Controlling Welding-induced Distortion through Numerical Modeling

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The Challenge of Controlling Welding-induced Distortion

During welded fabrication, high localized heat input and subsequent rapid cooling result in the creation of residual stresses that lead to distortion. When this distortion leads to fit-up issues, additional residual stresses are imparted as components are forced into place and weld sizes are increased to compensate for increased gaps. These residual stresses can significantly affect the fatigue resistance, cracking behavior, and load-carrying capacity of welded structures during service. Further, additional fitting and tacking time is often required to fit distorted subassemblies together, resulting in non-value added cost.

Using trial-and-error methods to determine which welding parameters, welding sequences, and fixture designs will most effectively reduce distortion is a time-consuming and expensive process. For complex structures with many welds, this approach can take up to six months. For this reason, efficient and accurate methods of mitigating distortion are in-demand across all industries where welding is used.

Numerical Modeling of Welding Processes

Analytical and computational methods have been used for over three decades to predict welding-induced residual stresses and distortion, and to quantify their effect on the performance of welded structures. Most welding simulation techniques use numerical computational methods such as finite element analysis (FEA), and employ enhanced commercially available or in-house-developed code. While the last approach works well for research organizations, most industrial end-users don't have the expertise required.

The most accurate and comprehensive numerical technique is coupled thermal-metallurgical elastic-plastic analysis. This method can simulate a wide range of welding phenomena including heat flow, metallurgical transformations in the weld and heat-affected zone (HAZ), and thermal-mechanical responses. Welding parameters, assembly sequence, welding sequence, fixturing, and welding direction can all be included in this analysis. This method has been repeatedly validated by EWI on commercial and government projects.

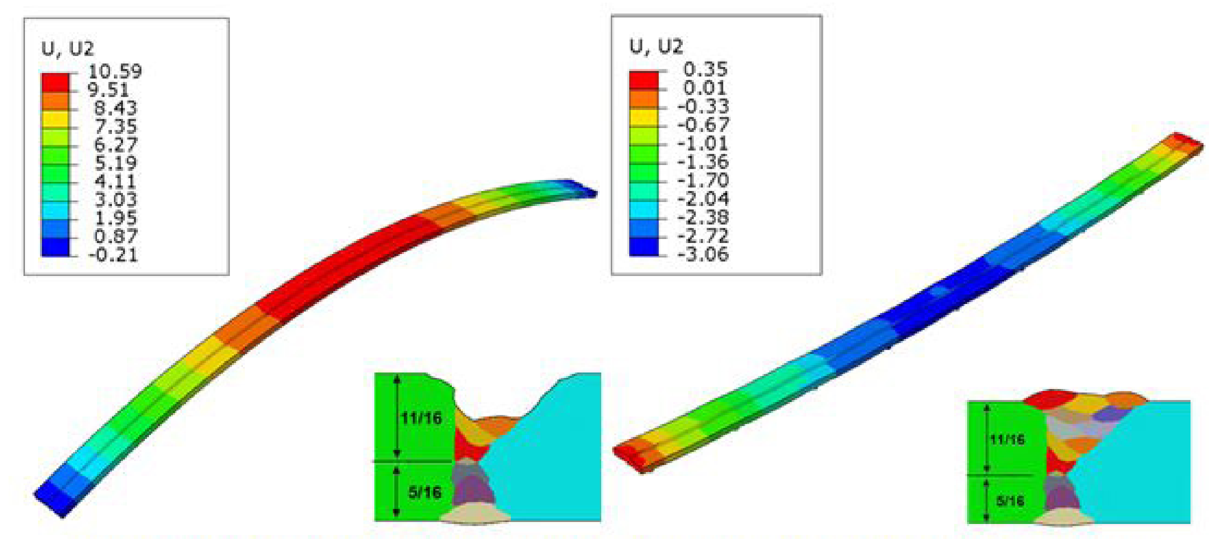

Figure 1: Using the mapping plastic-strain method to predict distortion (mm) of a two-sided weld

