Implications of Three-Dimensional Numerical Simulations of Welding of Large Structures

Distortion and residual stresses of large structures are analyzed using a simulated 3-D model

BY S. B. BROWN AND H. SONG

ABSTRACT. Common and important problems associated with the welding of large structures are induced distortion and residual stresses, both difficult to simulate accurately given the intensive computational demands of such severely nonlinear processes. Current simulations usually either involve small and simple structures such as butt-jointed plates, or emphasize the local weld zones, ignoring the surrounding structure. Such simulations, though not demanding computationally, de-emphasize effects of interactions between the weld zone and the remaining welded structure.

The coupling between a local weld zone and a surrounding structure, however, can have a significant effect on the final state of distortion and residual stresses. This coupling derives from several sources, some of which are complex and nonintuitive. A surrounding structure influences a weld both through the elastic constraint offered by the structure and through the distortion of the structure due to thermal expansion. Additionally, newly deposited weld material couples previously separated parts, thereby changing the nature of the structure as the welding electrode advances. Motion of opposing sides of a weld root opening due to structural asymmetry also complicates a simulation.

This paper examines structure/weld interaction issues during welding processes through two- and three-dimensional simulations of a ring-stiffened cylinder. Such a structure consists of a circular cylinder and a ring, which accentuate the effects of structure/weld interactions because of the high ratio of radius to cross-sectional dimension. Compromises and limitations involved in two-dimensional simulations are also discussed. Specific issues of weld root opening and fixturing are considered.

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Introduction

Distortion and residual stresses resulting from welding represent significant problems in the accurate fabrication of large structures. Although the capability to predict these phenomena would provide substantial assistance to the design and fabrication of welded structures, both welding distortion and induced stresses are difficult to simulate accurately given the intensive computational demands of such severely nonlinear processes. As a result, current simulations usually either involve small and simple structures such as butt-jointed plates, or emphasize the heat-affected zones, ignoring the surrounding structure. Such simulations remain computationally demanding, yet still de-emphasize effects of interactions between the local weld zone and the remaining welded structure.

Finite element simulation of the welding process has been remarkably successful in predicting certain features of welding, particularly temperature distribution, and to a lesser extent, stress, strain and displacement fields. Many of the papers published in the literature use two-dimensional models, focusing attention only to the local zone around the weld pool. A few researchers have performed three-dimensional modeling of welding processes over the last several years, nevertheless, these models are still of small and simple structures such as butt joint-welded plates and pipes.

KEY WORDS

Modeling
3-D Numerical Simulation
Large Structures
Induced Distortion
Residual Stresses
Ring-Stiffened Cylinder
Weld Zone
Root Opening
Elastic Coupling
Fixturing

Karlson and Josefson (Ref. 1) simulated the circumferential welding of a single pass groove weld on a cylinder using a three-dimensional model, and found substantial circumferential variations of residual stresses and displacements, indicating the importance of three-dimensional simulation. Mahin, *et al.* (Ref. 2), reported successful three-dimensional thermal and stress/strain simulations of welding process on plates. His results showed good quantitative agreements between predicted and experimental results on temperature and displacement, and qualitative agreements on stresses. Goldak, *et al.* (Ref. 3), examined the three-dimensional temperature, stress and strain fields associated with the butt joint welding of a bar, and has subsequently considered additional geometries (Ref. 4). Tekriwal, *et al.* (Refs. 5, 6), also simulated the butt joint welding of plates with three-dimensional models, including the deposition of weld metal. Ueda, *et al.*, simulated the multipass welding of plates and correlated his results with experimentally measured three-dimensional residual stress states (Ref. 7).

The results of these simulations cannot be easily extended to the welding of larger, more complex structures due to the interactions between the weld zone and the rest of the structure (Ref. 8). Successful simulation of larger structure welding processes should consider the important factors stated below, which are particularly associated with large structures.

Elastic Coupling

There are two types of elastic coupling: one from the weld behind the traveling electrode, the other from the overall structure. Newly deposited weld ma-

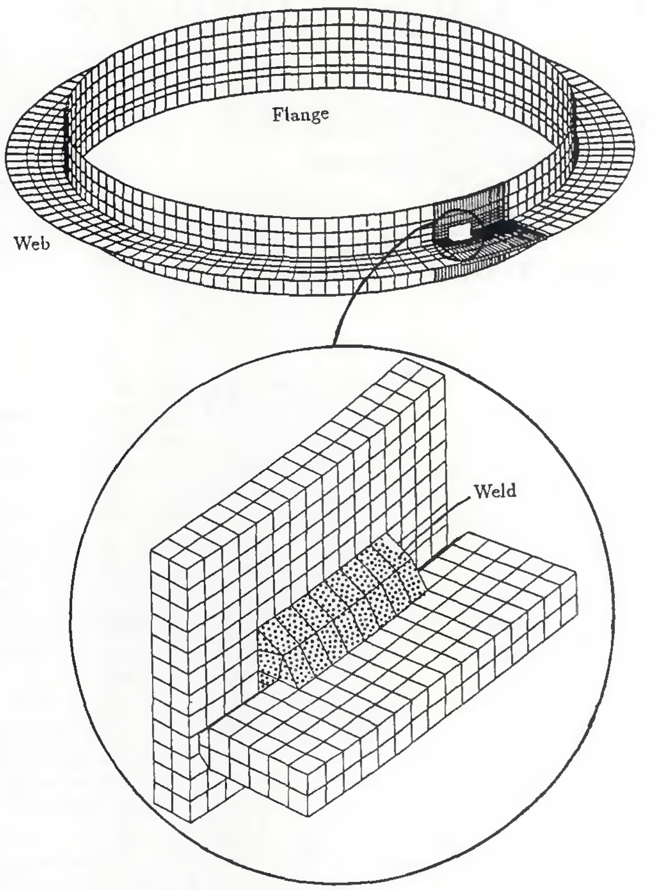


Fig. 1 — *Three-dimensional finite element mesh of a ring-stiffened cylinder. Magnified portion of model is used in full analysis. The remainder of model is reduced to elastic substructures.*

