Finite Element Analysis of Thermal Tensioning Techniques Mitigating Weld Buckling Distortion

Sensitivity studies indicate new method could eliminate residual stress and structural buckling in welding processes

ABSTRACT. Weld distortion in thin section structures usually is caused by buckling due to residual stresses. In addition to conventional techniques, including reduction of weld size and design modifications, new techniques such as thermal tensioning can be used to minimize welding-induced buckling. This paper presents a finite element analysis model of the thermal tensioning technique. A series of finite element simulations and corresponding experiments are performed to demonstrate the technique. Thermocouple measurements are performed to verify the transient thermal analyses and blind hole drilling measurements are used to verify the predicted residual stresses. Implementing the thermal tensioning conditions determined by the finite element simulations, the residual stresses of large size and high heat input welds are reduced below the critical buckling level.

Introduction

The use of welding in fabricating large structures offers advantages over mechanical joining methods in flexibility of design, weight and cost savings, and enhanced structural performance. However, in large structures made of relatively thin section components, welding can cause buckling that can lead to loss of dimensional control and structural integrity. Reducing the welding heat input and modifying the structural configuration reduces the occurrence of buckling (Refs. 1–3). Design considerations, however, can impose limits on such modifications. In this case, new manufacturing techniques, such as thermal tensioning, can be used to eliminate buckling due to welding.

The thermal tensioning technique for controlling welding residual stress and distortion, as discussed by Russian authors Burak, et al. (Refs. 4, 5), involves generating tensile stress at the weld zone, prior to and during welding, by imposing a preset temperature gradient. A combination of cooling and heating elements is used to this end. The authors suggest the use of a variational approach to determine the preheated temperature field approximately. They also suggest the heating elements be brought as close as possible to the cooling strip.

Chinese Patent No. 87100959 and International Patent No. PCT/GB88/00136 describe in detail the relevant apparatus for using the thermal tensioning technique to eliminate buckling distortions for butt joint welding of thin plates. For a specified joint geometry, materials and welding heat input, many repeated experiments are conducted to achieve the required pre-tensioning conditions. The excessive high cost associated with the experimental investigation renders this trial-and-error approach impractical.

With the development of high-speed computers and the progress in welding process simulations, the implementation of the thermal tensioning technique can be greatly improved by determining the required level of pre-tension and the means to achieve it.

Over the past 15 years, the finite element method has been used to predict distortion and residual stress due to welding. Simulations of welding processes involve performing thermomechanical finite element analyses of the weld zone. Transient nonlinear thermal analyses and small deformation quasi-static elastoplastic analyses are performed by many investigators (Refs. 6–8). Following such analyses, Michaleris and DeBiccari (Ref. 9) demonstrated that welding residual stress can be accurately predicted and consequently expressed as buckling load on a structure.

In this paper, finite element welding simulations are performed to investigate
Welding Residual Stress

The computational approach is presented as applied to stiffened panels used in shipbuilding. Figure 1 illustrates a typical geometry configuration of the analyses presented in this study and the corresponding finite element model, consisting of 9534 nodes and 3082 elements. To simulate the heat loss to the support during welding, a support plate connected to the panel with gap conductivity elements is added to the model. The plate, stiffener web and flange are assumed to be of a uniform 3/8 in. (4.76 mm) thickness. The plate width is set to 24 in. (0.6 m), representing a typical stiffener spacing for shipbuilding. In experimental tests, the panel length is set to 48 in. (1.2 m) such that end-effects are minimized. Both panel and stiffener are made of AH36 steel (0.18% C, 0.9-1.6% Mn, 0.1-0.5% Si). A baseline analysis and corresponding experiments are performed without thermal tensioning using flux cored arc welding with heat inputs of 7.8 and 18.2 kJ/in. (307 and 717 J/m) per torch, which corresponds to weld leg sizes of 3/8 in. (3.175 mm) and 1/2 in. (4.76 mm), respectively.

