM) are advancing, and the processes by which thermal stresses occur in welding a welded structure are being accurately analyzed and evaluated by elasto-plastic analysis.

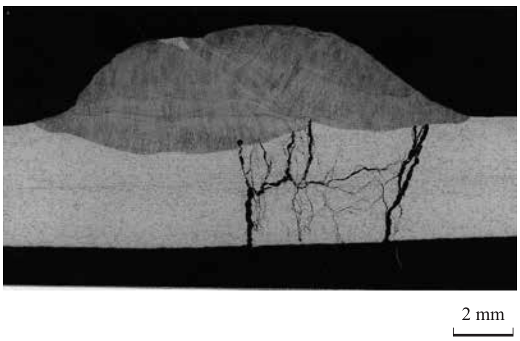


Fig. 1 Stress corrosion crack (SCC) caused by residual stresses during the welding process

However, evaluating the validity of the analysis results requires verification by stress measurement of the actual object, and there is rising demand to measure residual stresses in members even for evaluating the validity of the structural analysis results. In addition, actual measurement is effective for processes, such as shot peening and heat treatment, where stress analysis is difficult. Residual stresses are distributed locally, and the relationship between the measurement method and the measurement location must be ascertained. Additionally, residual stress measurement and evaluation demands that the purpose of measurement and measurement location of the member under test be specified clearly, and measured with the optimal technique. IHI Inspection & Instrumentation Co., Ltd. (IIC) provides residual stress measurement and evaluation services, and handles work such as ① X-ray stress measurement, ② the center hole drilling method, ③ Deep Hole Drilling (DHD) method, ④ sectioning method, and ⑤ structural analysis method. IIC covers nearly the full range of residual stress measurement technologies that are in demand.

Figure 2 illustrates the regions measurable by various residual stress measurement methods. Among these

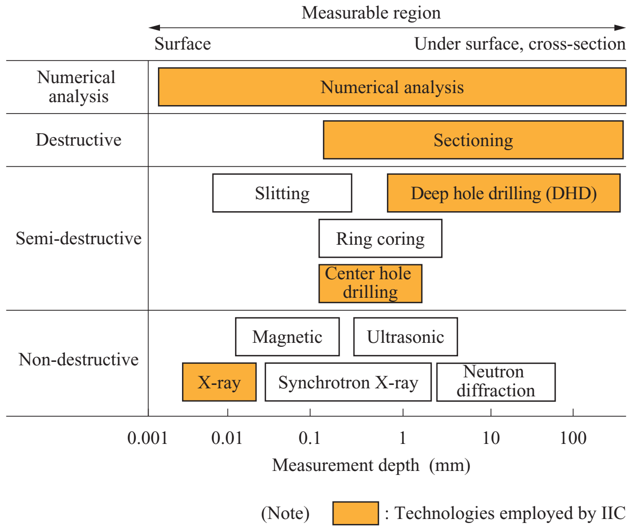
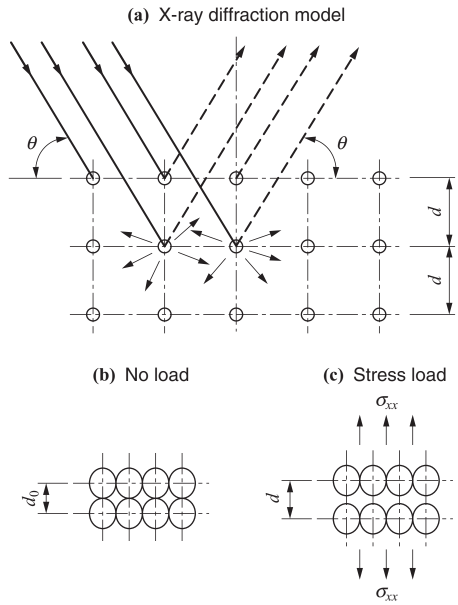


Fig. 2 Various residual stress measurement methods



(Note) $\lambda = 2d\sin\theta$
λ : Characteristic X-ray wavelength
d : Lattice spacing
θ : Bragg diffraction angle
$\varepsilon_{xx} = (d - d_0)/d_0$
$\sigma_{xx} = E \cdot \varepsilon_{xx}$
ν : Poisson's ratio

Fig. 3 Measurement principle of X-ray diffraction method using Bragg's law

measurement technologies, the X-ray stress measurement method and center hole drilling method are easy to use on site at comparatively low cost. These methods are introduced below.

