Welding Distortion of a Thin-Plate Panel Structure

The effect of welding sequence on panel distortion is evaluated

BY C. L. TSAI, S. C. PARK AND W. T. CHENG

ABSTRACT. Welding thin-plate panel structures often results in warping of the panels. Several mitigation methods, including preheating and prestressing the plates during assembly, have been investigated and used by some fabricators. This paper studies the distortion mechanisms and the effect of welding sequence on panel distortion. In this study, distortion behaviors, including local plate bending and buckling as well as global girder bending, were investigated using the finite element method. It was found that buckling doesn't occur in structures with a skin-plate thickness of more than 1.6 mm unless the stiffening girder bends excessively. Warping is primarily caused by angular bending of the plate itself. The joint rigidity method (JRM) was found to be effective in determining the optimum welding sequence for minimum panel warping.

Introduction

Warping is a common problem experienced in the welding fabrication of thin-walled panel structures. Several factors that influence distortion control strategy may be categorized into design-related and process-related variables. Significant design-related variables include weld joint details, plate thickness, thickness transition if the joint consists of plates of different thickness, stiffener spacing, number of attachments, corrugated construction, mechanical restraint conditions, assembly sequence and overall construction planning. Important variables are welding process, heat input, travel speed and welding sequence.

In principle, welding distortion control practices for thin-wall panel structures may be classified as follows:

Use design practices that make distortion-free panels easier to produce. These design practices include choosing plates with appropriate thickness, reducing stiffener spacing, using a bevel T-stiffener web, optimizing assembly sequencing, properly applying jigs and fixtures and using the egg-crate construction technique (Ref. 1).

Better control of certain welding variables will eliminate the conditions that promote distortion. This includes reducing fillet weld size and length, including tack welds; using high-speed welding; using a low heat input welding process; using intermittent welds; using a backstep technique; and balancing heat about the plate's neutral axis in butt joint welding.

Incorporate a welding QC program. This program should include personnel training on general quality control practice in order to reduce distortion through awareness, using flatter plates and straighter stiffeners to control the initial conditions, reducing weld size by improving joint fitup and eliminating structurally irrelevant rework.

KEY WORDS

Distortion
Thin Plate
FEM
Finite Element Method
Aluminum Plate
Gas Metal Arc
GMAW
Joint Rigidity
Buckling

The implementation of distortion mitigation techniques during welding counteracts the effects of shrinkage during cooling, which distorts the fabricated structure. These mitigation techniques include controlled preheating, mechanical tensioning, thermal tensioning, pre-bending fillet joints, presetting butt joints and using appropriate heat sinking arrangements. All these mitigation techniques are to balance weld shrinkage forces. Heat sinking also balances welding heat about the neutral axis of the joint.

Some of the aforementioned distortion control methods may increase fabrication costs due to requirements for more energy, increased labor and potentially high-cost capital equipment. Some methods may not be suitable for automated welding or may reduce the assembly speed due to interruption from fixtures or stiffener arrangements. Depending on circumstances of the fabrication environment and type of structures, different distortion control methods may provide more adequate solutions to certain problems than others. Understanding their capability and limitation of all these distortion control methods is critical to a successful welding fabrication project.

Literature Review

Warping of thin-walled panel structures has been investigated with both experimental and numerical methods used by many researchers (Refs. 2–15). In the 1950s, Watanabe and Satoh (Ref. 2) ob-

C. L. TSAI and W. T. CHENG are with The Ohio State University, Columbus, Ohio. S. C. PARK is with Hyundai Industrial Research Institute, Korea.

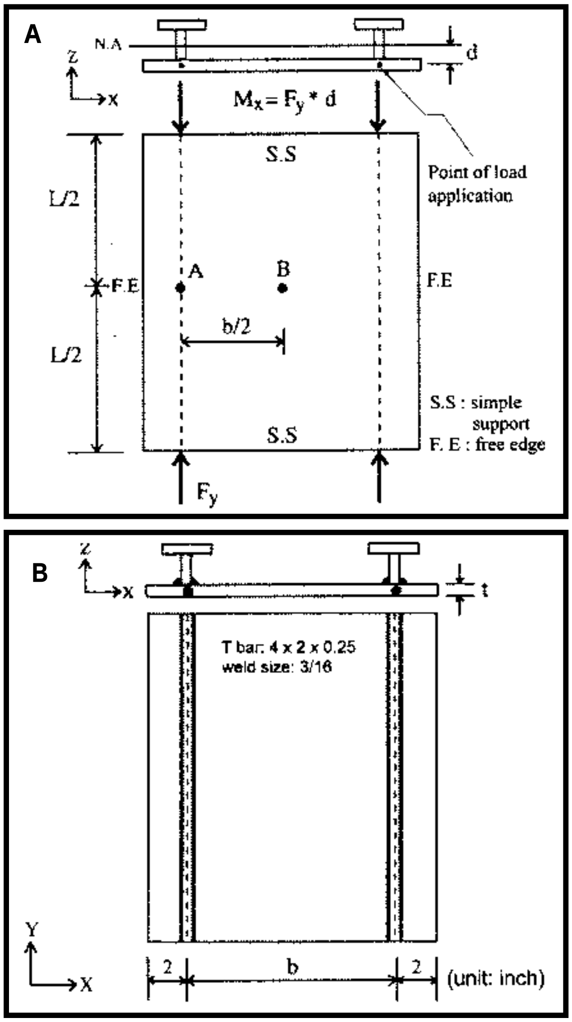

Fig. 1 — Stiffened panel under mechanical and thermal loads for buckling analysis. A — Mechanical model; B — thermal model.

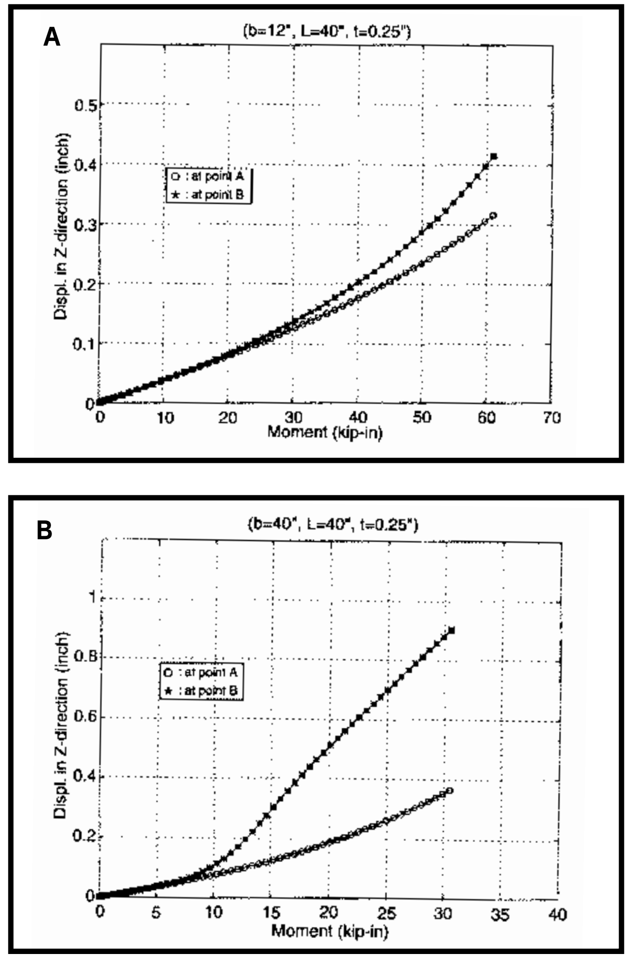

Fig. 2 — Load-displacement curves under mechanical load (width = 30.5 and 101.6 cm, length = 101.6 cm, thickness = 6.4 mm). A — Bending distortion (30.5 cm panel); B — buckling distortion (101.6-cm panel).

served bucking phenomenon in welding of a thin mild steel plate. Masubuchi (Ref. 3) later extended the work and observed a similar phenomenon. Both experimental studies used bead-on-plate coupons with relatively long and narrow strips.

