

Prediction and Compensation of Distortion in Multi-Pass Welding of Large-Scale Steel Structures Using Thermo–Elasto–Plastic Finite Element Analysis

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Abstract: The fabrication of large-scale steel structures through multi-pass welding is plagued by distortion phenomena arising from complex thermo-mechanical interactions during the welding process. This investigation presents an advanced computational framework combining thermo-elasto-plastic finite element analysis (FEA) with experimental validation to predict, analyze, and mitigate welding-induced distortion in structural steel components. A comprehensive three-dimensional finite element model was developed incorporating temperature-dependent material nonlinearities, phase transformation kinetics, and transient heat transfer phenomena with moving heat source effects. The model was rigorously validated through experimental studies involving gas metal arc welding (GMAW) of 10 mm thick ASTM A36 steel plates, with extensive thermographic analysis using infrared imaging and precise distortion measurements via laser scanning interferometry. The numerical predictions demonstrated exceptional correlation with experimental observations, with distortion magnitude discrepancies below 8% and thermal profile predictions within 5% accuracy. Systematic evaluation of distortion compensation strategies revealed that optimized pre-deformation techniques could achieve up to 45% reduction in final distortion, while intelligent welding sequence optimization provided additional 35-50% improvement over conventional approaches. The study establishes a robust methodology for virtual prototyping of welding processes, offering significant potential for reducing manufacturing costs and improving dimensional accuracy in heavy fabrication industries.

1. Introduction

Welding distortion constitutes one of the most persistent challenges in modern heavy fabrication industries, particularly in sectors such as shipbuilding, offshore construction, and bridge engineering where large-scale steel assemblies are prevalent. The fundamental mechanisms of welding distortion stem from the intense localized heating and subsequent non-uniform cooling that occurs during the welding process, generating complex three-dimensional stress fields that ultimately manifest as permanent deformation of the fabricated structure. In multi-pass welding scenarios, commonly employed for thick-section joints, this problem is exacerbated by the

cumulative thermal effects of successive weld passes, often leading to compounded distortion that exceeds simple linear superposition predictions [1].

The economic impact of welding distortion is substantial, with industry estimates suggesting that distortion-related rework accounts for 15-30% of total fabrication costs in major shipyards [2]. Traditional approaches to distortion control have relied heavily on empirical knowledge, trial-and-error methods, and post-weld mechanical straightening operations that are both time-consuming and potentially detrimental to material properties. The limitations of these conventional methods become particularly apparent when dealing with large structural components where even minor distortions can lead to significant assembly problems downstream in the manufacturing process.

Recent decades have witnessed remarkable advancements in computational welding mechanics, with thermo-elasto-plastic finite element analysis emerging as a powerful tool for understanding and predicting welding distortion. However, the application of these techniques to industrial-scale multi-pass welding scenarios presents unique challenges including computational efficiency requirements, accurate representation of material behavior at elevated temperatures, and proper accounting for the complex interactions between successive weld passes [3]. Current state-of-the-art in welding simulation still struggles with reliable prediction of distortion patterns in large structures where global stiffness effects interact with local thermal strains.

This study makes several key contributions to the field: (1) development of an efficient yet accurate thermo-elasto-plastic FEA methodology specifically tailored for multi-pass welding applications; (2) comprehensive experimental validation using advanced measurement techniques; (3) systematic evaluation of multiple distortion compensation strategies; and (4) practical guidelines for implementation in industrial settings. The research employs a combined numerical-experimental approach to bridge the gap between theoretical modeling and practical application, with particular attention paid to the manufacturability of proposed solutions.

2. Experimental Methods

The experimental program utilized ASTM A36 structural steel plates with dimensions of 300 mm × 150 mm × 10 mm, representing typical fabrication elements in shipbuilding applications. The chemical composition was verified through optical emission spectroscopy, showing 0.26% C, 0.75% Mn, 0.04% P, 0.05% S, and balance Fe, conforming to standard specifications. Prior to welding, all specimens underwent thorough surface preparation including grit blasting and degreasing to ensure consistent welding conditions [4].

The welding consumable selected was ER70S-6 solid wire with 1.2 mm diameter, chosen for its common use in structural applications. Shielding gas composition was optimized at 82% Ar - 18% CO₂ based on preliminary bead-on-plate trials evaluating arc stability and spatter generation. Base metal mechanical properties were characterized through tensile testing at room temperature and elevated temperatures up to 800 °C, with results showing typical temperature-dependent degradation of yield strength from 250 MPa at 20 °C to 35 MPa at 800 °C.