2. X-ray stress measurement method

The measurement of stress using X-rays is an established technology the methods of which have been standardized by the Society of Materials Science, Japan. When an electron beam is pointed at a specific metal, X-rays are produced containing characteristic X-rays of a fixed wavelength. If characteristic X-rays of a known wavelength are pointed at a test piece, a diffraction phenomenon (Bragg diffraction) is produced by the metal crystal lattice. **Figure 3** illustrates the principle of the X-ray stress measurement method by X-ray diffraction according to Bragg's law. If the diffraction angle θ is computed, the atomic lattice spacing d of the material can be computed. Although the atomic lattice spacing of a material is constant while not under a load, this lattice spacing varies depending on the stress load conditions. If the lattice is stretched, tensile stress acts on the material, whereas if the lattice is compressed, compressive stress acts on the material. With X-ray diffraction, stress is evaluated using the lattice variation, Young's modulus (the elastic constant) (E), and Poisson's ratio (ν). The range measurable with X-rays is diffraction at the uppermost surface approximately 20-50 μm from the surface of the test piece. The average stress in the surface region is measured. Also, X-ray stress measurement cannot be applied to all materials, and is subject to the following restrictions.

(1) The test piece is a polycrystal with a small crystal grain.
(2) The test piece has no coarse-grained crystals or is not strongly textured.
(3) The test piece is not of a composite structure.
(4) There are no steep stress gradients at the measurement area.
(5) The Young's modulus and Poisson's ratio of the material are known.
(6) The surface of the test piece is flat.

IIC actively uses the X-ray stress measurement apparatus (X3000) illustrated in **Fig. 4** for on-site measurement.

In order to verify the validity of the X-ray stress measurement method, a test piece is attached to a tensile test machine, and the correlation between external stress and X-ray stress measurement values is computed. **Figure 5** provides a view of a Prestressed Concrete (PC) steel bar on a tensile machine and stress measurement using the X-ray stress measurement apparatus. **Figure 6** illustrates the relationship between nominal stress and X-ray stress measurement values in the tensile test of a

Fig. 4 Portable X-ray stress measurement apparatus (X3000)

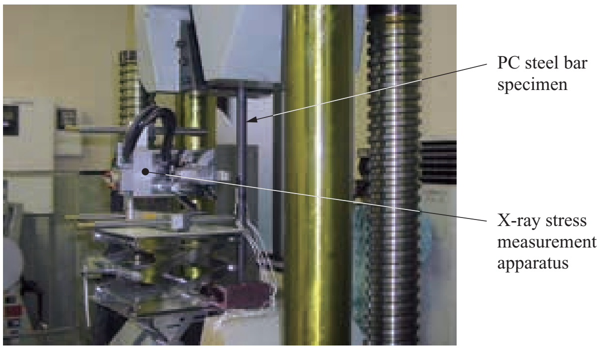


Fig. 5 Status of PC steel bar testing on a tensile machine and stress measurement by the X3000