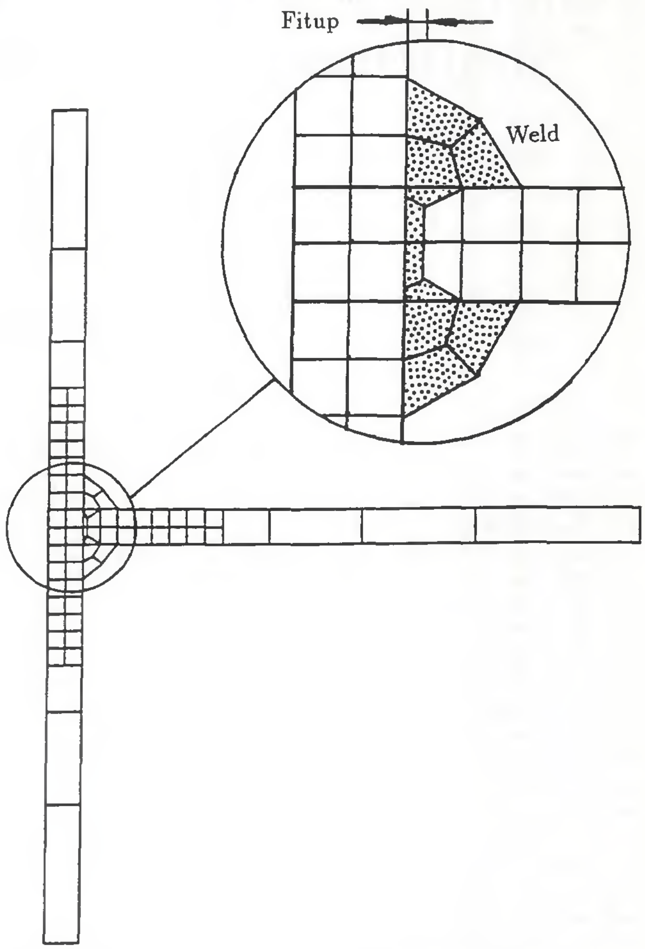


Fig. 2 — *Axisymmetric FE mesh of the ring and cylinder structure. The weld metal is indicated by shaded elements.*

terial couples two previously independent structures, thereby changing the response of the structures to the ensuing deposition of material. Heating and cooling of the overall structure during welding introduce distortions, which cannot be anticipated when examining only the weld zone. Such distortions depend on the geometry of the structure and may have a strong influence on the final residual stresses and state of distortion, within both the weld and the overall structure.

Large Structure Complexity

The geometric complexity of large structures requires commensurately large finite element models, where the weld zone represents only a small portion of the total structure. Conventional FEM simulations typically employ fine meshes along the weld path to capture the high gradients of temperature and stress, even though a particular part of the weld is only briefly nonlinear.

Large Deformations

Given the potentially large coupling between the weld and other parts of a structure, portions of the structure may move dramatically relative to each other, particularly during the initial heating of the first weld pass. These deformations can be so large that coupled simulations of the thermal and mechanical processes are required.

Two important subsets of this structural effect are the design of fixtures and weld root openings where small variations in location or tolerance may produce substantial variations in distortion or residual stresses. Additionally, newly deposited weld material couples previously separated parts, thereby changing the nature of the structure as the welding electrode advances. Motion of opposing sides of a weld joint due to structural asymmetry may also complicate a simulation by requiring a coupled thermomechanical analysis.

This paper examines large structure welding simulations using two-dimensional and three-dimensional models of a circular cylinder and ring structure, and demonstrates that the overall structure plays a more important role than has been appreciated. The need of three-dimensional simulation, and strategies in reducing the size of three-dimensional models are also discussed. The FEM code, ABAQUS, produced by Hibbitt, Karlsson & Sorensen, Inc., was used for all the simulations described in the following sections.

Two-Dimensional Simulation

A three-dimensional finite element model of a ring-stiffened cylinder is shown in Fig. 1. A two-dimensional axisymmetric model of the same ring-stiffened cylinder is shown in Fig. 2. The mesh density in the weld is coarse. An identical model with twice the mesh density was also analyzed, and the differences between the two models were relatively small. Most of the effects discussed in this article do not require precise definition of the local stress and strain gradients in the region of the weld. Indeed, an important consequence of this work is that the local weld zone does not have to be modeled with very fine finite element meshes to capture the larger structural effects of distortion or structural interactions. The results presented herein are therefore not meant to resolve local weld zone gradients; the emphasis is on the larger structural interactions. For that reason, the weld material is assumed to be the same as the base metal. Both thermal and mechanical material properties are given in Tables 1 and 2. All welds presented are assumed to be single pass operations, with the weld material being deposited during one welding procedure.