In the 1970s, Taniguchi (Ref. 4) investigated angular bending of fillet-welded aluminum panel structures using an integrated numerical and experimental approach. A relationship was developed between angular changes and plate thickness for various fillet sizes and span widths. Pattee (Ref. 5) conducted experiments to investigate buckling behaviors of aluminum plates with different boundary conditions. His experimental work reached similar conclusions.

In 1976, based on their comprehensive research results, Satoh and Terasaki (Ref. 6) proposed simple formulas that correlate residual stress, angular bending and transverse shrinkage to the welding heat input for different materials, including mild steel, high-strength steel, 9% Ni steel, Al 5083-O and stainless steel.

Terai, *et al.* (Ref. 7), investigated several mitigation methods to minimize welding distortion in thin-plate panels for ship superstructures. These methods included preheating, prestressing and presetting. Angular bending of the panel plates was reduced substantially when these mitigation methods were applied in welding fabrication.

Penso (Ref. 8) conducted numerical and experimental investigations to analyze bending distortion of a mild steel panel structure. An engineering method, commonly referred to as the "inherent shrinkage method," was used to determine the distortion. The numerical results were in good agreement with the experimental results. This work further analyzed the experimental panel structure, investigated by Terai, *et al*. (Ref. 7), and verified the beneficial effect of preheating and prestressing on out-of-plane distortion of the panel.

For many years, researchers have studied the predictive methods for welding-induced distortions using the finite element method (FEM). Models with various complexities were developed. Many complex models contributed to the knowledge of distortion, but might be impractical for industrial applications due to the required computational intensity. Simplified engineering approaches, such as the inherent shrinkage model, have been studied. Daniewicz (Ref. 9) presented a hybrid experimental and numerical approach to predict weld distortion of large offshore structures. Experimentally determined weld shrinkage values were implemented into the structural FEM model to predict the structural rigidity interaction and the final equilibrium state, namely, distortion.

More recently, Michaleris and DeBiccari (Ref. 10) studied the numerical analysis technique to predict welding-induced distortion in large and complex structures. The technique combined two-dimensional welding simulations

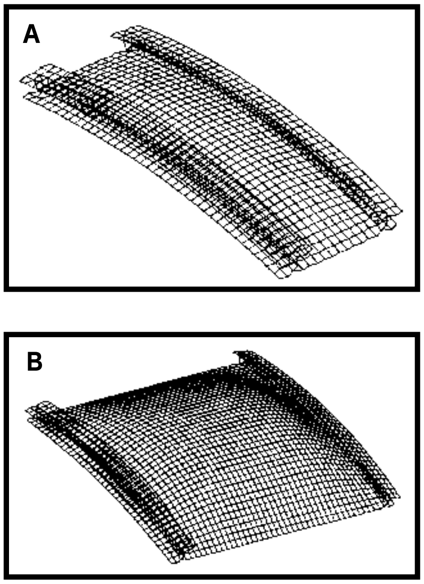

Fig. 3 — Distortion shape due to bending and buckling under mechanical load. A — Bending distortion (30.5-cm panel); B — buckling distortion (101.6-cm panel).

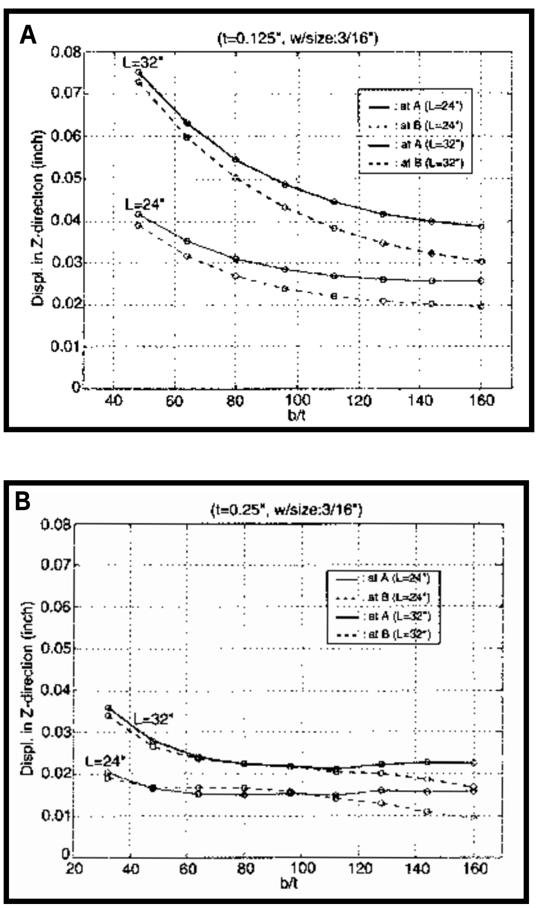

Fig. 4 — Displacement curves under thermal load (width = 101.6 cm, length = 101.6 cm). A — Thickness: 3.2 mm; B — thickness: 6.4 mm.

with three-dimensional structural analyses in a decoupled approach. The numerical technique was used to evaluate welding-induced buckling. Thermal-elastic-plastic welding simulation, along with elastic and eigenvalue finite element analyses was performed to predict both the applied weld load and the structure's critical buckling load. This method was intended to be used by the authors to assess various distortion mitigation techniques such as thermal tensioning to prevent buckling in the thin-walled panel structures.

Several patents on welding distortion mitigation techniques using thermal management during or after welding have been granted. The Japanese patent JP-A-6018292 presents a postweld thermal management process for controlling angular distortion of thick plates. Immediately after completion of welding, cooling the weld zone while heating both sides of the joint creates an appropriate temperature gradient that results in minimum angular distortion. The Soviet patent SU-A-1066765 applies the thermal management process during welding to control welding distortion. Using strong heat sinking of volatile materials to reduce thermal diffusion into the joint, temperature in the base materials adjacent to the weld can be kept low. This reduces shrinkage in the adjacent base materials resulting in less angular distortion.

Another Japanese patent JP-A-5311138 describes a method for controlling angular distortion of panel structures by applying a secondary heating and a mechanical restraining condition, simultaneously, during welding. The tensile stresses induced by the temperature gradient, which results from cooling the weld and heating the base materials adjacent to the weld, tends to compensate the compressive stresses resulting from the welding heat source. The joint is restrained by clamping jigs along both sides of the weld. This method was investigated experimentally by Burak, *et al.* (Ref. 11), with good results for panel plate thickness of 4 mm and above. However, this method was later found ineffective in distortion control for plates less than 4 mm thick by Guan, Guo, *et al.* (Ref. 12).

The Chinese patent No. 87100959 by Guan, *et al.* (Ref. 13), and a joint international patent specification No. PCT/GB88/00136 by Guan, Brown, Guo, *et al.* (Ref. 14), present a similar concept to the Japanese patent JP-A-5311138 but use more active secondary heating and cooling while restraining the transient out-of-plane movement of the joint by appropriate jigging constraints. The joint is clamped along two lines parallel to the weld on each side of the joint. The secondary heating is applied between these two lines and strong cooling is applied underneath the weld. Guan, *et al.,* refers to this mitigation technique as the "low stress nondistortion (LSND)" method. It is reported that buckling distortion in thin-walled (less than 4 mm thickness) structures can be prevented completely (Ref. 12).