Welding Simulation

Two-dimensional thermomechanical welding simulations are performed to determine the residual stresses. The welding simulations follow the work of previous investigators (Refs. 6, 7). The computational procedure, material properties and boundary conditions are presented in detail in Ref. 9. Two-dimensional nonlinear transient heat flow finite element analyses are performed in the plane perpendicular to the welding direction. The heat generated by the welding process is modeled with a double ellipsoid heat source model for each fillet (Ref. 6), using a body heat flux distribution moving along with the torch. Radiation and convection boundary conditions are assigned to all free surfaces. Generalized plane strain quasi-static finite element analyses follow the heat transfer analyses and use the computed temperature history as input. Elastic-plastic material response is assumed with kinematic work hardening. Solid-state phase transformations are not considered in this study.

Development of Welding Residual Stress

Residual stresses are formed by the plastic deformations during the thermal cycle of welding (Ref. 2). Figure 2 illustrates the computed temperature and longitudinal stress profile at the bottom surface of the panel, at times before, during (2.28 s after the first torch reaches the analysis plane), and after welding, for fillet welds of 18.2 kJ/in. heat input.

Before welding, the structure is assumed to be 1) at room temperature and 2) stress free — Fig. 2. During welding, the high temperature at the weld region causes compressive stress due to thermal expansion. This compressive stress exceeds the yield stress at the corresponding temperature. Away from the weld, the stress is tensile in equilibrium with the compressive stress over the analysis plane. The yield strength of AH36 steel is 50 ksi (345 MPa) at room temperature, and it gradually drops with increasing temperature (Ref. 9). Therefore, during welding, the compressive stress at the weld centerline is low as the material has plastified, and the yield stress is low due to local high temperatures.

At locations adjacent to the weld centerline, the temperature drops and the yield stress increases. Consequently, the magnitude of the compressive stress increases. At the completion of the welding heat cycle, the temperature drops to room temperature. The stress reverses sign from compressive to tensile at the locations that have plastified during welding, and a band of residual stress at the material yield level (at room temperature) is developed in the weld region. Away from the weld, the residual stress is compressive. It should be noted here that the uniform level compression built over the plate away from the weld is a result of the generalized plane strain condition, which assumes that a linear distribution of total strain is developed over the entire cross section.

The temperature and stress history of the welds made with 7.8 kJ/in. heat input is similar to that made with 18.2 kJ/in. heat input. However, with lower heat input, the size of the region that plastifies during the welding heat cycle is smaller, as shown in Fig. 3.

To confirm the finite element computations, the residual stress is measured at the bottom surface of the plate by using the blind hole drilling method — Figs. 2, 3. The objective of the measurement is to verify the size of the tension band, as it is well known that the residual stress at the weld zone is of yield magnitude (Refs. 2, 3). Considering the limitations of the
blind hole drilling technique, namely averaging of residual stresses over an 8-mm-diameter circle and a ± 5 ksi (± 35 MPa) error, excellent correlation between measured and computed values is obtained.

The compressive load resulting from the compressive residual stress at the free spans of the plate can cause buckling if it exceeds the critical buckling load of the specific panel size (Refs. 3, 9). At the selected panel size and thickness for this work, the 18.2 kJ/in. heat input welds cause buckling, and the 7.8 kJ/in. do not — Fig. 4. However, as it has been demonstrated before (Ref. 3), even welds with 7.8 kJ/in. heat input will cause buckling on large panels typically used in ship production.

A welding heat input of 7.8 kJ/in. is close to the minimum that can be consistently manufactured with flux cored arc welding. Moreover, design considerations can impose a minimum weld leg size and therefore a minimum heat input requirement. Consequently, even welds with minimum heat input still will cause buckling on large size panels.

### Thermal Tensioning

To reduce the welding residual stress, and therefore eliminate welding buckling distortion, many techniques have been investigated by different authors (Refs. 2, 10). Among the list of the proactive techniques, thermal tensioning appears to be the most effective when limits on welding heat input are present.