The two-dimensional model assumes symmetry of the welding process where the weld is performed simultaneously about the circumference of the structure. This assumption is rigorously valid only when the traveling velocity of the electrode is high enough to make the three-dimensional effect negligible. Such electrode velocity rarely, if ever, occurs in actual welding. In spite of this rather severe approximation, features of structure/weld interactions can be investigated in two-dimensional models.

The interaction between the ring and cylinder before any material is deposited is modeled by interface elements, which allow no interaction before contact, and stick together after touching. The use of such interface elements prevent any material overlapping or penetration, while sliding between the contacting surfaces is permitted. The ability to define such interface behavior is accomplished via specific interface element constitutive behavior available within ABAQUS.

Decoupled analyses were performed assuming small energy coupling and small relative motion between the parts in a structure. The stress/strain analysis is based therefore on the temperature field history from a previous, separate heat transfer analysis. Details of both the thermal and mechanical analyses are provided in a separate article (Ref. 8).

In the welding process, the fitup between parts, along with the appropriate fixture style and positions, are usually selected based on individual design experience. Our analysis suggests that the importance of such selections on the final states of residual stress and distortion has been underappreciated. Distortion and residual stresses are highly dependent on the setup of the welding process, *i.e.*, the fitup condition, and the position and style of fixtures. The 2-D FEM analyses described below illustrate the sensitivity of distortion and residual stress to various weld parameters.

Fitup Effect

The relative configuration of components to be welded has a significant effect on the distribution of stresses near the weld. Welded components are frequently asymmetrical, and distort either due to asymmetrical elastic distortion or due to asymmetry of the welding process. If interaction between the components (contact, for example) occurs before deposition of the weld material, the deformation pattern due to such interaction will obviously be different from that when no contact occurs.

The ring-stiffened cylinder considered here illustrates this sensitivity to fitup. The cylinder is more flexible radially than the ring, and when heated, it expands more in the radial direction. If contact occurs during heating, further expansion of the cylinder is confined by the ring. Such incompatibilities result in deformation and stress/strain fields different from the case when no contact occurs. These differences are accentuated after cooling. We present two cases here, with fitup between the ring and cylinder being 3.2 mm (0.125 in.) and 0.4 mm (0.016 in.). There is no contact during heating for the former case, while contact occurs in the latter before the end of heating.

Figure 3 shows the stresses at integration points near the free surface of the weld. Although the Mises equivalent tensile stresses are similar, there is a large difference in individual components of stress. The highest principal stress values for the case of 0.4 -mm fitup is about 50 to 100% higher than those for the case of 3.2 mm of fitup clearance. Mean normal or hydrostatic stresses in the 3.2-mm fitup case are lower than those in the 0.4-mm case. More significantly, the mean normal stresses are either negative or close to zero in the former case but positive in the latter case. The change of signs in the hydrostatic stress will change the state of quality of the weld since a positive hydrostatic stress (negative pressure) favors void nucleation and hot cracking. We emphasize that due to the mesh density used in the weld zone, the stress values presented here should be used only for comparison between fitup conditions. More accurate resolution of the stress gradients within the weld require a finer mesh.

Quality criteria based on crack or void initiation and growth indicate that, a fitup of 3.2 mm appears significantly less susceptible than a fitup of 0.4 mm. The major difference between the two fitups is the interaction in the opening between the cylinder and ring during heating. The fitup case with 0.4-mm opening generates contact between the

Table 1—Thermal Material Constants Used in Finite Element Model

Temperature (°C)	k Thermal Conductivity (W/m —K)	c_p Specific Heat (J/kg —K)	ϵ Emissivity	h Convective Heat Transfer Coeff. (W/m^2 —K)
0	51.9	450	0.2	2.5
75	—	486	—	4.4
100	51.1	—	0.4	5.4
175	—	519	—	—
200	49.0	—	0.45	6.4
225	—	532	—	—
275	—	557	—	—
300	46.1	—	0.475	7.0
325	—	574	—	—
375	—	599	—	—
400	42.7	—	—	—
475	—	662	—	—
500	39.4	—	0.54	7.7
575	—	749	—	—
600	35.6	—	—	—
675	—	846	—	—
700	31.8	—	—	—
725	—	1432	—	—
750	—	—	0.58	8.2
775	—	950	—	—
800	26.0	—	—	—
1000	27.2	—	0.59	8.5
1500	29.7	400	—	—
1540	—	400	—	—
1590	—	847	0.60	9.1
1840	—	847	—	—
1890	—	400	—	—
2050	—	400	—	—
5000	—	400	0.65	10.0

Note: Material constant values are interpolated when values are not given for a temperature.

Table 2—Mechanical Materials Properties Used in Model

Temperature (°C)	σ_y Yield Stress (MPa)	E Young's Modulus (GPa)	σ_y at Strain of 1.0 (MPa)	α Thermal Expansion Coefficient (10^{-6}1/°C)
0	290	200	314	10
100	260	200	349	11
300	200	200	440	12
450	150	150	460	13
550	120	110	410	14
600	110	88	330	14
720	9.8	20	58.8	14
800	9.8	20	58.8	14
1200	—	2	—	15
1550	0.98	0.2	1.0	—
1600	0.0098	0.00002	0.01	—
5000	0.0098	0.00002	0.01	15.5

Note: Material constant values are interpolated when values are not given for a temperature.

