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Residual stress evaluation in welded large thin-walled structures based on eigenstrain analysis and small sample residual stress measurement

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ABSTRACT

This paper presents an evaluation method of residual stresses in large welded thin-walled structures based on eigenstrain analysis and small sample residual stress measurement. In this method, small samples containing weld and heat-affected zones are firstly cut from large thin-walled structures, then residual stress in the small samples are measured to determine the welding-induced eigenstrains using a finite element-aided inverse solution. Finally, residual stress in large thin-walled structures are evaluated based on the obtained eigenstrain distribution. The feasibility of the proposed method was validated by evaluating residual stresses in welded plates with different lengths or widths. The method was then applied to evaluating residual stress in a welded skin-stiffener panel. Good agreement between the evaluated residual stress and measurement by diffraction technique has demonstrated the practicability of the method.

1. Introduction

The application of advanced welding technologies in aircraft integral metallic structures is recognized as one of the most promising methods for further cost and weight savings. However, residual stresses are introduced during a welding process and consequently influence the structural integrity assessment [1–4]. Therefore, it is important and necessary to evaluate the magnitude and distribution of residual stresses for predicting the durability and damage tolerance performance and avoiding premature failure in service, and thus promoting the integral thin-walled structures. There are two major approaches to evaluate residual stress in welded components, i.e. experimental measurement of welded structures or simulation of the welding process.

The most popular techniques for measurement of welding residual stresses include the diffraction methods and mechanical methods. Diffraction-based techniques, such as the X-ray diffraction and neutron diffraction techniques, are non-destructive means and are more accurate and automatic compared to the mechanical methods. However, the neutron diffraction technique is limited to resources and specimen size, and difficulties may arise for certain alloys due to inhomogeneous microstructure and strong and varying crystallographic texture in the welds [5,6]. Mechanical methods are based on the strain relief principle and hence mostly destructive or semi-destructive. The hole-drilling method, the crack compliance method and the contour method are the most commonly used methods. The hole-drilling method requires commonly available equipment and is easy to operate. However, it has a limited spatial resolution and errors could arise due to localized yielding [7]. The crack compliance method improves the resolution of the residual stress variation, but the surface gauge used in the method could give weak response to the release of sub-surface stresses and might result in instability problems [8]. Nowadays, the contour method proposed by Prime and Gonzales has become more and more popular owing to its straightforward theory and simple implementation [9]. Nevertheless, the assumption of a flat cut in the contour method is overly restrictive and misleading, which makes error minimization and correction important and necessary [10].

In addition to experimental measurement techniques, residual stresses can be evaluated by simulating the welding process using the finite element (FE) method. Joshi et al. presented a simulation of welding-induced residual stresses in a circular hollow section T-joint to explore the influential factors to the initiation and propagation of fatigue crack [11]. A sequentially coupled thermal-stress analysis was conducted by Lee et al. to model the welding process of a Y-shaped joint, and a small scale parametric study was carried out to investigate the influences of key welding parameters on the magnitude and distribution of residual stress [12]. Paulo et al. built a novel shell element

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Nomenclature

$\boldsymbol{B}$	Eigenstrain calibration coefficient matrix
$\boldsymbol{B}^{-1}$	Inverse matrix of $\boldsymbol{B}$
$\boldsymbol{B}^{\mathrm{T}}$	Transpose matrix of $\boldsymbol{B}$
B_{ij}	$\boldsymbol{B}$ matrix component representing the residual stress in the ith interval caused by a unit eigenstrain in the jth interval
$\boldsymbol{B}_{\mathrm{eva}}$	$\boldsymbol{B}$ matrix correlated to a specimen in which residual stress is to be evaluated
$\boldsymbol{B}_{\mathrm{mea}}$	$\boldsymbol{B}$ matrix correlated to a specimen in which residual stress has been measured by experiment
m, n	Total number of intervals of eigenstrain zone and residual stress field, respectively
$U_j(x)$	Pulse function
$\boldsymbol{\varepsilon}^*$	Eigenstrain
ε_y^*	Eigenstrain component in y direction
$\boldsymbol{\sigma}$	Residual stress
$\boldsymbol{\sigma}_{\mathrm{eva}}$, $\boldsymbol{\sigma}_{\mathrm{mea}}$	Residual stresses that are to be evaluated and have been measured, respectively

FE model to simulate the friction stir welding process of building an integral stiffened panel to predict the residual stress, material softening and geometric distortion [13]. Although these simulation results were comparable with experimental measured residual stresses, the thermo-mechanical models required large number of material properties and welding process parameters. Moreover, thermo-elasto-plastic FE analysis of large complex welded structures requires high-performance computers and significant amount of computing time.