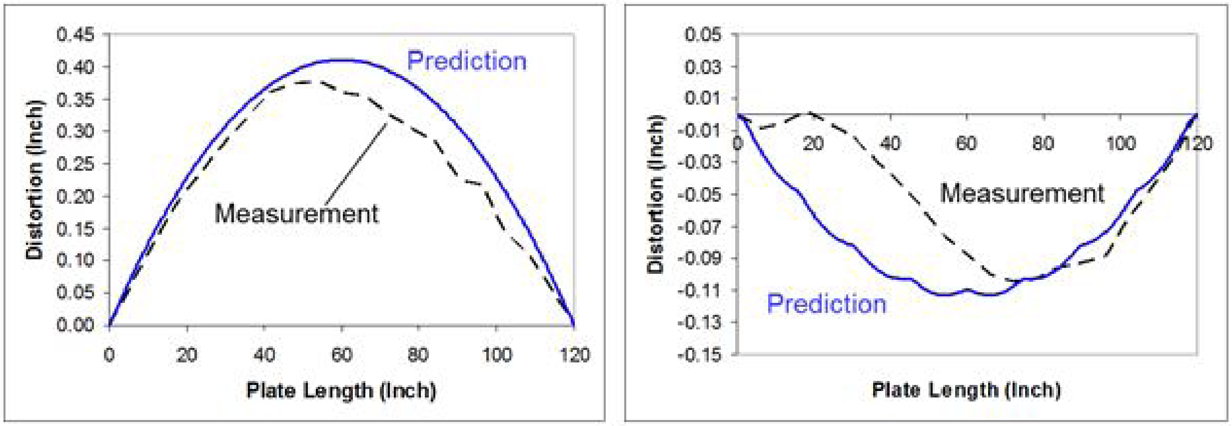

Figure 2: Predicted vs. measured distortion

The mapping plastic-strain method utilizes both local and global finite element models. In this method, local models are used to create the plastic strains which are a function of welding sequence and weld location. A global model is then used to predict distortion with an elastic analysis or elastic-plastic analysis by mapping the predicted plastic strains from the local models. For multi-pass welding, the plastic strain evolution induced by welding each pass must be considered during distortion prediction. Figures 1 and 2 illustrate the use of this method to predict distortion of a two-sided weld in one-inch thick plate.

Efficient Modelling Methods for Complex Structures

Welding simulation is particularly complex as it is non-linear and is often difficult to converge numerically due to the change in material behavior at elevated temperatures. A fine mesh is required along the welds and HAZ to accurately simulate the high temperatures and stress gradients in these regions. Despite ongoing technological advances, the long computing times required for complex structures may be prohibitive. In response, simplified analysis techniques have been developed, including the inherent strain/ deformation method, the shrinkage volume method, and the plasticity-based analysis method (Q-Weld).

These techniques have been successfully used to predict and control weld-induced distortion of large-scale welded structures by optimizing welding sequences. They have also been used to design effective welding fixtures, and to evaluate new distortion control concepts.

Designing Welded Structures to Reduce Distortion

Design plays a significant role in determining whether a structure will be prone to excessive distortion. Simple guidelines have been developed for designers, including balancing weld placement and orienting welds near a neutral axis whenever possible. Numerical weld modeling provides a more advanced tool, allowing designers to determine whether a structure will buckle, predict the magnitude of distortion for various weld sizes, and estimate the effect of weld residual stresses on the overall strength and fatigue life of the structure. Using these data, material thicknesses and weld sizes can be selected to minimize buckling distortion, providing significant cost savings during fabrication.

Designing Effective Welding Fixtures

Since numerical weld modeling can be used to determine where distortion will occur, welding fixtures can be designed with adequate restraint in these problematic areas. The effectiveness of fixture designs can also be predicted before they are constructed by conducting a weld analysis using numerical boundary conditions to simulate the restraint. Numerical modeling can also be used to determine what level of pre-camber is required to create a part with minimal distortion once it is unclamped and to calculate and compensate for weld shrinkage.

Welding Sequence Optimization

For structures with multiple welds, determining the ideal welding sequence is challenging, even with significant experience and/or industrial distortion-control guidelines. Using numerical modeling, multiple welding sequences can be quickly evaluated to predict their effect without conducting time-consuming welding trials, holding up production, or unnecessarily wasting material.