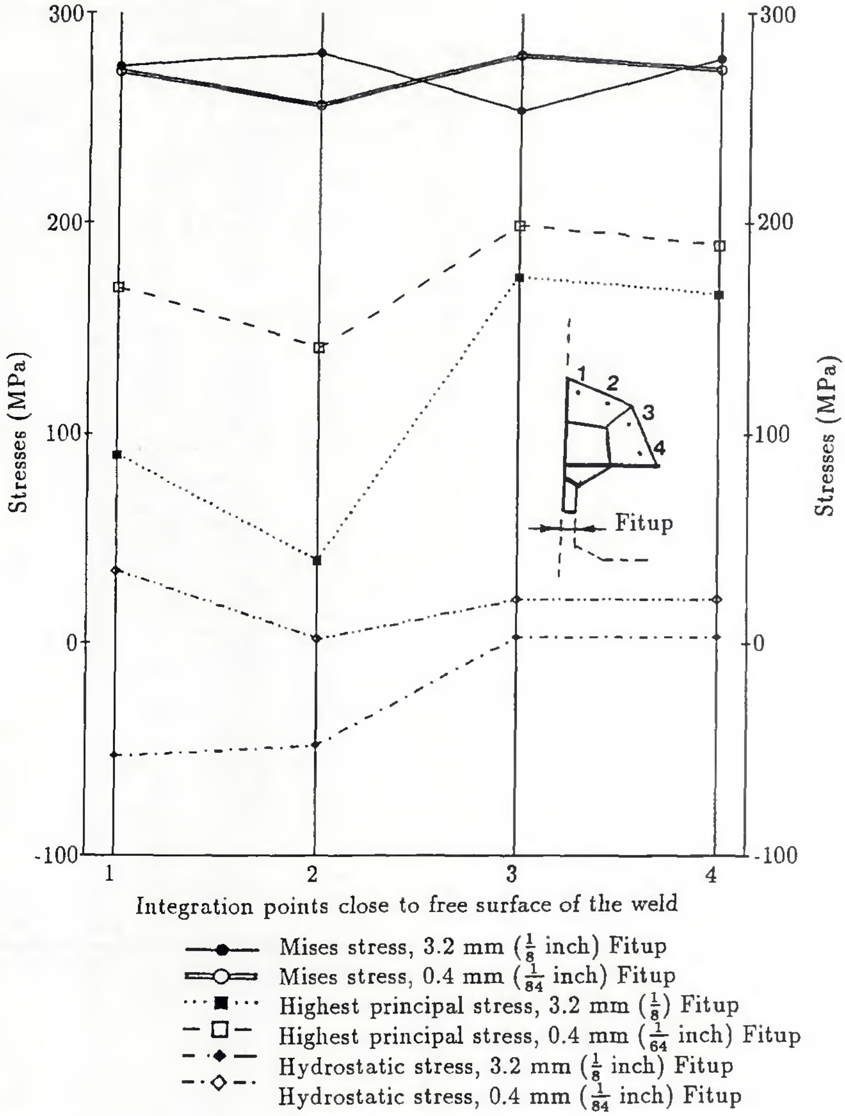
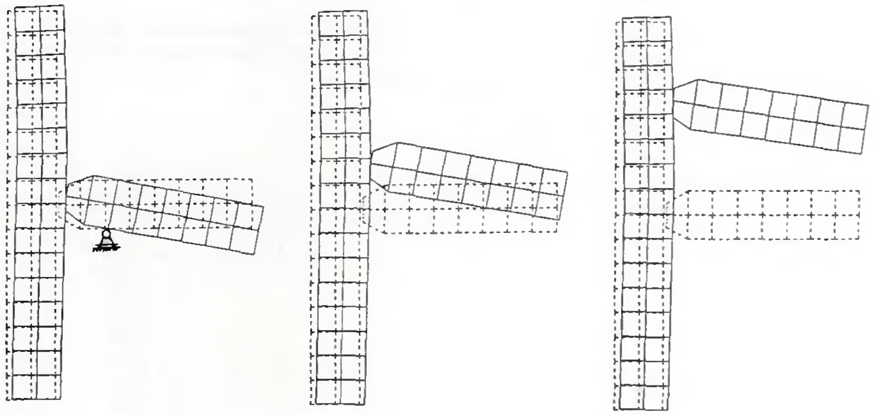


Fig. 3 — Values of residual stresses at integration points near the free surface of the first weld. Two-dimensional model.



(a) Pinned near the weld as indicated (b) Pinned at middle of web (c) Pinned at outside edge of web.

Fig. 4 — Deformed shapes of two-dimensional models at end of heating for different fixture locations. Only a portion of model near the weld region is pictured.

ring and cylinder during heating. Other FEM calculations show that the stress fields are similar in cases with no joint contact. Cases where contact occurs possess commensurately similar stress fields. The critical fitup for the two-dimensional model that determines the occurrence of contact or no contact is in the range of 0.8 mm (0.03 in.) to 1.6 mm (0.062 in.) for this particular structure. The value of critical fitup depends on the heat input, material properties and geometry of the structure. The two-dimensional model additionally does not capture the three-dimensional aspects of this weld joint clearance or fitup response. This response exists in actual structures, and can accentuate the effect since thermal distortion in one portion of the structure will induce changes in joint clearance in other segments of the weld path. Tack welding prior to the actual welding procedure attempts to compensate for this effect, but the consequence will be different distortion patterns.