Scope of Current Study

With knowledge accumulated from previous studies in welding distortion control, the objective of this paper is to address the basics of the warping mechanisms by studying the thermal and mechanical behaviors of a thin aluminum panel structure using the finite element method. The essential conditions for plate buckling to occur in the panel structures were determined in this study.

To study the effect of welding sequence on panel warping, a method dubbed as the "joint rigidity method" (JRM) was developed to determine the optimum welding sequence for minimum distortion. This paper demonstrates the principles of the JRM method by showing a practical example.

Effect of Global Bending

The panel structures consist of a relatively thin-skin plate reinforced by a series of longitudinal and transverse stiffening members. The commonly used stiffening members are strip plates, Ts and angle shapes. When welding these stiffeners to the plate, the stiffened panels act like a girder due to tack welds made prior to the structural welding. Weld shrinkage may bend the panel depending upon the relative distance between the centroid of welds and the neutral axes of the panel cross sections. Bending of the panel structure shows a global nature to the panel distortion. The skin plate is usually in compression under bending. Buckling of the skin plate under this compressive bending stress is one possible form of panel distortion.

To study the effect of global bending on plate buckling, a simple panel (aluminum 5456-H116) with two T stiffeners attached to the skin plate (Fig. 1) was used for the analysis. Two types of analysis were performed to study the buckling

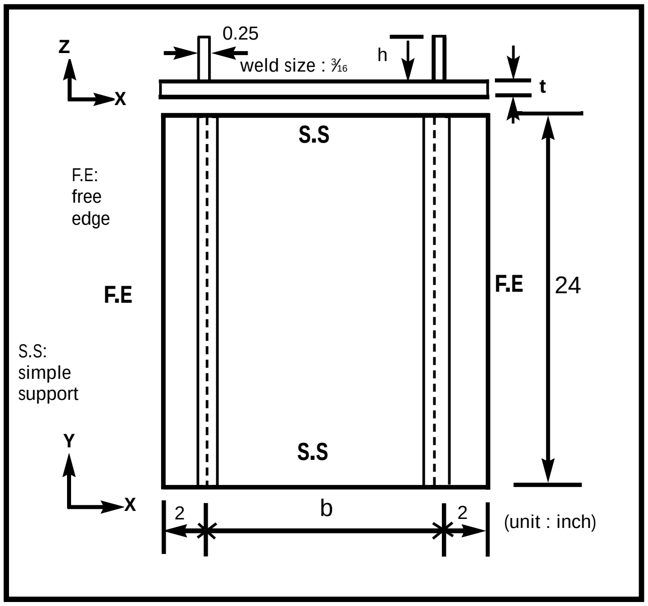

Fig. 5 — Stiffened aluminum panel for residual stress characterization.

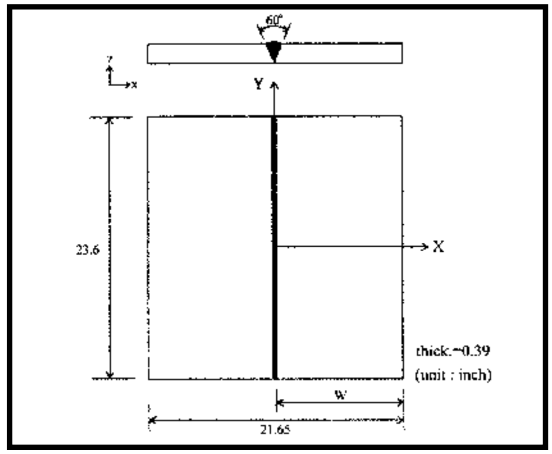

Fig. 6 — Butt joint groove-welded rectangular aluminum plate for residual stress characterization (Ref. 6).

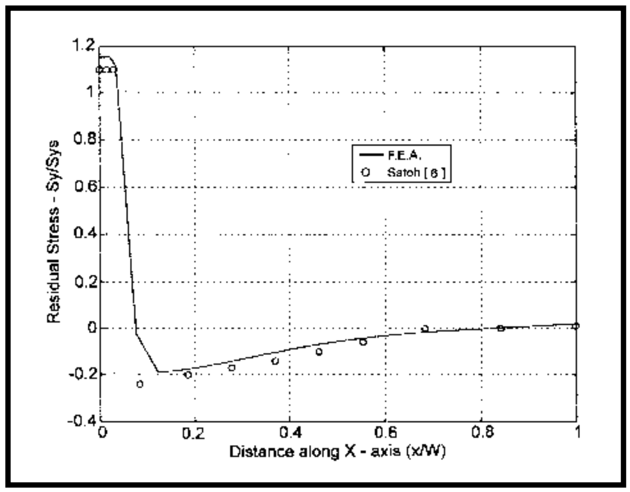

Fig. 7 — Comparison of longitudinal residual stresses determined by the inherent shrinkage method and experimental measurement.

behavior under global bending. Figure 1A shows the panel under the mechanically induced bending moment by pressing the Ts at the joint skin plate intersection. The compressive force was increased incrementally to a design limit when the flange of the Ts reached 60% of the material yield strength. The compressive stress in the skin plate results only from the global bending effect.

During the welding of the assembly, the Ts were first tack welded to the skin plate to build up the initial panel rigidity. Shrinkage of the finished fillet welds would cause the panel to bend in a global nature and the skin plate to warp, which is a local distortion behavior. This weld shrinkage also induces compressive stresses, in addition to the bending-induced stresses, in the skin plate. Figure 1B shows the panel under thermal loading due to shrinkage of welds.

To study the buckling behavior of the skin plate, the mechanically loaded model provides baseline information. The thermally loaded model simulates the real welding assembly of a stiffened panel structure. Monitoring the vertical displacements at the midpoint of the left T stiffener (point A) and the center of the skin plate (point B) as applied moment increases in the mechanical model, or the geometric parameter changes in the thermal model, shows the critical buckling conditions in the skin plate. Figure 2 shows the load-displacement curves for two different panel widths, 30.5 and 101.6 cm. The length of panels is 101.6 cm and the skin thickness is 6.4 mm. The T stiffeners are 101.6 x 50.8 x 6.4 mm.

As shown in Fig. 2, the displacement curves at the stiffener location show the global bending of the panel and those curves at the center of the panel indicate warping of the skin plate due to global bending. For the 30.5-cm-wide panel, the displacement curve shows only the bending phenomenon. However, for the 101.6-cm-wide panel, a large increase in the displacement magnitude is shown when the applied moment reaches approximately 12 kip-in. Figure 3 shows the predicted buckling form of the skin plate under this load. The same figure also shows the displacements of the 30.5-cm-wide panel without buckling. This demonstrates that a skin plate of 6.4 mm could buckle under global bending if the panel is sufficiently wide.

Figure 4 shows the displacement curves at the same two locations with various width-to-thickness ratios (b/t) and length of the panel for two thicknesses, 3.2 and 6.4 mm, when four welds (4.8 mm fillet) are applied to the joints that connect the Ts to the skin plate. The moment force induced by weld shrinkage depends primarily on the welding condition, which is reflected by the fillet size requirement. For a given skin-plate thickness, the shrinkage-induced moment force is independent of panel width. Therefore, the wider the panel, displacements at both locations decrease due to an increase in the structural rigidity of the skin plate. Greater displacements are also shown for a longer panel due to global bending. No buckling is observed in the skin plate.

In this study, panels with smaller skin-plate thicknesses were also analyzed by the finite element method. It was found that weld shrinkage alone would not cause the skin plate to buckle regardless of the plate width unless the plate was thinner than 1.6 mm. However, the skin plate could buckle if the global bending due to welding was large and the panel was wide. This means that only excessive curvature caused by the global bending effect may cause skin-plate buckling in wide panels.