Eigenstrain is a generic name given by Mura to such nonelastic strains caused by thermal expansion, phase transformation, initial strains, plastic strains and misfit strains, and residual stresses are created owing to the incompatibility of the eigenstrains [14]. Ueda et al. proposed the concept of inherent strain as the source of residual stress and developed a general theory for evaluating residual stresses based on estimation of the inherent strain [15]. Obviously, eigenstrain has the same meaning as the inherent strain. In the following sections, the terminology given by Mura was used, i.e. the inelastic and non-compatible strains are called eigenstrain. For a welded joint, the eigenstrain consists of thermal, transformation and plastic strains induced by the welding process.

There are many advantages offered by the eigenstrain approach for evaluating the welding residual stress; once the eigenstrain distribution is deduced, the residual stress can be determined by using a linear elastic model rather than a nonlinear elasto-plastic one [16]; the eigenstrain approach enables prediction of the object's distortion and residual stress re-distribution during any subsequent machining operation [17]. Ueda et al. presented a series of work demonstrating practical applications to cases such as butt-welded joints, long welded joints, axisymmetric shaft, and T- and I-shaped joints, etc., describing a way of determining the inherent strain and residual stress [18–21]. Hill et al. proposed a localized eigenstrain method focusing on finding residual stress only in the weld bead region of the joint, therefore the required experimental effort was greatly reduced in comparison with Ueda's method [22]. Korsunsky et al. developed a framework for predictive modelling of the residual stress due to surface peening and inertia friction welding [23–25].

This paper presents a method for evaluating residual stresses in large welded thin-walled structures based on the eigenstrain analysis and small sample residual stress measurement. In this method, residual stresses in small samples cut from large structures were measured at first, then the eigenstrain introduced by the welding process was determined using an FE-aided inverse method. Finally, residual stress in large thin-walled structures was evaluated based on the obtained eigenstrain. Two case studies were carried out to demonstrate the applicability of the presented method: residual stresses in welded plates of different lengths or widths, and residual stress distribution in a welded skin-stiffener panel.

2. Method

2.1. Procedure

Based on the postulate that a residual stress field can be uniquely determined by elastic equilibration of a distribution of eigenstrain in an object, the procedure of the presented method for evaluating residual stresses in welded large thin-walled structures involves three steps: (1) residual stresses in the small sample, which is cut from the large structure and contains the same weld and heat-affected zone, is measured using an established techniques, e.g., the diffraction method; (2) a calibration coefficient matrix denoted as $\boldsymbol{B}_{\mathrm{mea}}$ is established by performing FE analysis. The matrix is related to the small sample, in which the residual stress has been measured. Eigenstrain distribution induced by the welding process is then determined by solving linear algebraic equations relating the $\boldsymbol{B}_{\mathrm{mea}}$ matrix and the measured residual stress; (3) a calibration coefficient matrix related to the thin-walled structure, in which residual stress will be evaluated, is established by FE analysis and denoted as $\boldsymbol{B}_{\mathrm{eva}}$. Then residual stress field in the welded large thin-walled structure can be evaluated based on the obtained eigenstrain and $\boldsymbol{B}_{\mathrm{eva}}$ matrix. A flowchart of the proposed method and calculation procedure is shown in Fig. 1.

In fact, the implicit limitation of the presented method is that the welds in reference samples and large actual structures must be the same, i.e. the welding process parameters and the weld dimensions in the small sample and the large thin-walled structure should be maintained the same. Considering that the transverse residual stresses (perpendicular to weld) are usually much smaller than those in the longitudinal direction (parallel to weld) in welded thin-walled structures [26], only the longitudinal residual stresses are taken into account in this paper.

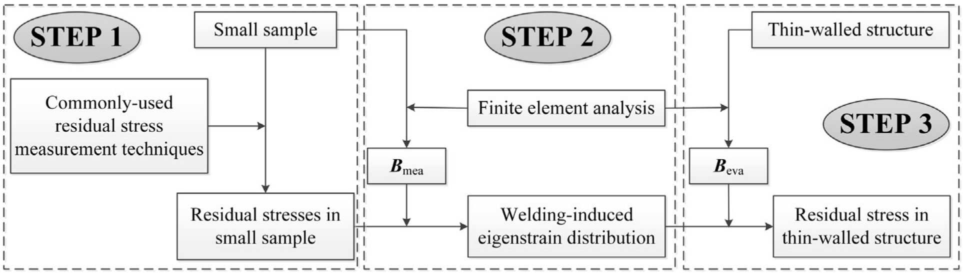

Fig. 1. Flowchart of the proposed method and calculation procedure.