Fixturing

Although the analysis of fixturing may be considered to be a subset of the larger topic of elastic coupling, we consider here an example of fixturing to illustrate how small variations in the linear elastic portion of a structure can lead to potentially very large variations in deformation and stress response. Fixturing limits the deformation of a structure during welding by the imposition of what can be considered to be very stiff elastic constraints on the structure. The appropriate location of fixtures plays an important role in the final quality of welds, particularly in terms of distortion and residual stresses. Different aspects of the influence of fixtures are considered below.

Pinning of Axial Rigid Body Motion

Since an axisymmetric finite element model requires that at least one node on each independent structure be constrained in the axial direction to prevent rigid body motion, we simulate the positioning of a fixture via the required removal of one node's axial degree of freedom. We fix both the cylinder and the ring in the axial direction (vertical in the figures), but permit radial displacement. After the first welding pass, the two structures are joined, requiring only one constraint.

The fixture or constrained node on the cylinder is placed at its bottom edge, and the fixture on the ring is placed at different positions along its lower surface. Figure 4 illustrates the relative motion of the two structures at the end of the first heating sequence for three positions of the ring fixture: near the ring, at the middle of the ring, and at the outside edge of the ring. Only the portion of the model near the weld is illustrated. Heat is applied in this simulation first to the upper weld.

Clamping Both Sides of the Ring

The model was modified to more accurately simulate a clamping fixture that restricts motion of both sides of the ring. The effect of this greater constraint, imposed again through the elimination of the axial degree of freedom on opposing nodes on the upper and lower ring surfaces, is to reduce rotation of the ring.

Figure 5 illustrates the deformed shape of the cylinder/ring structure after simulating the deposition of one weld pass. Much less distortion results relative to that illustrated in Fig. 4, but greater residual stresses result.

Higher principal residual stresses develop near the free surface of the weld metal. The less constrained fixture geometries, on the other hand, have reduced highest principal stresses near the free surface.

Correlation with a Welded Structure

Instrumented welding of a full circular ring and cylinder structure has been performed, permitting comparison with our two-dimensional analyses. The cylinder and ring in the test specimen were machined to reduce the root opening to less than 1.6 mm. Both the ring and cylinder rested on supports but were otherwise not clamped. Welding was performed using an indexing table, which rotated the structure relative to a fixed welding gun. The weld path traversed a 90-deg arc, or approximately 71.88 cm (28.3 in.), joining one side of the joint. Welding was then stopped due to excessive distortion.

The primary distortion consisted of axial motion of the ring from the center line of the cylinder due to thermal expansion of the ring. Other distortions included tilting of the ring toward the cylinder in the welded region and some loss of axisymmetry of the cylinder.

A special two-dimensional model of the actual welding process was necessary to duplicate the boundary conditions used in the experiment. A rigid surface was defined below the ring to simulate the support without clamping. Soft spring elements were attached to the ring to remove rigid body motions. The remainder of the simulation employed the same boundary conditions and material constants in the previously described analyses with the exception of the accommodation of large deformations. In this case, uncoupled thermal and mechanical analyses were performed twice. The first analysis obtained an estimate of the motion of the ring relative to the cylinder. The second analysis then duplicated this motion by positioning the heat input to the cylinder at the predicted, distorted location, thereby accomplishing a more accurate simulation

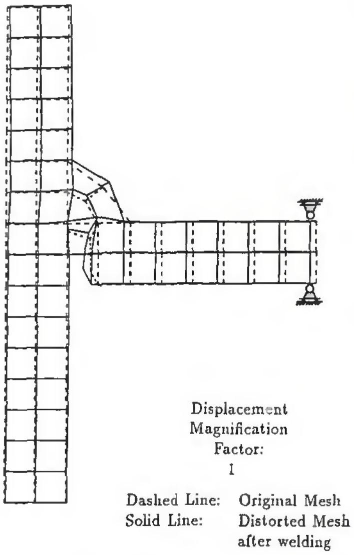
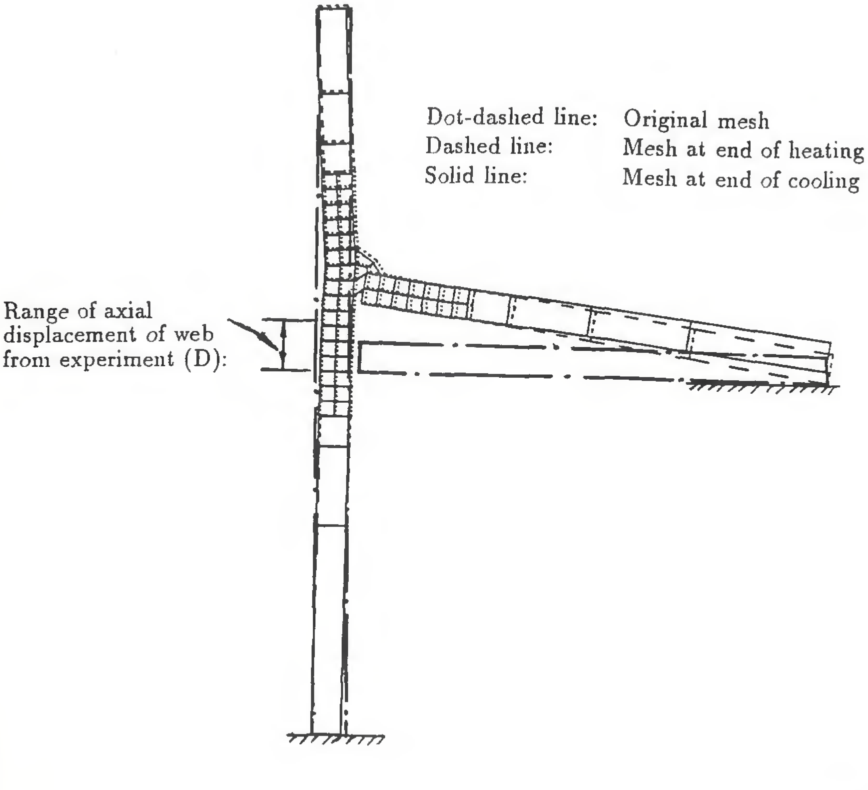