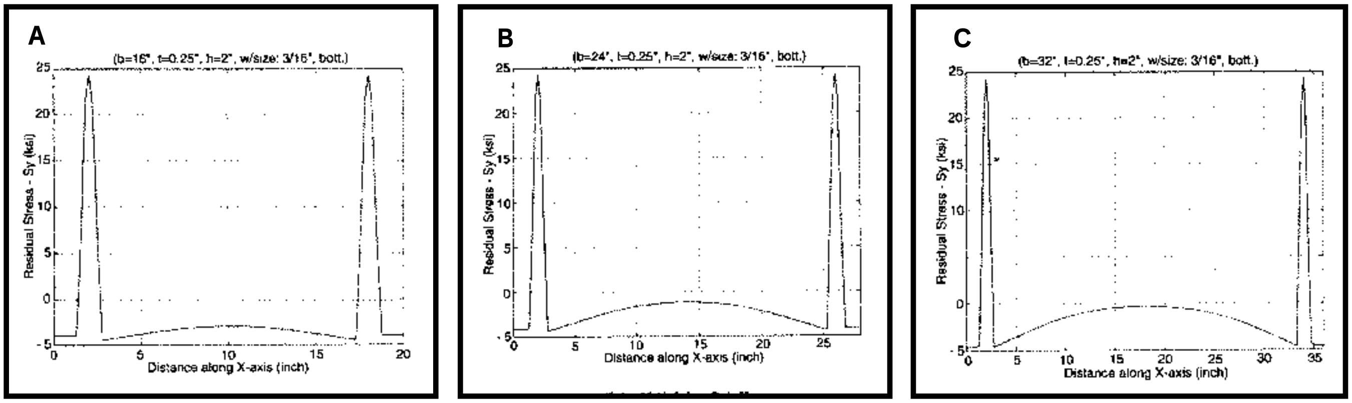

Fig. 8 — Distribution and magnitude of the longitudinal residual stress at the panel's mid-length. A — Width: 40.6 cm; B — width: 61 cm; C — width: 81.3 cm.

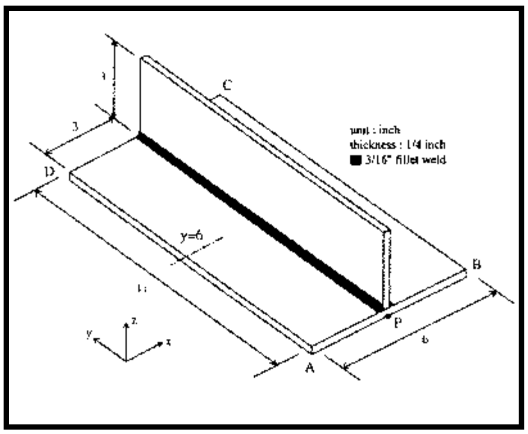

Fig. 9 — Aluminum T-joint specimen for angular distortion characterization.

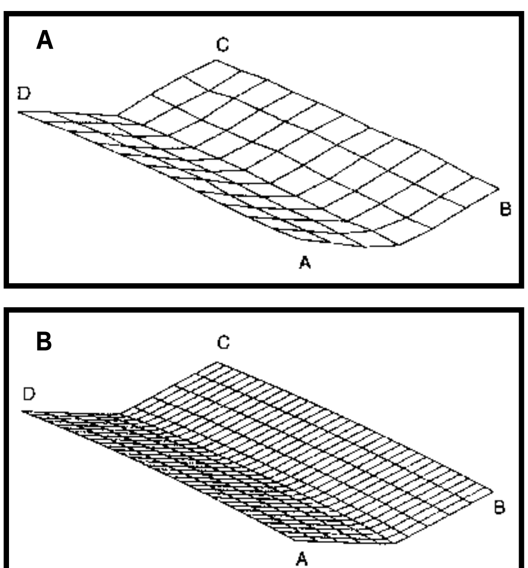

Fig. 10 — Final deformation shape on the back side of the T-flange. A — Measurement grid and measured deformation; B — calculated deformation using the inherent shrinkage method.

Effect of Residual Stresses

Residual stresses in welded structures are unavoidable. High-tensile stress exists in the weld areas. It changes to compression in the areas away from the weld. To investigate residual stress distribution and magnitude for stiffened plates, numerical analysis was performed for the stiffened aluminum Al-5456 plate panel shown in Fig. 5. The stiffened plate panel for numerical analysis was 61 cm long and 6.4 mm thick. Three panel widths, 40.6, 61 and 81.3 cm, were simulated. The inherent shrinkage method was applied to determine the residual stress distributions.

To verify the inherent shrinkage method for residual stress determination, analysis was first performed on an Al-5083 rectangular plate, shown in Fig. 6. Experimental data obtained by Satoh (Ref.6) were referenced for comparison with the numerical results. In Satoh's study, two pieces of plates (60 cm long, 27.5 cm wide and 10 mm thick) were butt joined together with an included angle of 60 deg using the gas metal arc welding process. The welding conditions were 24 V, 230 A and 53.3 cm/min travel speed. Residual stresses were measured using the sectioning method by measuring dimensional changes in the transverse cross sections cut from the weldment. The distribution of the longitudinal residual stresses along the axis transverse to the weld was determined from the relaxed strains. Average values between strains measured from top and bottom surfaces were reported.

In the numerical analysis, the finite element meshes were refined around the weld. The inherent shrinkage strains were incorporated in the analysis by prescribing the initial weld temperature at 649°C (1200°F). As the weld cools down from this initially prescribed temperature, heat diffusion into the base metal takes place and results in volumetric shrinkage upon cooling. These shrinkage strains interact with the plate rigidity. Residual stresses can be predicted at a state of structural equilibrium. Figure 7 shows a comparison of the predicted results with the experimental data. Good agreement in both stress magnitude and distribution was obtained using a calibration factor. This factor was used for the remaining residual stress analyses throughout this study.

For the Al-5456-H116 panel under study, Fig. 8 shows the distribution of the longitudinal residual stresses for three different panel widths. The panel width doesn't change the tensile stresses, but it affects the magnitude of the compressive stresses. As the panel gets wider, the maximum compressive stress becomes smaller. This is due to the fact that the compressive force must be in equilibrium with the tensile force (*i.e.,* areas beneath the tension curve and the compression curve must be equal).

From the point of view of distortion resistance, the moment of inertia of the cross section of the entire panel structure increases as the skin plate width increases. Since the weld shrinkage force remains unchanged, the magnitude of global bending of the panel structure is reduced by the increasing cross-sectional rigidity.

For wider panels, the reducing magnitude in compressive residual stresses and the increasing panel rigidity explain why the weld shrinkage-induced, com-

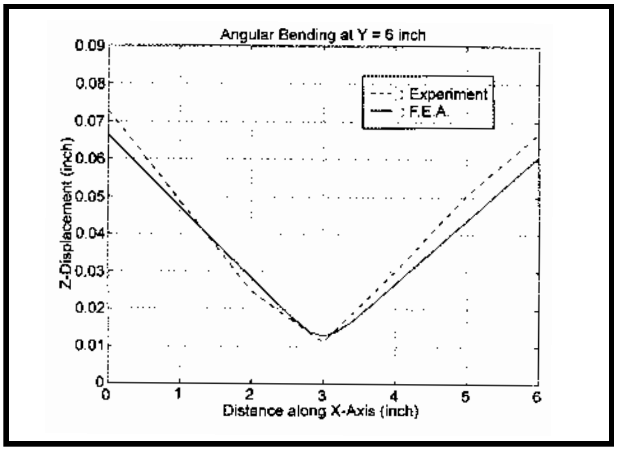

Fig. 11 — Comparison of angular distortion on the back side of the T-flange determined by the inherent shrinkage method and experimental measurement.