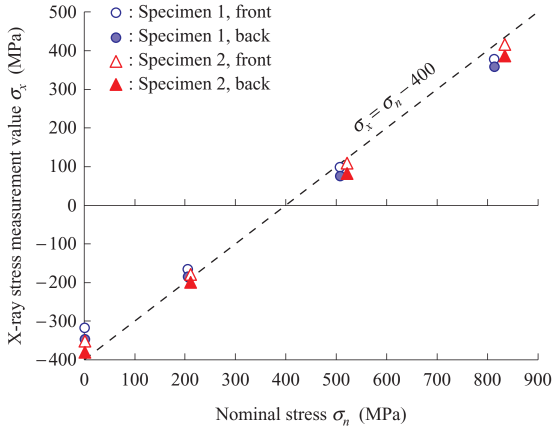


Fig. 6 Relation between nominal stress and stress measured by the X3000 in the tensile test of a PC steel bar

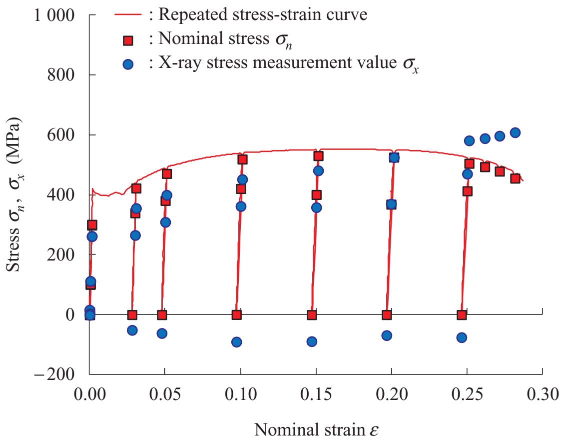


Fig. 7 Relation between strain (ε), nominal stress (σ_n) and stress measured by the X3000 (σ_x)

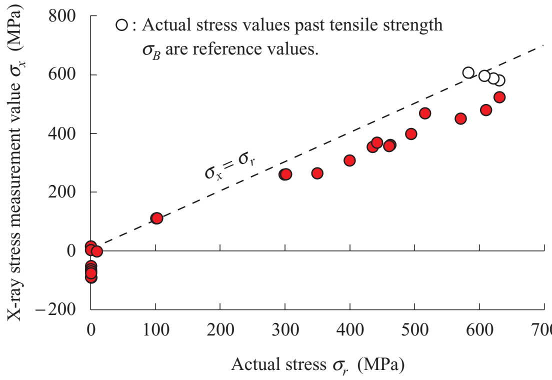


Fig. 8 Relation between actual stress (σ_r) and stress measured by the X3000 (σ_x)

PC steel bar. This test material is used under the large compressive residual stress that had been purposely applied to its surface during the manufacturing process. From the X-ray stress measurement results, we obtained a linear relationship between the change in nominal stress due to external load and the X-ray measured stress, from the initial compressive stress to the tensile stress range. This indicates that the X-ray stress measurement method is able to accurately measure stress conditions on the surface of the test piece.

Next, **Fig. 7** illustrates the relationship between the load and the X-ray stress measurement values under repeated load conditions exceeding the yield point for the SM490 material adopted as the welding structure. **Figure 8** illustrates the relationship between the actual stress σ_r and X-ray measured stress σ_x under each load.

Unlike the nominal stress that is typically adopted, actual stress is a value calculated according to the actual sectional area while under the stress load. The X-ray stress measurement values indicate a good correlation with the actual stress values. These results confirm that the X-ray stress measurement values will give the actual stress status of the material under load, irrespective of elasto-plastic deformation.

The above test results demonstrate that X-ray stress measurement is not only applicable to internal stresses, and but also able to measure the combined internal and external stresses on a material. Consequently, X-ray stress measurement can also be used to measure the load stress conditions of a structure (also called dead load or static load), and expand its role from a measurement method specializing in residual stresses to a measurement method capable of measuring a wider variety of structural conditions.