A fully instrumented robotic GMAW system was employed for all welding trials, ensuring precise control and repeatability of welding parameters. The system incorporated a 350-amp power source with adaptive voltage control and a 6-axis robotic manipulator capable of 0.1 mm positional accuracy [5]. Welding parameters were established through design of experiments (DOE) methodology, with final parameters set at 24 V, 220 A, and 5 mm/s travel speed for all test welds. Interpass temperature was maintained below 150 °C through controlled cooling periods between passes [6].

Comprehensive thermal monitoring was achieved through three complementary techniques: (1) embedded K-type thermocouples at 5, 10, 20, and 30 mm from the weld centerline; (2) infrared

thermal imaging using a high-speed camera with 640×512 resolution and 100 Hz sampling rate; and (3) non-contact pyrometry for spot verification. The thermal data acquisition system provided synchronized recording with $0.1 \text{ }^\circ\text{C}$ resolution and 10 Hz sampling across all channels.

Post-weld distortion characterization employed a multi-sensor metrology approach combining: Laser scanning interferometry for full-field out-of-plane displacement mapping with 0.01 mm resolution [7]. Coordinate measuring machine (CMM) for discrete point verification with $\pm 2 \text{ }\mu\text{m}$ accuracy. Digital image correlation (DIC) system for in-plane strain measurement during cooling [8].

The measurement protocol included initial baseline scans, interim measurements after each weld pass, and final comprehensive mapping after complete cooling to ambient temperature [9]. All measurements were conducted in a temperature-controlled metrology laboratory maintained at $20 \pm 1 \text{ }^\circ\text{C}$ to eliminate thermal expansion effects.

The numerical simulation was implemented in ABAQUS/Standard 2021 with a sequentially coupled thermal-stress analysis approach. The thermal analysis phase employed a Goldak double-ellipsoidal heat source model with parameters calibrated through inverse analysis of experimental thermal data. The heat source model accounted for the varying power distribution between the front and rear ellipsoids, with parameters $a_f = 3 \text{ mm}$, $a_r = 6 \text{ mm}$, $b = 4 \text{ mm}$, and $c_f = c_r = 2 \text{ mm}$ determined through optimization.

The mechanical model incorporated temperature-dependent elastoplastic material properties with nonlinear isotropic hardening. A modified Norton-Hoff viscoplastic model was implemented to better capture the high-temperature deformation behavior. The annealing effect was modeled through a temperature-dependent yield surface reduction approach, with complete stress relaxation assumed above $800 \text{ }^\circ\text{C}$.

The finite element mesh employed approximately 150,000 8-node linear brick elements (C3D8T for thermal analysis and C3D8 for mechanical analysis), with refined zoning near the weld region (1 mm elements) transitioning to coarser meshing (5 mm elements) in distant regions. The model included contact interactions between the workpiece and backing plate, with friction coefficient of 0.3 based on experimental measurements.

3. Uncertainty and Sensitivity Analysis Framework

Accurate prediction of welding-induced distortion using thermo-elasto-plastic finite element analysis is inherently influenced by uncertainties originating from material properties, process parameters, numerical modeling assumptions, and boundary condition representations. In large-scale multi-pass welding applications, such uncertainties may accumulate across successive weld passes and interact with evolving structural stiffness, potentially affecting both the magnitude and spatial distribution of predicted distortion [10]. Therefore, beyond deterministic numerical simulation, it is necessary to establish a systematic framework to evaluate the sensitivity of distortion responses to key input parameters and to assess the robustness of the proposed modeling approach under realistic manufacturing variability.

In the present study, uncertainty sources were categorized into four principal groups: material-related uncertainties, process-related uncertainties, numerical modeling uncertainties, and boundary condition uncertainties [11]. Material-related uncertainties primarily involve temperature-dependent mechanical and thermal properties, including elastic modulus, yield strength, thermal conductivity, specific heat capacity, and coefficient of thermal expansion. These properties exhibit significant scatter at elevated temperatures due to microstructural evolution, phase transformations, and experimental measurement limitations. To reflect realistic variability, temperature-dependent material parameters were treated as uncertain inputs within bounded ranges derived from

experimental characterization and published data [12].

Process-related uncertainties arise from inevitable fluctuations in welding parameters, even when automated welding systems are employed. Key variables considered include arc efficiency, heat input, welding speed, and interpass temperature [13]. Although nominal values of these parameters were tightly controlled during the experimental program, variations may occur in industrial practice due to arc instability, torch positioning tolerance, and environmental conditions. These uncertainties directly influence the transient thermal cycles and, consequently, the development of thermal strains and residual stresses during multi-pass welding [14].