Fig. 5 — Relative distortion of two-dimensional model for clamped-ring fixturing. Distortion represents condition after first weld pass and removal of fixtures. Only portion of model near the weld region is pictured.

of the thermal analysis while still employing an uncoupled analysis.

Figure 6 shows the predicted final shape of the structure superimposed with the range of distortion encountered in the experiment. The model duplicates the primary, axial deformation of the ring that results from the thermoelastic expansion of the elastic portion of the ring. The counterclockwise rotation of the ring toward the cylinder, due to cooling



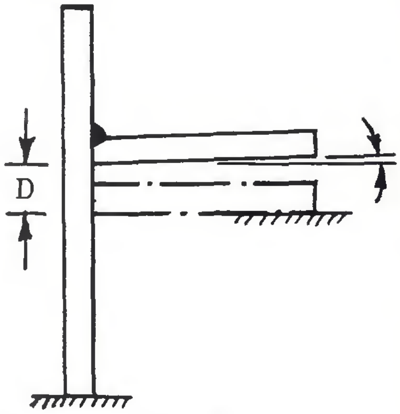


Fig. 6 — Left — Predicted distortion of ring and cylinder using axisymmetric model; Above — schematic drawing of measured distortion after completion of 90-deg weld.

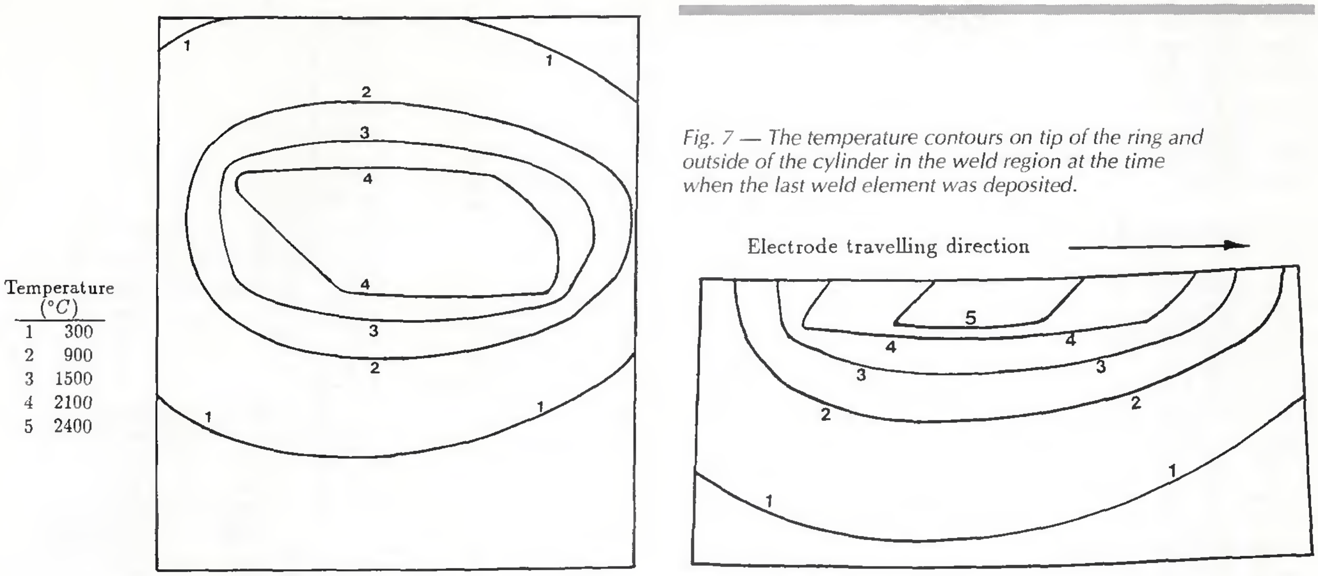


Fig. 7 — The temperature contours on tip of the ring and outside of the cylinder in the weld region at the time when the last weld element was deposited.

of the weld material, is also predicted, although the initial, heat-induced, clockwise rotation of the ring is much larger in the finite element simulation.