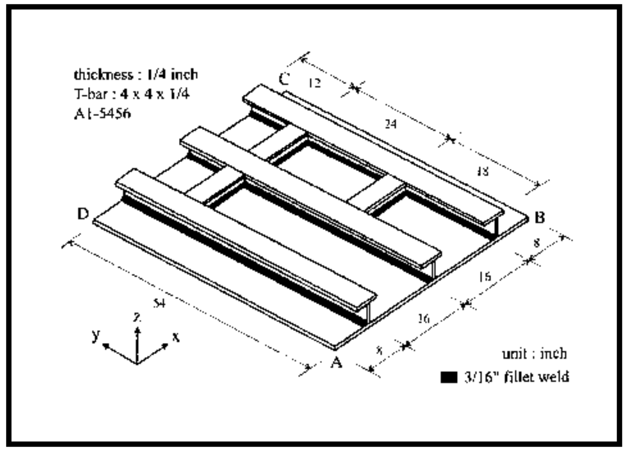

Fig. 12 — Aluminum panel for study on welding sequence effect on angular distortion.

pressive residual stresses may not buckle the skin plate in the stiffened, thin-plate panels, except for the panels with skin plates thinner than 1.6 mm

Angular Distortion of the Skin Plate in an Aluminum Panel

In addition to the global bending effect, welding can cause warping of the skin plate due to weld shrinkage that does not coincide with the plate middle plane and because of the thermal gradients through the plate thickness. This local warping phenomenon is usually referred to as angular distortion, angular bending or out-of-plane distortion.

In this study, the inherent shrinkage method was again used to analyze the angular bending phenomenon. To verify the inherent shrinkage method, numerical analysis and experimental investigation were conducted on an Al-5454-H34 T-joint specimen — Fig. 9. The gas metal arc welding process was used with A5556 welding wire (1.6-mm diameter). The welding conditions were 200–220 A, 24 V, 53.3 cm/min, electrode positive and 1.13 m^3/h argon shielding. As for the welding sequence, the right-hand joint was welded first. After completely cooling back to room temperature, the left-hand joint was welded. After completing both sides of the joint and the joint cooled to room temperature, vertical displacements at various locations in the back side of the flange surface were measured using a coordinate measurement machine (CORDAX RS-30 DCC, Sheffield Measurement System). Figure 10A shows the measured distortion shape.

The calculated final deformation shape of the T-joint plate bottom surface is shown in Fig. 10B. By comparing the displacement variations in a transverse cross section at the joint mid-length (y = 6 in.), Fig. 11 shows good agreement between the predicted results and the measurement data. The same calibration factor determined from the residual stress analysis was used. When the appropriate calibration factor is introduced, the inherent shrinkage method is a good alternative to the moving heat source model for characterizing residual stresses and distortion of weldments.

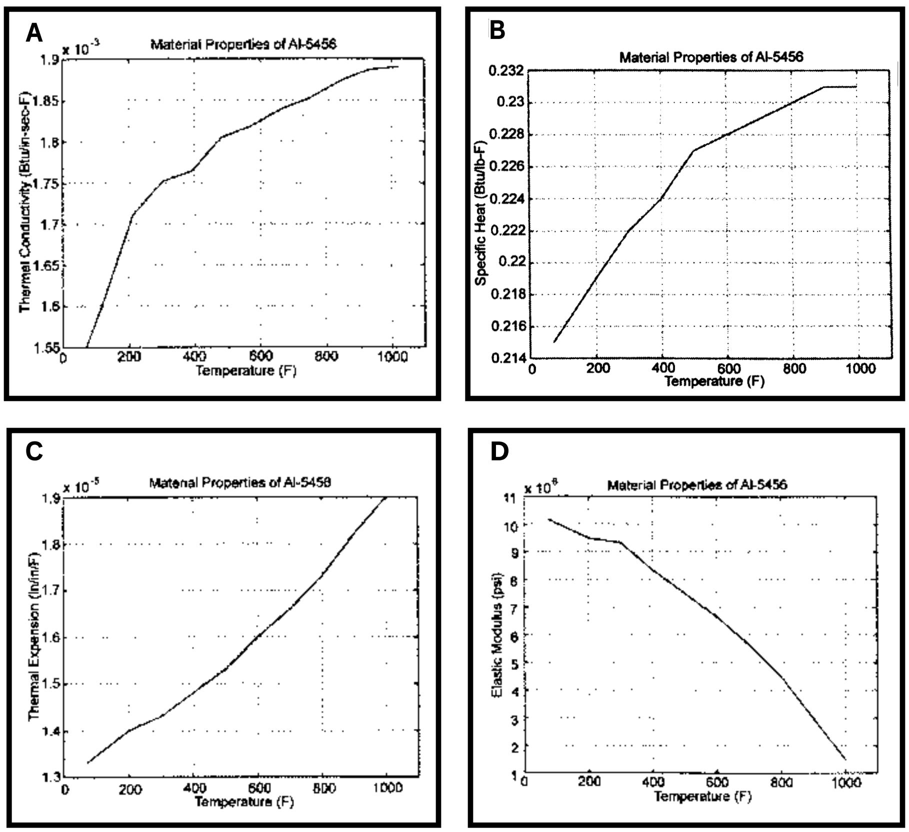

Fig. 13 — Temperature-dependent thermal properties of Al-5456-H116 used in the FEA studies (Refs. 16–19). A — Thermal conductivity; B — specific heat; C — thermal expansion coefficient; D — elastic modulus.

To study the welding sequence effect on angular distortion of an aluminum

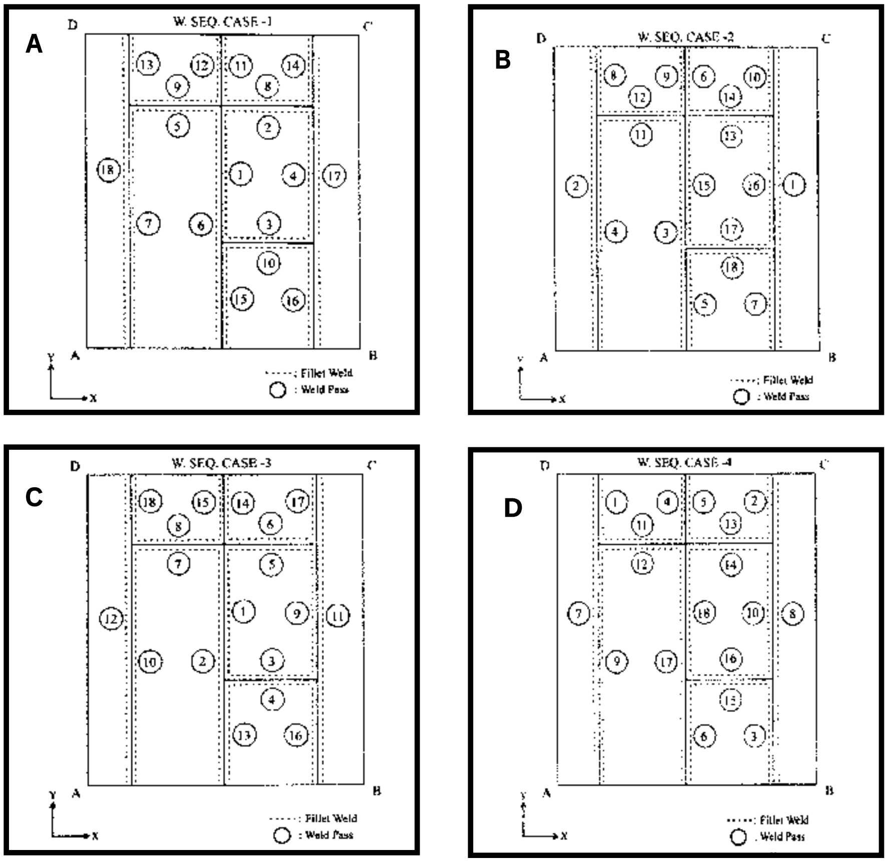

Fig. 14 — Welding sequences for angular distortion analysis of aluminum panel structure. A — Welding sequence No. 1; B — welding sequence No. 2; C — welding sequence No. 3; D — welding sequence No. 4.