3. Center hole drilling method

At IIC, the sectioning method has been adopted as a measurement method with a history of past achievements and high technical reliability for measuring residual stresses in welded parts. Meanwhile, the center hole drilling method was reviewed several times, but was not adopted because a technology for accurately drilling holes had not been established. However, after having the experience of applying the DHD method to thick pressure vessels in collaboration with VEQTER Ltd. (University of Bristol) in the UK, we rediscovered the fact that stress measurement by center hole drilling had been technologically established and is highly reliable. Finding it easier than DHD and already in widespread usage in Europe and North America, we adopted the residual stress measurement technology using the center hole drilling method.

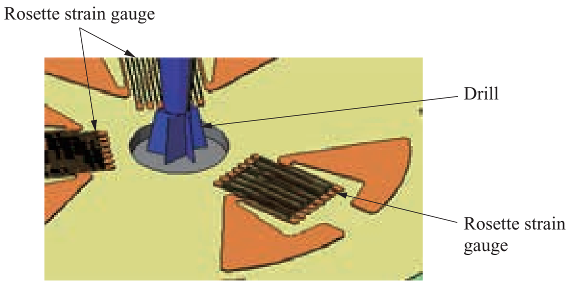
With the center hole drilling method, a rosette strain gauge like the one illustrated in **Fig. 9** is first attached to the measurement location, and then a center hole is made in the center of the rosette strain gauge in successive stages using a drill driven by an air turbine. The strain released at this point is successively measured, and the residual stress that originally existed at the position of the hole is analyzed on the basis of two-dimensional planar stress theory.

The measurement method is defined in detail by the American Society for Testing and Materials (ASTM) standard E837-08. **Figure 10** illustrates the appearance of the hole drilling system. After attaching the rosette strain gauge to the test piece, the microscope of the drilling apparatus is used to align the drill center with the center of the strain gauge. After that, a center hole is drilled under automatic computer control, and the strain released by each stage of drilling can be measured. Based on data such as the measured strain, the actual measured value of the center hole diameter, and the mechanical properties (E, ν) of the material, the released residual stresses are analyzed using special-purpose analysis software.

To compare the center hole drilling method to the X-ray method, a uniaxial tensile test was performed on an SM490 steel sheet. **Figure 11** illustrates the status of the uniaxial tensile test. In this test, known load stresses (three cases) were applied, and the results of stress measurements with both methods were compared.

Figure 12 illustrates a comparison of the uniaxial tensile test results. A good correlation was obtained with both methods. One strength of the center hole drilling method was that the hole size and hole depth were 2 mm or less, and by repeatedly measuring while drilling 0.05 mm at a time in the depth direction, a non-uniform stress distribution up to a depth of 1 mm was able to be measured. The principal stress and its direction was also able to be

(a) Center hole drilling (concept)



(b) Rosette strain gauge after drilling (actual)