The overestimation of the rotation of the ring during the heating segment of the simulation results from two limitations of the finite element analysis. First, friction between the actual ring and cylinder constrains their relative motion. Second, and perhaps more importantly, the real three-dimensional structure provides an out-of-plane elastic constraint absent in the two-dimensional analysis. The implicit, two-dimensional assumption of simultaneous, circumferential heating ignores the character of electrode motion. Material behind and ahead of a moving electrode constrains distortion at the electrode. Accurate simulation of the complete features of welding distortion therefore requires a full three-dimensional analysis.

Three-Dimensional Simulations

Three-dimensional analyses have also been performed on the ring-stiffened cylinder, as shown in Fig. 1. A short weld pass of 25.5 mm (1 in.) (an arc of 3.2 deg) is deposited in the model. The shorter weld reduces the size of the model, permitting analyses on a VAX workstation. A dense mesh is used in the weld region to capture the high local gradients. Decoupled thermal and mechanical analyses are also employed.

Heat Transfer Analysis

Heat transfer during welding is a process of heat absorption, fast heat conduction to the rest of the structure, and eventual heat release through boundary convection and radiation. The heat flux pattern strongly affects the temperature distribution in the local weld zone, and latent heat also plays an important role in the temperature field when phase changes are experienced.

Heat flux from an electrode to a flat plate is commonly assumed to be distributed as a Gaussian function (Ref. 9). A three-dimensional double ellipsoidal heat flux model, proposed by Goldak, *et al.* (Ref. 10), can capture the flux penetration effectively, important for high-energy-intensity welding processes such as laser beam and electron beam welding. The Gaussion function was used here since arc welding involves less flux penetration. The T-shaped joint in the ring-stiffened cylinder requires modification of this distribution to produce reasonable temperature fields. The total power was divided into two components, one to the cylinder and the other to the ring. Only part of a two-dimensional Gaussian function is used for both of these two components. The total power and width of the Gaussian curve are adjusted so that the base material in both the ring and the cylinder were above the liquidus temperature before the deposition of any weld material. Boundary conditions are modeled by nonlinear heat convection and heat emissivity coefficients.

Figure 7 shows the temperature distribution within the local weld region. The plotted areas cover the outside surface of the cylinder and the top surface of the ring. Temperatures outside of the local region remain below 300°C (572°F).

Deformation Analyses

The deformation process is assumed to be rate independent. A thermo-elastic-plastic constitutive model is used in both our two- and three-dimensional analyses where all the material properties are assumed temperature-dependent, including Young's modulus, yield stress, isotropic strain hardening, and linear expansion coefficient.

Three degrees of freedom are associated with each node in the deformation analysis, instead of one in the heat transfer. The computational effort is approximately a cubic function of the total degrees of freedom, which implies that the CPU time needed would be 27 times that needed for heat transfer analysis if the same mesh were used. We therefore use a denser mesh for the local weld zone where high temperature, nonlinearity and high field variable gradients result. The stress-strain analysis also employs a substructure to represent the effect of the structure on the local weld zone. The substructure contains a collection of three-dimensional brick elements and shell elements, and provides elastic, equivalent boundary conditions to the local zone. The total number of degrees of freedom decreases substantially by the substructuring technique, as can be seen in Fig. 1. The size of the local zone is chosen based on the temperature field from the heat transfer analysis, and the substructure is assumed to remain isothermal and elastic during the entire welding process.

Boundary conditions on the three-dimensional structure were applied to the dense mesh near the local weld region, removing rigid body motions. These