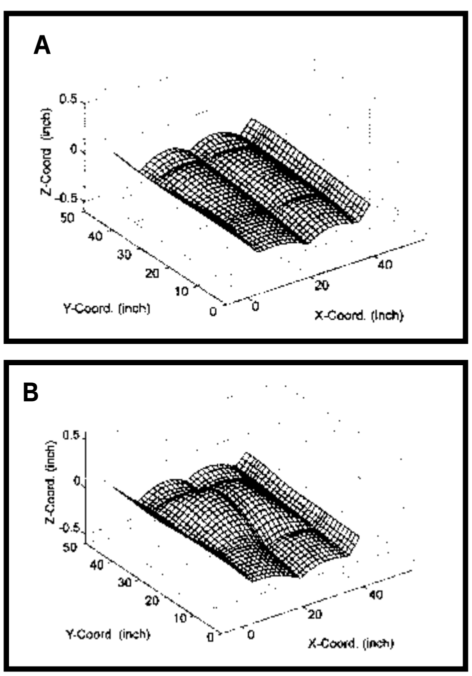

Fig. 15 — Distortion shape resulting from welding sequences No. 2 and No. 4. A— Welding sequence No. 2; B — welding sequence No. 4.

panel, Fig. 12 shows the geometric configuration of the panel structure under investigation. Both experimental and numerical analyses have been conducted. This paper presents only the details of numerical investigations. Some comparisons with the experimental results are also presented in this paper. Details of both numerical and experimental studies can be found in Ref. 15.

The numerical model assumed that the Ts were tack welded to the skin plate before structural welding. This indicates that the initial structural rigidity of the T-stiffeners was built into the panel and provided an initial condition for the finite element analysis. The welding sequence simulation included 1) laying the tack welds along the joints and 2) laying structural welds at various joints with different sequences. The initial temperature condition for each welding pass was room temperature. The analysis was to investigate the effect of welding sequence on angular distortion of the skin plate.

In the finite element analysis, the gas metal arc welding process with 18 weld passes was simulated. The MPC commend in the *ABAQUS* finite element analysis code was used to employ the tack welds. Temperature-dependent material properties of Al-5456, given in Refs. 16–19 and shown in Fig. 13, were used in the finite element analysis. Weight of the panel was also incorporated in the analysis. The panel is point-supported by ball joints at three corner locations (B, C and D in Fig. 12).

Four welding sequences (Fig. 14) were investigated in this study. Sequence No. 1 deposits welds from inner panels outward, while sequence No. 2 lays welds from outer panels inward. Sequences No. 3 and No. 4 are similar sequences to No. 1 and No. 2, respectively, with a consideration of changing structural rigidity of each joint in the panel and the changing distance between the center of the depositing weld and the gravity center of the whole panel structure. Sequence No. 3 searches for the joint with highest restraint to deposit the next weld as the assembly process progresses. Sequence No. 4 lays the next weld at the least restrained joint.

Figure 15 shows the final distortion shape of the panel produced by welding sequences No. 2 and No. 4, respectively. Both the global and local distortions are shown. The welding sequence that deposits the weld at the least restrained joint, sequence No. 4, results in more serious warping in the skin plate.

Figure 16 shows the vertical displacements along four panel cross sections for the four welding sequences investigated. The coordinate origin is at the left, lower corner (point A in Fig. 12). The cross sections at x = 40.6 cm and 81.3 cm bisect the inner panels, respectively, along the middle, longitudinal lines (in the y direction). The cross sections at y = 23.6 cm and 76.2 cm bisect the inner panels transverse to the longitudinal stiffeners. The cusps in the displacement curves indicate the stiffener locations. Angular bending of the skin plate is shown by the warping curvature at each stiffener location.

The global distortion of the panel in all cases shows a downward movement and tilting toward the unsupported corner due to structural weight. The panel warps about the middle, longitudinal stiffener. Sequences No. 2 and No. 4 result in greater angular bending curvatures than the other two sequences. The angular distortions of the skin plate from sequences No. 1 and No. 3 are similar in their magnitude and shape. It appears that the welding sequence that follows the most restrained joint for depositing the next weld during the assembly process results in smaller angular distortion in the skin plate.

Experimental Comparisons

To measure vertical displacements of the deformed panel after each weld pass, a custom-designed, gantry-type measuring system was developed by the International Welding Technology Research Laboratory at National Taiwan University. The measuring system consists of three major components: 1) a frame structure with linear, optical scale tracks and a three-axis movement mechanism, 2) the electronic displacement measuring dial gauge with computer interface and 3) a three-point, ball-joint, panel support table with rollers.

The frame keeps a constant reference and level for the table that supports the panel. It also provides a precision travelling mechanism for locating the measurement points. When the panel is finished with any weld pass off the measurement system, it is placed on the table at three ball-joint supports, which are fixed at three adjustable corner locations. These three-point supports always maintain a reference triangular plane for the panel when the table is jacked up to the reference seatings in the frame. Each time after loading and unloading of the panel, the panel displacements are always measured in the same reference and leveling condition.

Figure 17 shows the comparisons between the predicted distortions and the measured displacements across two longitudinal cross sections (x = 40.6 cm and 81.3 cm) and two transverse cross sections (*i.e.,* y = 23.6 cm and 76.2 cm) for welding sequence No. 4. Good agreement between predicted and measured displacements in all four cross sections is shown.

Optimum Welding Sequence by Joint Rigidity Method

Joint rigidity can be defined as the resistance to angular bending of a T-joint under a unit moment applied to the joint — Fig. 18. For example, a unit moment applied to the middle joint of a panel results in smaller angular rotation of the skin plate at the joint than applying the same unit moment to the T joints at the free edge of the panel. Several general trends in the welding sequence effect were observed from extensive numerical simulations (Ref. 15). The welding sequence that starts with more rigid joints and moves progressively toward less rigid joints would result in less bending in the skin plate. One example of this welding sequence is, first, welding both sides of the middle stiffener in any order, second, welding the inside joint of the edge stiffeners in any order and, finally,

