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Sensitivity analysis of the thermomechanical response of welded joints

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Abstract

A computational procedure is presented for evaluating the sensitivity coefficients of the thermomechanical response of welded structures. Uncoupled thermomechanical analysis, with transient thermal analysis and quasi-static mechanical analysis, is performed. A rate independent, small deformation thermo-elasto-plastic material model with temperature-dependent material properties is adopted in the study. The temperature field is assumed to be independent of the stresses and strains. The heat transfer equations emanating from a finite element semi-discretization are integrated using an implicit backward difference scheme to generate the time history of the temperatures. The mechanical response during welding is then calculated by solving a generalized plane strain problem. First- and second-order sensitivity coefficients of the thermal and mechanical response quantities (derivatives with respect to various thermomechanical parameters) are evaluated using a direct differentiation approach in conjunction with an automatic differentiation software facility. Numerical results are presented for a double fillet conventional welding of a stiffener and a base plate made of stainless steel AL-6XN material. Time histories of the response and sensitivity coefficients, and their spatial distributions at selected times are presented.

Keywords: Welding; Finite element analysis; Thermal analysis; Lagrangian frame; Residual stresses; Sensitivity analysis

1. Introduction

Welding has become a prevalent mechanical joining methodology in various industries because of its many advantages over other joining methods including design flexibility, cost savings, reduced overall weight, and enhanced structural performance. However, the local high temperature in a welding process

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induces residual stresses and distortions (Gunnert, 1955; Terai, 1978; Shim et al., 1992; Connor, 1987). These residual stresses and distortions are undesirable in general since they have bad effects on the structural performance. Although a number of approaches have been proposed to minimize the residual stresses and distortions, including selecting the type of welding, controlling the welding process parameters, and modifying the structural configuration (Burak et al., 1977, 1979), the residual stresses are inevitable in essence.

Numerical simulation techniques to study the various phenomena associated with welding have been developed. For example, weld-pool physics, heat and fluid flow, heat source–metal interactions, weld solidification microstructures, phase transformations, and residual stresses and distortions have been studied. Recent studies of residual stresses and distortions in welded structures are reported in Goldak and Bibby (1988), Tekriwal and Mazumder (1991), Argyris et al. (1982), Hibbitt and Marcal (1973), Braudel et al. (1986), Oddy and Goldak (1990), Bertram and Ortega (1991), Wang and Murakawa (1998), Roelens and Maltrud (1993), Rybicki and Stonesifer (1979) and Chakravati et al. (1986). In these numerical studies of welding, the accuracy of temperature-dependent material properties plays an important role in the accuracy of predicted residual stresses.

Since current measurement technology does not allow the accurate determination of the material parameters that are used in the analytical models, it is useful to assess the sensitivity of the thermomechanical responses of welded joints to variations in the various material parameters. The present study focuses on this topic. Specifically, the objective of this paper is to present a computational procedure for evaluating the sensitivity coefficients of the quasi-static response of welded joints. Uncoupled thermomechanical analysis is performed. A rate independent, small deformation thermo-elasto-plastic material model with temperature-dependent material properties is adopted.

Numerical results are presented for the temperature—and residual stress—time histories and their sensitivity coefficients for a double fillet conventional welding of a stiffener and a base plate made of stainless steel AL-6XN. A two-dimensional generalized plane strain model is used, which is adequate for predicting the residual stresses. However, the prediction of welding distortions requires a global three-dimensional model (Brown and Song, 1992), which is beyond the scope of the present study.

2. Finite element equations

Uncoupled thermomechanical analysis is performed. The temperature field is assumed to be independent of stresses and strains. The heat transfer equations emanating from a finite element semi-discretization are integrated using an implicit backward difference scheme to generate the time history of the temperatures. The mechanical response during welding is then calculated by solving a generalized plane strain problem. A rate independent, small deformation thermo-elasto-plastic material model with temperature-dependent material properties is adopted in the study. The governing equations for the thermal and mechanical analyses are summarized subsequently.

2.1. Thermal analysis

The governing equation for transient heat transfer analysis is given by:

$$\rho c_p \frac{\mathrm{d}T}{\mathrm{d}t}(\mathbf{r},t) = -\nabla \cdot \mathbf{q}(\mathbf{r},t) + Q(\mathbf{r},t) \tag{1}$$

where ρ is the density of the flowing body, c_p is the specific heat capacity, T is the temperature, $\mathbf{q}$ is the heat flux vector, Q is the internal heat generation rate, t is the time, $\mathbf{r}$ is the coordinate in the reference configuration, and ∇ is the spatial gradient operator.