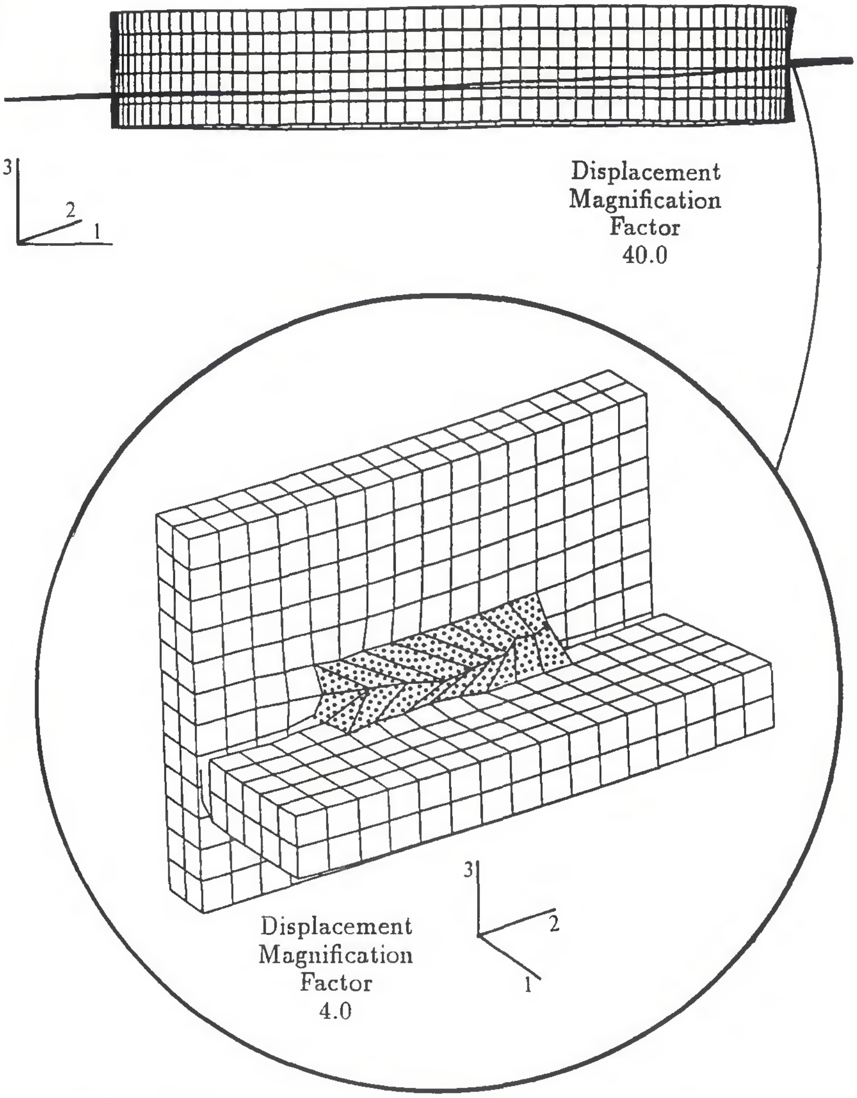


Fig. 8 — The distorted ring-stiffened cylinder after welding of a 25.5-mm weld path along the cylinder and ring joint.

constraints near the weld served to reduce large displacements, which would have invalidated the decoupled thermal/mechanical analyses and changed the location of weld material deposition.

The final distorted shape of the ring-stiffened cylinder is shown in Fig. 8. The axisymmetric distortion in the overall structure results from weld-induced processes occurring in the small region indicated in the magnified inset. All of the structure, other than the inset region, was treated as an elastic substructure during the analysis. Significant interaction therefore results between the local, nonlinear welding process and the rest of the structure.

The modeled distortion follows that obtained from actual experiments. The model predicts a tilting of the ring relative to the structure axis of symmetry. A similar amount of tilting was also observed in the actual welded ring-stiffened cylinder. Although the magnitude of displacement was similar between the model and experiment, different boundary conditions changed the direction of displacement. In the experiment, the ring was constrained from moving downward due to vertical supports; therefore, it displaced upward in the region of the weld. The simulation constrained the region of weld, and the ring accommodated the same deflection by displacing downward.

The asymmetry of the three-dimensional distortion also illustrates the limitations of two-dimensional efforts to model welding distortion and/or residual stresses. Nonlinearities associated with welding and differences in elastic coupling prevent the extrapolation of two-dimensional results to three-dimensional situations.

Conclusions

Results of both the two- and three-dimensional simulations clearly indicate the importance of structure/weld interactions in the welding processes. The two-dimensional simulations illustrate strong sensitivities to relatively small changes in structure, such as joint clearance (fitup) and location of constraints (fixturing).

The three-dimensional analysis indicates both a similar structure/weld coupling and the necessity of performing full three-dimensional simulations if this coupling is to be accurately modeled. Such three-dimensional simulations carry substantial complications, however. First, geometrically complicated weld paths also complicate thermal analyses, since asymmetric or geometrically varying weld joints make it difficult to select appropriate weld energy flux distributions and magnitudes.

Second, three-dimensional analyses remain computationally demanding. The length of the simulated weld is a small fraction of the circumference of the cylinder. The distortion resulting from a larger weld pass would generate a different deformation and residual stress state. The short weld pass actually simulated still required substantial computational time. The analyses presented in this paper were performed on three machines: a VAX workstation (VAXstation 3500), an Apollo DN10000, and a Cray/XMP supercomputer. Analyses of both the three-dimensional thermal and mechanical problems required more than 100 mbyte of disk space and approximated one week of CPU time on the VAX workstation (roughly 6 h on the Cray). Even though we can expect steady reductions in computational time as faster hardware becomes available, additional strategies to reduce computational effort are still required before such analyses become readily available for welding design.

One such strategy involves exploiting the characteristics of welding as a highly nonlinear region translating through a linear (elastic) body. Although substructures were employed in the three-dimensional stress/strain analyses to characterize portions of the structure not affected by either the weld-induced thermal or stress field, a longer weld path may have prevented substantial substructuring. An alternative is to extend the concept of substructures such that the substructure is redefined dynamically as the nonlinear region translates along the structure. The nonlinear region can therefore be modeled precisely using a translating, dense finite element mesh, while the surrounding structure may be captured as an evolving substructure. Such a procedure acts to dramatically reduce the number of degrees of freedom associated with such models.

Another strategy may exploit the quasi-static character of the weld zone when the electrode reaches a constant velocity. Once characterized, it may be possible to superimpose the nonlinear thermal and/or mechanical solution in the local nonlinear region about the electrode without resolving the same problem continuously along the weld path.

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Clarification

The article, "A Study Concerning Intercritical HAZ Microstructure and Toughness in HSLA Steels," which appeared in the December 1991 Research Supplement, did not contain the magnifications of the photomicrographs. Those magnifications, as supplied by author D. P. Fairchild, are as follows: Fig. 6 upper half – 1440X, lower half – 2880X; Fig. 7A–B – 2528X; Fig 8A – 126,400X, 8B – 160,000X; Fig. 9A – 140,000X, 9B – 58,800X; Fig. 10A – 25,600X, 10B – 51,200X; Fig. 11 – 53,500X.