Impact Objectives

- Investigate ways to estimate three-dimensional (3D) residual stresses
- Improve the accuracy of predictions for the lifetime of mechanical structures

Better estimation of mechanical stress

***Dr Masaru Ogawa** and **Professor Alexander M Korsunsky** talk about their current research into residual stresses and some of the results the team have achieved so far*

Dr Masaru Ogawa

Professor Alexander M Korsunsky

What type of research are you currently involved in?

MO: My team is working on a demonstration experiment of the non-destructive eigenstrain method for estimating 3D residual stresses using X-ray diffraction. Our target is not only fusion welded joints, but also friction stir welded joints for aircraft materials, spot welded joints for automobiles and welded pipes in energy power plants and chemical plants.

You have a particular interest in residual stress and the importance of the ability to estimate 3D welding residual stresses non-destructively. Can you explain in lay-person terms what this means?

AK: Various non-destructive techniques have been developed for the detection of cracks within structures. However, in order to predict the safe remaining lifetime in the presence of these cracks it is necessary to evaluate not only their distribution, size and shape, but also the 3D residual stresses, because crack growth rate and crack propagation direction are dependent on these stresses under fatigue loading and stress corrosion cracking conditions. If residual stresses can be estimated non-destructively, mechanical structures can be used more safely for a longer time.

What methods are you using for your research?

MO: The methods we use can be applied with a commercially available X-ray diffractometer and the finite element method. For the fast linear analysis carried out in the Finite Element framework it is necessary to know only Young's modulus, Poisson's ratio and the structure geometry. In contrast, welding simulation based on the thermoelastic and plastic finite element analysis requires determining a large number of parameters. It is laborious to evaluate temperature-dependent parameters such as yield strength and creep resistance.

One of your projects involves the friction stir welding (FSW) technique. What did the results of this study help to clarify and why is this valuable information?

AK: It is important to select judiciously the unknown parameters in the inverse analysis because this method estimates 3D eigenstrains from two-dimensional (2D) surface strains. In our approaches to this task we made use of Artificial Intelligence algorithms. For the particular case of FSW joints, it has been observed that eigenstrains are distributed relatively uniformly along the welding direction. Therefore, the estimation accuracy of this method becomes relatively high. The measurement accuracy of X-ray diffraction in the stir zone can be higher because of the refined crystalline structure. For reliable residual stress evaluation, it is important to carry out measurements within the stir zone, as well as outside it.

Have you seen any results that you are particularly pleased with?

MO: When plates or pipes are jointed under relatively uniform heat input conditions, 3D residual stresses can be estimated with rather high accuracy by using X-ray diffraction and the eigenstrain method. Only the eigenstrain method using X-ray diffraction can estimate 3D residual stresses non-destructively on site.

How important are partnerships and collaborations?

AK: It is crucially important to collaborate with the manufacturers who deal with practical design challenges related to residual stresses. We seek to work with colleagues in industry to advance the eigenstrain method for evaluating 3D residual stresses.

What do you hope to be exploring next?

MO: We aim to estimate 3D residual stresses with higher accuracy for the broadest range of residual stress related problems. It is important to refine inverse analysis techniques to obtain best estimates of eigenstrains for each feature, such as one-sided welded material, surface modified material, or spot-welded structures. Furthermore, we would like to study how to estimate internal residual stresses for relatively small structures such as printed circuit boards. ●

Accurately estimating 3D residual stresses

*A team of researchers based in the **Department of Mechanical Systems Engineering, Kogakuin University** and **MBLEM lab, University of Oxford** is using the eigenstrain reconstruction method and X-ray diffraction to estimate 3D residual stress distributions*

It is interesting to consider just how many of us think about the importance of mechanical engineering when we go about our daily lives. Whether we are crossing bridges, getting into our cars, riding on trains, flying in planes or entering buildings, we are relying on mechanical engineers and researchers to have performed an enormous amount of calculations to ensure the integrity of these structures. Indeed, the main purpose of many engineering activities is to design structures against failure. By employing physics, mathematical principles, experience, technical knowledge and modelling capabilities, teams can confidently predict the safe operations of complex engineering systems.

Professor Alexander M Korsunsky, who heads the MBLEM Lab at the Department of Engineering Science, University of Oxford in the UK, is an expert in this field. He says that over the past few decades, the scientific community has rapidly improved the knowledge and ability to determine the properties of engineering materials for design. 'It is now possible to characterise the materials at resolutions down to microns and nanometres, and use sophisticated numerical models to describe them,' confirms Korsunsky. 'However, there still remains one key aspect that affects the ability to predict the behaviour and that is residual stress.'

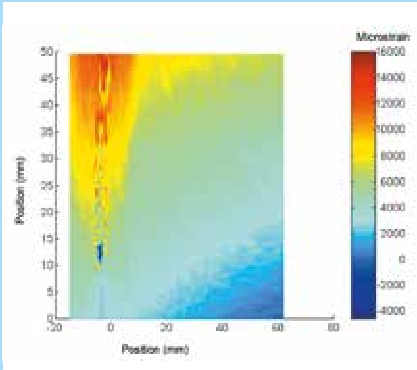

Illustration of residual strain mapping around a weld using X-ray diffraction

Residual stresses are a natural result of the processing operations on materials, such as casting, forging, welding and heat treatment. These residual stresses affect the failure conditions, sometimes to such an extent that the very way in which failure occurs changes completely. 'Ultimately, this means that the design calculations used to predict the integrity of a structure could turn out to be completely wrong,' highlights Korsunsky.