Numerical modeling uncertainties are associated with idealizations and simplifications adopted in the finite element formulation. In this study, such uncertainties include assumptions related to heat source representation, mesh discretization near the weld zone, and constitutive model selection at high temperatures. While the Goldak double-ellipsoidal heat source model has been widely validated, its parameters may not be uniquely defined, leading to potential variability in predicted thermal fields. Similarly, mesh density and element formulation can affect local stress gradients and distortion predictions, particularly in regions with steep temperature gradients.

Boundary condition uncertainties constitute another critical source of variability, especially for large structural components. Fixture stiffness, contact interaction between the workpiece and backing plate, and frictional constraints are often simplified in numerical models but can significantly influence global deformation behavior. To address this issue, boundary conditions were parameterized to allow controlled variation in constraint stiffness and contact properties, enabling evaluation of their influence on distortion outcomes.

A combined sensitivity analysis strategy was adopted to quantify the influence of individual uncertain parameters on welding distortion. First, a local (one-at-a-time) sensitivity analysis was conducted, in which selected input parameters were independently perturbed around their nominal values while all other variables were held constant. This approach enables identification of dominant parameters governing distortion behavior and provides qualitative insight into the directionality of parameter influence. Perturbation ranges were defined based on experimental scatter, equipment specifications, and engineering judgment, ensuring physical realism.

Following the local sensitivity assessment, a global uncertainty propagation approach was implemented for parameters identified as influential. These parameters were assigned statistical distributions, and multiple numerical simulations were performed to propagate input uncertainty to output distortion metrics. The primary response quantities considered include maximum angular distortion, longitudinal bending curvature, and overall out-of-plane displacement after completion of all welding passes. This stochastic framework enables quantitative evaluation of the dispersion of predicted distortion and provides a basis for assessing model robustness under realistic manufacturing variability.

The uncertainty and sensitivity analysis framework described above serves several important functions within the overall research methodology. It provides a structured means of evaluating the reliability of welding distortion predictions, identifies critical parameters that require strict control in industrial applications, and supports informed decision-making in distortion compensation design. Moreover, by integrating uncertainty analysis directly into the numerical modeling workflow, the framework enhances the practical relevance of the proposed approach and establishes a foundation for future extensions toward probabilistic welding simulation and digital twin-based process optimization.

4. Results

The transient thermal analysis successfully captured the complex thermal cycles characteristic of

multi-pass welding. Table 1 shows the comparison between predicted and measured thermal histories at various locations, demonstrating excellent agreement with maximum discrepancies of less than 5% in peak temperature prediction.

Table 1. Thermal Cycle Characteristics Comparison

Location	Peak Temp (°C)	Time Above 800 °C (s)	Cooling Rate 800-500 °C (°C/s)
TC1 (Exp)	1420	4.2	28.5
TC1 (FEA)	1385	4	27.8
TC2 (Exp)	985	2.8	18.2
TC2 (FEA)	1010	2.9	17.5

The thermal model accurately predicted the heat-affected zone (HAZ) extent, with simulated HAZ width of 5.2 mm compared to measured 5.0-5.5 mm in metallographic analysis. The interpass temperature evolution showed similar accuracy, critical for proper modeling of multi-pass effects.

The mechanical analysis successfully predicted both the magnitude and pattern of welding distortion. Table 2 illustrates the characteristic "angular distortion" pattern observed in both experiments and simulations, with maximum displacements occurring at the plate edges.

Table 2. Distortion Magnitude Comparison (mm)

Pass	Experimental Max	FEA Prediction	Error
1	1.25	1.18	5.60%
2	2.85	2.72	4.60%
3	4.15	3.98	4.10%
4	5.6	5.41	3.40%

The progressive accumulation of distortion with each pass was accurately captured, including the nonlinear interaction effects between passes. The model also correctly predicted the transition from primarily angular distortion after the first pass to combined angular and longitudinal bending distortion in later passes.

The residual stress distributions showed characteristic patterns with tensile stresses in the weld region balanced by compressive stresses farther away. Neutron diffraction measurements confirmed the FEA predictions within 15% accuracy.

Table 3. Residual Stress Magnitudes (MPa)

Location	Longitudinal (Exp)	Longitudinal (FEA)	Transverse (Exp)	Transverse (FEA)
Weld	315	298	185	172
HAZ	280	265	150	142
10mm	195	183	95	88
30mm	-120	-110	-65	-58

The systematic evaluation of distortion compensation methods yielded significant findings:

Table 4. Pre-deformation Effectiveness

Pre-bend (mm)	Final Distortion (mm)	Reduction
0	5.6	0%
1	4.25	24%
1.5	3.8	32%
2	3.1	45%
2.5	3.3	41%

The non-monotonic behavior beyond 2.0 mm pre-bend indicates the existence of an optimal pre-

deformation magnitude beyond which additional bending becomes counterproductive.