Fig. 9 Rosette strain gauge

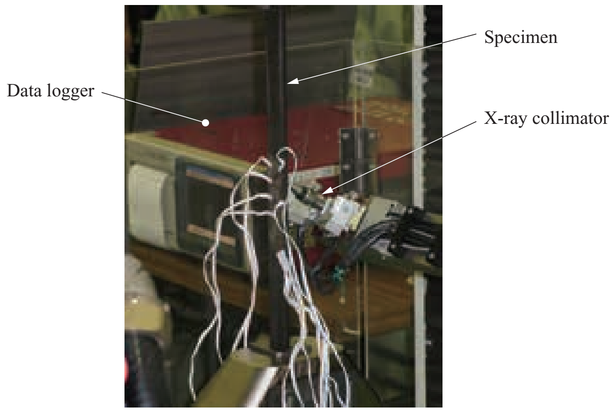


Fig. 11 Status of the uniaxial tensile test

(a) Appearance of drilling device

(b) Overview of hole drilling system

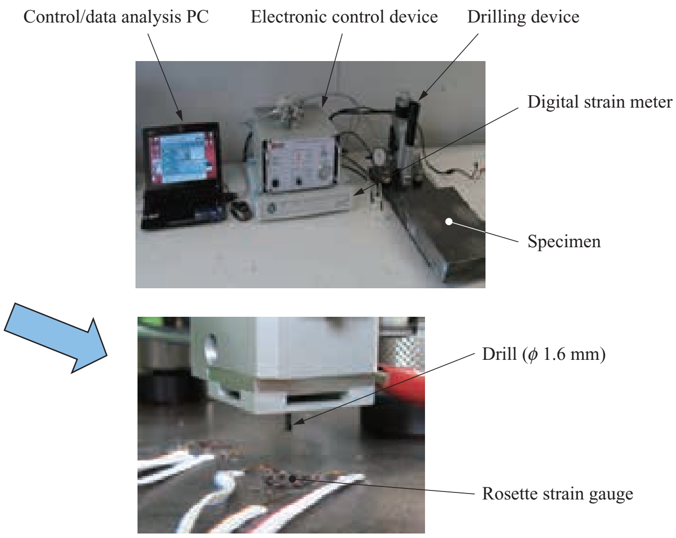
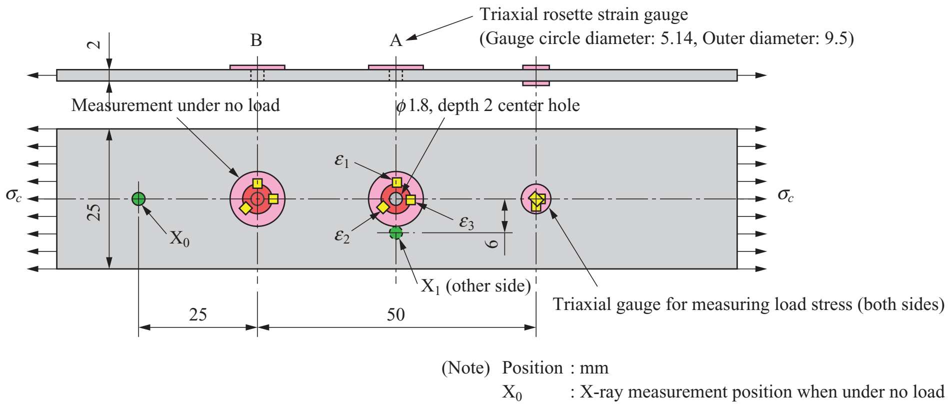


Fig. 10 Appearance of the hole drilling system

(a) Measurement Position



(b) Comparison of center hole drilling and X-ray methods

Case No.	Test load (MPa)	Center hole drilling (position A) residual stress (MPa)	X-ray (position X_1) residual stress (MPa)
1	100	103	$\sigma_x = 98$ (±12.7)
2	150	161	$\sigma_x = 130$ (±13.4)
3	200	216	$\sigma_x = 225$ (±11.6)

Fig. 12 Test results of the uniaxial test

measured at each depth position. Since the measurement depth of the X-ray stress measurement method is approximately 20-50 μm, the center hole drilling method is better for cases where drilling into the test piece is allowed.

4. Conclusion

In the past, residual stress measurement technology was a specialized field of study for experts, but it is now becoming a general-purpose technology thanks to advances in automated measurement by measurement equipment. In residual stress measurement, it is important not to limit oneself to a single technique, but to consider factors such as the measurement environment of the test piece and the demanded precision, and make a comprehensive evaluation that includes analyses made using compound techniques. Residual stress itself exhibits complex distributions, which necessitates accurate measurement of a clearly defined measurement location.

Recently, numerical analysis methods are also maturing, and although numerical values of a location to be evaluated can be grasped using a numerical model, actual measurement by some technique must also be conducted in order to verify the validity of the calculations. If the actual values and the validity of the analysis results can be confirmed locally, the validity of the analysis results can be recognized as verified, and the analytical evaluation's scope of application can be extended.

IIC will continue to provide comprehensive stress measurement and evaluation technology services, including numerical analysis.