D. Bifurcation Phenomenon in Plate Welding

by Chon L. Tsai, The Ohio State University and Myoung S. Han, Deawoo Shipbuilding and Marine Engineering Inc.

Introduction

Buckling is one of the most prevalent types of welding-induced distortion in fabricating thin plate panel structures. This distortion problem is of a particular concern when dealing with higher strength materials, which design tends to use thinner plates while the welding induced compressive stress in the plate is also higher. The common engineering approach to this problem has been to apply the eigenvalue analysis to the compressive residual stress in the plate resulting from welding. The average compressive residual stress is externally applied to the panel with other structural support conditions described to estimate the critical panel dimensions and the threshold welding heat input. This approach postulating the buckling instability under the residual stress state may inaccurately estimate the buckling strength of the panel due to the observation in this study of incipient bifurcation in the weldment during the weld cooling cycle. If this phenomenon continues until completion of the weld cooling cycle, panel would buckle at lower threshold stress values than that predicted by the stress-based eigenvalue solution.

The evolution of the buckling phenomenon starts during the weld cooling cycle caused by an onset inelastic strain incompatibility condition. This initial bifurcation phenomenon may continue to grow until the completion of the cooling cycle, which results in the final buckling distortion of the plate. With lower heat input and/or smaller plate dimensions this initial instability may stop during the cooling cycle due to diminishing strain incompatibility and recovering of the plate rigidity.

Procedure

In this study, an integrated experimental and numerical approach was used to investigate the mechanics of welding-induced buckling phenomenon. In the experimental study, bead-on-plate welding was performed along the middle line of AH36 steel plates using the submerged arc welding process. The effect of welding heat input on distortion was evaluated with heat input ranging between 560 J/mm and 1280 J/mm. The plate size effect was also studied for a constant heat input (1097 J/mm). The purpose of this experimental study was to establish the baseline data for calibration and comparison with the numerical analysis.

In the numerical studies, three-dimensional, thermo-elastic-plastic, large deformation analyses were performed on the weld experimental models to understand the distortion process observed in the experiments. The distorted shape and the magnitude of vertical displacements obtained from the numerical analyses were compared with those obtained from experiments. The numerical models were extended to analyze the transient evolution of the bifurcation phenomenon during welding and after completion of the weld thermal cycle for the buckling criterion.

Results and Discussion

This paper has demonstrated a numerical procedure to determine the peak temperature-based buckling criterion for welding thin steel plates. Several key discussions of the analyses presented in this paper can be summarized as follows:

1. A bifurcation phenomenon starts in weld plates during the weld cooling cycle regardless of heat input and plate size. However, this phenomenon stops when the weld plate cools off to lower temperatures for smaller plates and lower heat inputs.
2. The longitudinal weld distortion is primarily caused by the inherent longitudinal shrinkage strains accumulated during the weld thermal cycles.
3. The inherent longitudinal shrinkage strains can be uniquely determined based on the peak temperatures in the weld plate. This is due to high stiffness of weld plate in the longitudinal direction.
4. The characteristic peak temperature that determines the formation of plastic strains is defined as "nil-plasticity peak temperature," which is influenced by welding heat input and plate size. There exists a bi-linear relationship as function of heat input and plate size.
5. The critical buckling threshold can be determined using the eigenvalue FEA analysis procedure using the maximum longitudinal inherent shrinkage strains for a given heat input as the perturbation strain load applied using the equivalent thermal loading temperatures. The threshold value is the first-mode eigenvalue that decreases with increasing weld heat input or plate size.
6. The buckling driving parameter, $(\varepsilon_{xx}^{ie})_{III}$ is proportional to the nil-plasticity shrinkage temperature (T_h), the material factor (R_H) considering the material softening effect, and the thermal expansion coefficient evaluated at material's mechanical melting temperature.

Conclusions

The longitudinal stresses causing the buckling phenomenon of thin plate can be uniquely related to the peak temperature distributions. Material softening is the primary root cause for the shrinkage strain buildup in the weldment. For distortion modes caused by the transverse shrinkage strains have weaker relations with the peak temperatures due to variability in constraints or rigidity of the joint in the direction perpendicular to weld axis.