Evaluating Proposed Distortion Control Methods

Numerical modeling can be used to assess the effectiveness of multiple distortion-mitigation

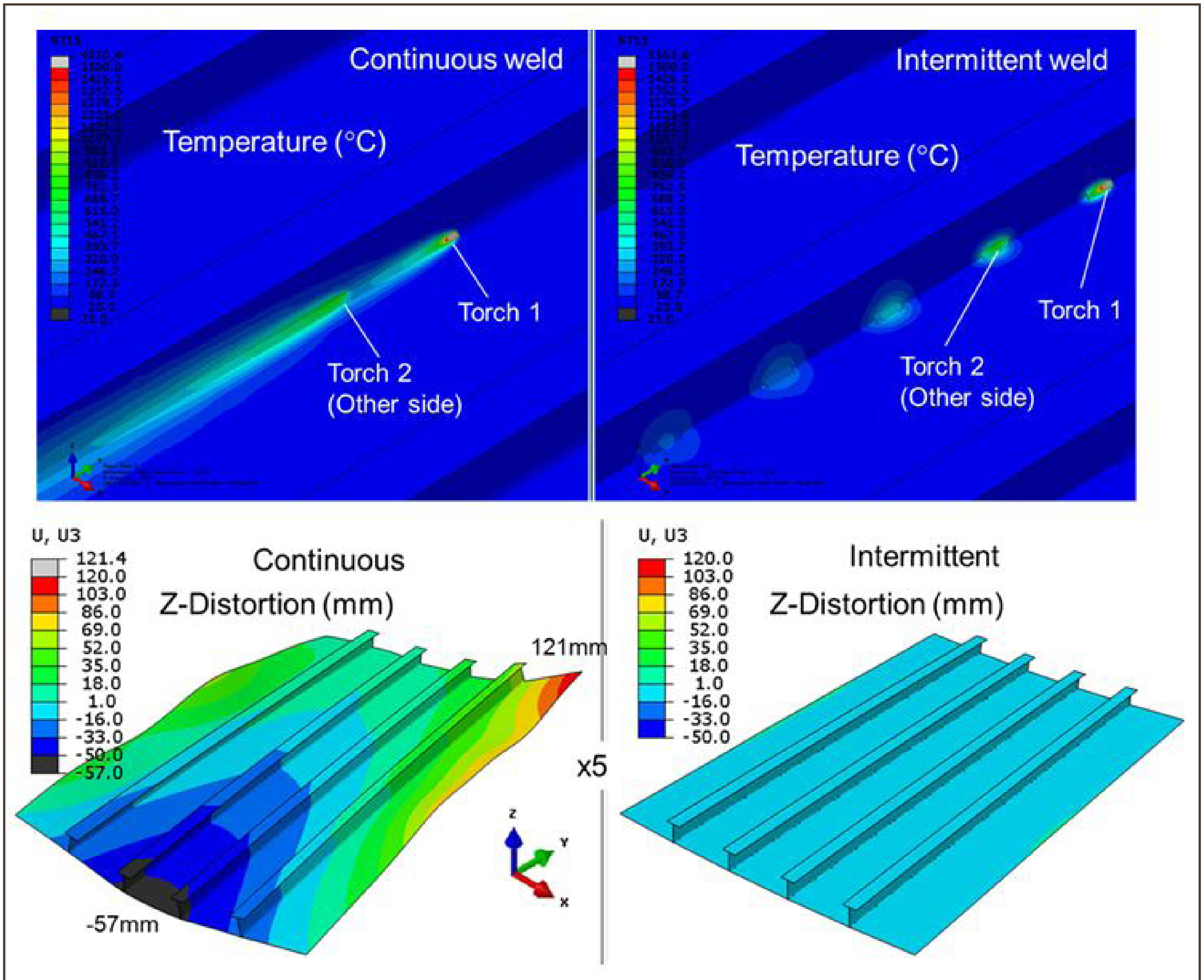

Figure 3: The effect of continuous welds vs. intermittent welds on distortion

concepts to predict which method or combination of methods will be most effective. As an example, numerical models have been developed to determine pre-cambering shape and magnitude for distortion control. Figure 3 illustrates the use of numerical modelling to evaluate intermittent welding as a method of eliminating buckling distortion.

How EWI Can Help

EWI has significant expertise in modeling welding-induced distortion to aid in new product development, design effective welding fixturing, and optimize welding sequencing.

Yu-Ping Yang *is an principal engineer in EWI's structural integrity and modeling group. His main area of expertise is computational modeling of thermal related processes to predict temperature, microstructure, residual stress, and distortion in large and complicated structures. Yu-Ping has extensive experience in finite-element analysis of welded structures including static, dynamic, creep, and fatigue simulation. He also has experience in welding and thermal forming software development, and has in-depth knowledge in the mitigation of weld residual stress, distortion, and cracking.*

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