Table 5. Welding Sequence Comparison

Sequence	Angular Distortion (°)	Longitudinal Curvature (mm/m)
Unidirectional	2.45	12.8
Alternating	1.72	8.4
Symmetrical	1.15	5.9
Staggered	1.85	7.2

The symmetrical sequence proved most effective, reducing angular distortion by 53% compared to conventional unidirectional welding. The staggered sequence, while less effective than symmetrical, offers practical advantages in complex geometries.

5. Discussion

The comprehensive experimental and numerical results provide significant insights into the mechanisms and control of welding distortion in multi-pass scenarios. The excellent agreement between predicted and measured thermal histories (Table 1) validates the heat source modeling approach and confirms that the essential physics of the welding process are properly captured. The slight underprediction of peak temperatures (typically 2-3%) may be attributed to simplifications in the arc plasma modeling and could be improved through more sophisticated heat source formulations.

The distortion prediction accuracy (Table 2) demonstrates the capability of the developed FEA framework to handle the complex interactions in multi-pass welding. The progressive reduction in prediction error with successive passes (from 5.6% to 3.4%) suggests that the model effectively captures the cumulative nature of distortion development. This has important implications for industrial applications where accurate prediction of final distortion is crucial.

The residual stress results (Table 3) reveal several important characteristics. The longitudinal stresses consistently exceed transverse stresses by approximately 60-70%, confirming that distortion is primarily driven by longitudinal shrinkage. The stress magnitudes show good agreement with neutron diffraction measurements, though the slight underprediction (typically 5-10%) may indicate that the model slightly overestimates stress relaxation at high temperatures.

The compensation strategy results (Tables 4-5) provide practical guidance for distortion control. The pre-deformation results demonstrate that optimal compensation requires careful calibration - excessive pre-bending can actually increase final distortion due to nonlinear structural responses. The welding sequence comparison clearly shows the benefits of balanced heat input, with symmetrical welding providing the best results. However, practical implementation must consider accessibility constraints in complex structures.

Several limitations of the current study should be noted. The material model assumes isotropic behavior, while real weldments often exhibit anisotropic properties due to microstructural texture. The phase transformation effects, while included in simplified form, could be more rigorously treated through coupled metallurgical-mechanical modeling. Computational efficiency remains a challenge for full-scale industrial components, suggesting the need for further development of substructuring and adaptive remeshing techniques.

6. Conclusion

This study has successfully established a robust thermo-elasto-plastic finite element analysis framework capable of accurately predicting and effectively mitigating welding distortion in multi-pass welded steel structures. Through a comprehensive experimental program incorporating

advanced measurement techniques such as infrared thermography, laser scanning interferometry, and neutron diffraction, the numerical model has been rigorously validated, demonstrating exceptional prediction accuracy for both thermal cycles and distortion patterns. The results reveal the complex nonlinear accumulation of distortion across successive weld passes, highlighting the importance of considering structural stiffness evolution during multi-pass welding simulations. The characteristic residual stress distributions identified in this study, with longitudinal stresses significantly dominating transverse components in the weld region, provide valuable insights into the fundamental mechanisms driving distortion formation.

The investigation of distortion compensation strategies has yielded practical solutions with significant industrial relevance. Pre-deformation techniques, when properly calibrated, emerge as a highly effective approach, with optimal pre-bend magnitudes achieving substantial distortion reduction. The comparative evaluation of welding sequences clearly demonstrates the advantages of balanced heat input strategies, particularly symmetrical welding, in minimizing angular distortion. These findings collectively advance the field of welding simulation by bridging the gap between theoretical modeling and practical application, offering manufacturers reliable tools for virtual process optimization.

The demonstrated accuracy and reliability of the numerical predictions suggest promising potential for implementing this approach in digital twin applications within heavy fabrication industries. Such implementation could revolutionize traditional manufacturing practices by enabling real-time distortion prediction and compensation during actual production processes. While the current study focuses on relatively simple joint geometries, the fundamental methodology establishes a strong foundation for extension to more complex structural configurations. Future research directions should address the remaining challenges of computational efficiency for full-scale components and incorporate more sophisticated material models to capture anisotropic behavior and detailed phase transformation effects. The insights and methodologies developed through this research contribute significantly to the ongoing advancement of smart manufacturing technologies in welding-intensive industries, promising substantial improvements in production efficiency and product quality.

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