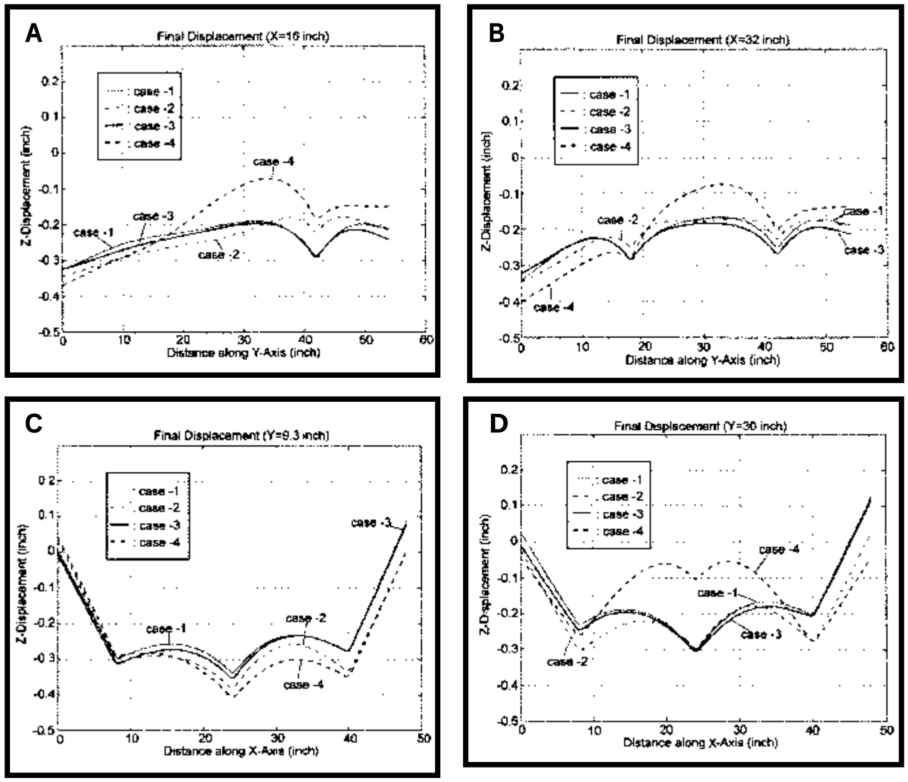

Fig. 16 — Distortion displacements at four cross sections of the panel from four welding sequences. A — At x = 40.6 cm; B — at x = 81.3 cm; C — at y = 23.6 cm; D — at y = 76.2 cm.

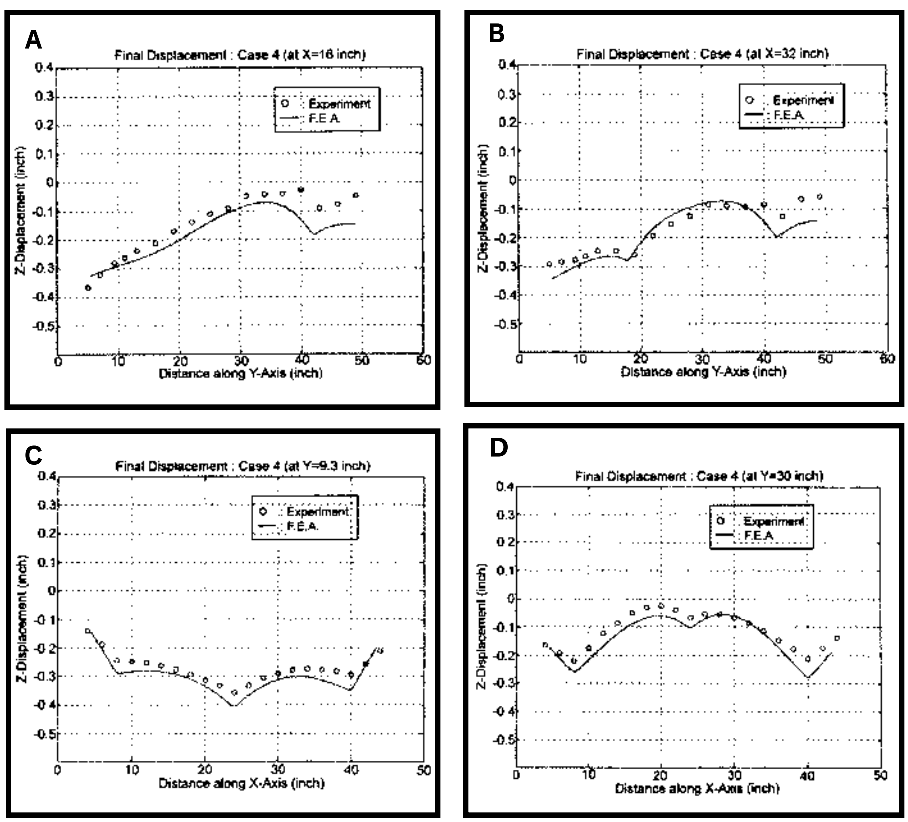

Fig. 17 — Comparisons between predicted and measured distortions along four cross sections in the aluminum panel, welding sequence No. 4. A — At x = 40.6 cm; B — at x = 81.3 cm; C — at y = 23.6 cm; D — at y = 76.2 cm.

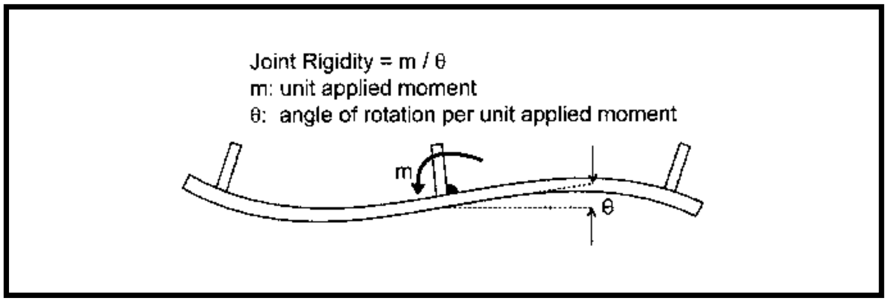

Fig. 18 — Definition of joint rigidity.

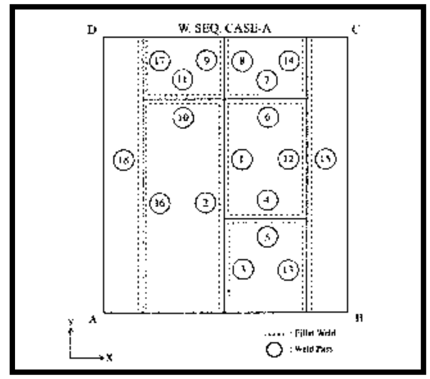

Fig. 19 — Optimum welding sequence (sequence A) determined by JRM.

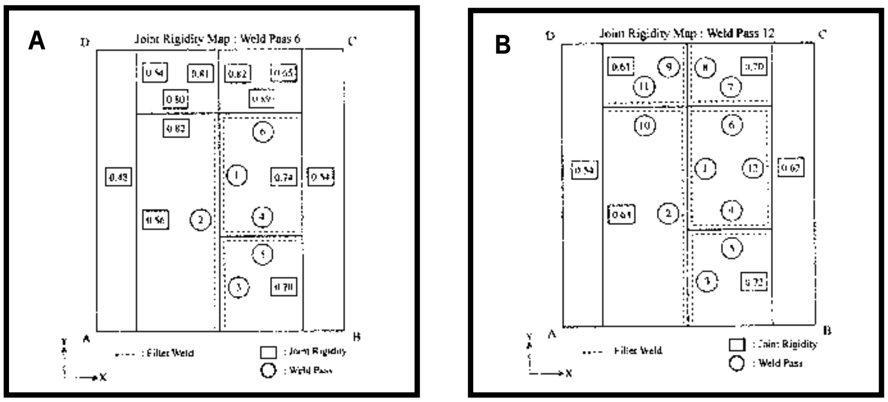

Fig. 20 — Joint rigidity indices at the unwelded joints. A — After 6th weld pass; B — after 12th weld pass.