EIGENSTRAIN RECONSTRUCTION METHOD

Dr Masaru Ogawa, who is based at the Department of Mechanical Systems Engineering, Kogakuin University, is working alongside Korsunsky and a number of researchers to elucidate the origins and effects of residual stresses. They are using the eigenstrain reconstruction method to estimate 3D residual stress distribution. 'The term eigenstrain refers to the misfit strains that occur within a body and serve as the source of residual stresses. One can understand this by imagining cutting out a wedge-like strip out of a piece of fabric, and gluing the sides of the cut back together,' explains Korsunsky. 'If one wants to keep the fabric flat, material further away from the tip of the cut needs to stretch, to adapt to the change and adopt the new shape. In the general theory of eigenstrain, its introduction into a body causes it to respond by developing accommodating elastic strains, which, in turn, give rise to stresses.'

Conventional X-ray diffraction only allows the measurement of surface residual stresses. 'While it is possible to measure internal residual stresses using neutron diffraction or high energy synchrotron X-rays, these measurements can only be accomplished at special facilities, and in any case at a limited number of discrete points,' outlines Korsunsky. By using the eigenstrain method, the researchers are able to estimate the complete 3D residual stress distribution within the entire body - even if only partial measurements are conducted by diffraction methods.

NUMERICAL SIMULATIONS

To validate the findings of the research they are conducting, it is necessary for Ogawa, Korsunsky and their teams to perform demonstration experiments using actual structures. The estimation accuracy can be evaluated by comparing the residual stresses estimated by this method with the results measured by other reliable methods, such as the contour method and neutron diffraction.

However, it is also important to verify the effectiveness of this method using numerical simulations. 'First, an exact residual stress field is assumed. Second, measurement values are artificially made by adding measurement errors into the exact elastic strains. Third, eigenstrain distributions are estimated using this method,' says Ogawa. ▶

> *In the general theory of eigenstrain, its introduction into a body causes it to respond by developing accommodating elastic strains, which, in turn, give rise to stresses*

'The estimation accuracy of this method is evaluated by comparing the exact residual stresses with estimated values calculated from the installed eigenstrains.'

Through the course of their work, they have learned that the eigenstrain reconstruction method is a powerful tool to assess 3D residual stress distribution. Eigenstrains for the entire structure can be estimated from only partial elastic strains measured by diffraction methods, but it is possible to increase the estimation accuracy when three conditions are satisfied: inelastic strains are distributed relatively uniformly; the area of inelastic strains can be restricted; and the measurement accuracy of the elastic strain is sufficiently high.

OVERCOMING CHALLENGES

Although the team's findings so far have been insightful, the research they have conducted has not been without its challenges. The eigenstrain method using X-ray diffraction, through the use of appropriate advanced techniques, in combination with eigenstrain methods, can be used as an on-site measurement technique to estimate 3D residual stresses non-destructively. This approach makes it possible to predict the remaining lifetime of welded pipes for energy power plants and chemical plants.

However, it is important to note that if only elastic strains on the outer surface can be measured, then the accuracy of residual stress reconstruction by X-ray diffraction and eigenstrain can be limited. 'It is essential to measure as many points as possible to improve the estimation accuracy,' states Korsunsky. 'Moreover, eigenstrains can also be estimated by measuring relief strains with strain gauges when the reinforcement of the weld is removed. For example, the toe of the weld may become a crack starter and needs to be removed. Therefore, the elimination of the weld reinforcement can be essentially regarded as non-destructive treatment.'

LIFETIME PREDICTION

Once the team has fully established the methods they have been using during the course of their research, it will be possible to predict better the lifetime of mechanical structures such as cars, trains and airplanes. This will obviously have far-reaching consequences, including product safety and increased performance, as well as the associated economic benefits. Ogawa and Korsunsky hope that their work will lead to increased profits for the manufacturing industry. The value of the team's work is clearly demonstrated by the fact that friction stir welding could one day become an alternative technique to riveting in the manufacturing of airplanes.

Ultimately, the teams hope their findings will lead to a more widespread usage for real-world outcomes to be realised. 'Today, elastic-plastic finite-element method simulations are typically used to evaluate residual stresses,' says Korsunsky. 'However, it is found that residual stresses may still vary greatly even under similar processing conditions, such as welding. Therefore, quantitative experimental evaluation is important to assess individual differences.'

Ogawa wants to make his methods more accurate and easier to use in industry because if the eigenstrain method finds more widespread use, it will be possible to build better correlations between manufacturing conditions and eigenstrains. The significance of applying eigenstrain methods in modern mechanical design for energy, transport, and surface engineering has been demonstrated by Ogawa and his team. It now needs to be adopted by industry for the full potential to be realised. ●

Project Insights

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BIO

Dr Masaru Ogawa gained his PhD from the Tokyo Institute of Technology. He then received the Japan Society of Mechanical Engineers Award (The Best Paper) for 3D residual stress estimation method using eigenstrain method and X-ray diffraction. Ogawa is currently working at Kogakuin University to demonstrate the technique.

Professor Alexander M Korsunsky holds his doctorate (DPhil) from Merton College, Oxford. He is a world-leader in engineering microscopy for optimisation of design, durability and performance. He leads the Multi-Beam Laboratory for Engineering Microscopy at Oxford, and the Centre for In-situ Processing Science (CIPS) at Harwell. Korsunsky consults Rolls-Royce plc. on residual stress and structural integrity, and is Editor-in-Chief of *Materials & Design* (IF 5.770).