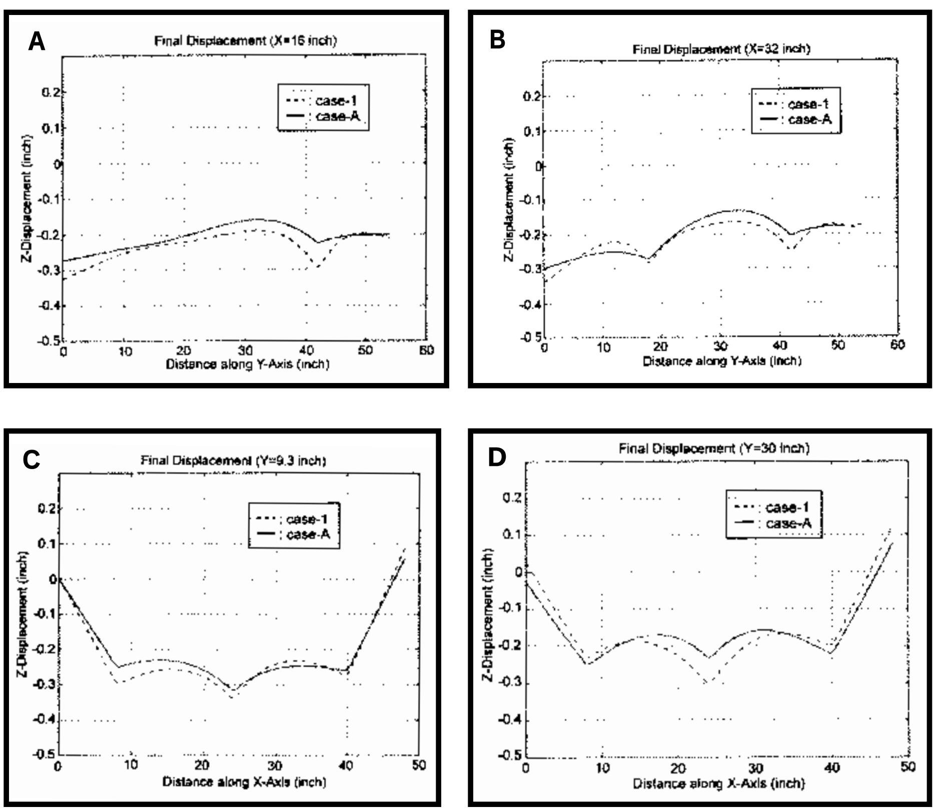

Fig. 21 — Comparison of distortions resulting from welding sequence No. 1 and the optimum welding sequence A. A — At x = 40.6 cm; B — at x = 81.3 cm; C — at y = 23.6 cm; D — at y = 76.2 cm.

welding the outer joints of the edge stiffeners in any order. This chasing-the-rigidity method is referred to as the joint rigidity method (JRM).

Using the concept of JRM, the optimum welding sequence, designated as A (Fig. 19), was determined for the aluminum panel structure under investigation. The determination procedure is summarized as follows:

After completing each weld pass (including tack welds), a distributed unit moment is applied to each joint one at a time to determine the elastic angular rotation at all joints in the panel structure. The magnitude of the calculated joint curvatures is normalized by the maximum value obtained from the panel structure under its prescribed initial conditions (*i.e.,* before structural welding starts with all tack welds completed). This normalized parameter is the rigidity index of each joint. The joint rigidity indices may change after completing each weld pass since the solidified weld becomes an integral part of the panel structure. Therefore, the rigidity index calculations repeat after each welding pass to locate the most rigid joint for laying the next weld.

To illustrate the joint rigidity of each individual joint after completion of any weld pass, Fig. 20A shows the calculated rigidity index of the remaining joints after completing the sixth weld pass. The optimum location for the seventh pass is shown by the highest index number (0.89). After completing the 12th weld pass, the optimum next pass location is shown by the index of 0.72 — Fig. 20B. The rigidity index is the joint stiffness normalized by the maximum value calculated in the panel during the assembly process. The index values vary from 0 to 1.

Figure 21 shows the displacement comparisons between sequence No. 1 and the optimum sequence A. It shows a significant reduction in angular distortion in the skin plate when the optimum welding sequence is used.

Concluding Remarks

This study demonstrated that during the welding assembly of a panel structure a skin plate of normal thickness (*e.g.,* >1.6 mm) can only buckle when the panel bends globally to cause a large curvature in the skin plate. The structural weight and bending of the stiffeners result in the global panel bending. Weld shrinkage in the T joints causes angular distortion in the skin plate.

Locating welds closer to the neutral axes of the panel cross sections can control the global bending and minimize welding distortion of a stiffened panel. Other mitigation methods include using heavier stiffeners to increase the moment of inertia of the cross section or the egg-crate fabrication method to drastically improve the bending resistance of the panel structure.

Using the optimum welding sequence can improve the flatness of the panel and minimize angular distortion in the skin plate. The joint rigidity method is effective in determining the optimum welding sequence for minimum angular distortion in the skin plate of stiffened panel structures.

Acknowledgments

The authors would like to acknowledge China Shipbuilding Corp., Hyundai Heavy Industries, Ltd., and International Welding Technology Research Laboratory for supporting this study.

References

1. Terai, K., and Kurioka, T. 1969. *Future Shipbuilding Methods.* Kawasaki Heavy Industries, Ltd.

2. Watanabe, M., and Satoh, K. 1959. Fundamental study on buckling of thin steel plate due to bead-welding. *J. Japan Weld. Soc.* 27(6): 13–20.

3. Masubuchi, K. 1959. New approach to the problem on residual stress and deformation due to welding. Transportation Technical Research Institute Report 8(12).

4. Taniguchi, C. 1972. Out-of-plane distortion caused by fillet welds in aluminum. Master's thesis. MIT, Cambridge, Mass.

5. Pattee, F. M. 1975. Buckling distortion of thin aluminum plates during welding. Master's thesis. MIT, Cambridge, Mass.

6. Satoh, K., and Terasaki, T. 1976. Effect of welding conditions on residual stress distributions and welding deformation in welded structures materials. *J. Japan Weld. Soc.* 45(1): 42–53.

7. Terai, K., Matsui, S., Kinoshita, T., *et al*. 1976. *Study on Prevention of Welding Deformation in Thin-Skin Plate Structures.* Kawasaki Technical Review 61: 61–66.

8. Penso, J. A. 1992. Development of a PC-based FEM model to predict weld distortion. Master's thesis. The Ohio State University, Columbus, Ohio.

9. Daniewicz, S. R., McAninch, M. D., McFarland, B., and Knoll, D. 1993. Application of distortion control technology during fabrication of large offshore structures. *Proc. of AWS/ORNL International Conference on Modeling and Control of Joining Processes.*

10. Michaleris, P., and DeBiccari, A. 1997. Prediction of welding distortion. *Welding Journal* 76(4): 172-s to 179-s.

11. Burak, *et al.* 1977 and 1979. *Automatic Welding*, 3 and 5.

12. Guan, Q., Leggatt, R. H., and Brown, K. W. 1988. Low stress, non-distortion (LSND) TIG welding of thin-walled structural elements. The Welding Institute Research Report 374. Abington, Cambridge, U.K.

13. Guan, Q., Guo, D., *et al.* 1987. Method and Apparatus for Low Stress and Non-Distortion Welding of Thin-Walled Structural Elements. Chinese Patent No. 87100959.

14. Guan, Q., Brown, K. W., Guo, D., *et al*. 1988. International patent specification No. PCT/GB88/00136.

15. Park, S. C. 1988. Distortion mechanisms and control methodology for welding thin-plate panel structures. Ph.D dissertation, The Ohio State University, Columbus, Ohio.

16. Thermophysical Properties Research Center. 1973. Properties of aluminum and aluminum alloys. TPRC Report 21. Purdue University.

17. *Metals Handbook*, Vol. 2, 10th edition. 1990. ASM International, Materials Park, Ohio.

18. *CINDAS*, *Structural Alloys Handbook*. 1994. Purdue University.

19. Voorhees, H. R., and Freeman, J. W. 1960. Report on the elevated temperature properties of aluminum and magnesium alloys, ASTM STP no. 291.