In this work, to investigate the effect of thermal tensioning, the high heat input welding conditions (18.2 kJ/in.) are selected, such that a reduction of residual stress can be visually demonstrated on relatively small panels (24 x 48-in./0.6 x 1.2 m) by the elimination of buckling. Otherwise, using low heat input welds would require an experimental program on large size panels, which is not cost effective. Nevertheless, the same methodology can be used for any size panels.

Figure 5 illustrates the thermal tensioning device employed in this study. Prior to welding, a temperature differential is developed by cooling the weld region with impingement tap water below the plate, and heating by the plate with resistive heating blankets. Both cooling and heating are applied over the entire length of the plate. When the desired temperature differential is achieved, the heating blankets are turned off and welding commences. The water cooling is turned off 30 min after the completion of welding.

### FEA Simulation of Welding under Thermal Tensioning

Welding under thermal tensioning is modeled by two-dimensional thermo-mechanical analyses. A steady state analysis initially is performed to simulate the thermal pre-tensioning conditions. The welding simulation follows using the thermal pre-tensioning as initial condition.

The resistive heating of the thermal blanket is modeled using a one-dimensional Gaussian distribution heat source. More specifically, the heat flux equation for the resistive heating is as follows:

\[
q(x) = \frac{2 \pi Vt}{\pi} \left[ \frac{3}{\pi} e^{-\frac{3x^2}{\sigma^2}} \right]
\]
where, \(x\) is a local coordinate at the center of the heater, \(d\) and \(L\) are the width and length, respectively, \(V\) and \(I\) are the voltage and current of the heater, and \(\eta\) is the heater's efficiency. The equation is derived by setting the integral of the heat flux over the heater surface equal to the power of the heater (Ref. 6).

The effect of cooling water is modeled by a convection boundary condition. The temperature of the tap water is measured to be 53.96°F (12.2°C). The convection coefficient of the cooling water, and the heating efficiency of the resistive thermal blanket are determined by correlating computed and measured temperatures at the top surface of the plate at weld centerline (Fig. 5, Point A) and heater centerline (Fig. 5, Point B) locations. The measured temperatures at these locations just prior to initiation of welding are 71.96°F (22.2°C) and 374.72°F (190.4°C), respectively. A convection coefficient of \(1.39 \times 10^3\) W/m²°C and a heating efficiency of 0.33 result in a comparison between the calculated temperature history vs. the measured temperature history for points A and B in Fig. 5. Good correlations are obtained in general, with the temperature at the weld region being slightly overpredicted. This is attributed to the two-dimensional effect of the current model in which the heat flow in the welding direction is not considered.

Figure 7 illustrates the computed temperature and longitudinal stress at the bottom surface of the panel for fillet welds of 18.2 kJ/in, heat input under thermal tensioning. The figure presents the temperature and corresponding stress states at times before, during (0.65 s after the first torch reaches the analysis plane), and after welding. Before welding, the temperature at the weld region is approximately that of the tap water. The temperature increases at the heating blanket locations and gradually drops at the plate edges. This temperature distribution generates a pre-tensioning at the weld region of approximately 40 ksi (276 MPa).

During welding, the temperature at the weld region increases. However, the peak temperature is lower compared to that when cooling is not used. During welding, the longitudinal stress is compressive at the weld centerline and tensile adjacent to it. As the peak temperature is reduced by the cooling water, the yield strength increases and more load is sustained elastically. Moreover, a part of the compressive load generated by the welding heat is balanced by the pre-tension, thus plastic deformations are further reduced. At the completion of welding, the temperature drops to room temperature and a very small band at the weld region is under tension. The magnitude of the residual stress is approximately 20 ksi (139 MPa), which is significantly reduced from that of 50 ksi (345 MPa) when thermal tensioning is not implemented.

Figure 7 also demonstrates the correlation of the computed residual stress distribution and several blind hole drilling measurements. Considering that the objective of the measurements is to identify the size and magnitude of the tensile residual stress band, excellent agreement is obtained. However, blind hole drilling reveals high compression at the plate edge. Taking into account that the stress distribution measured by the blind hole drilling is not in equilibrium, the compressive stress measured at the plate edge is attributed to possibly a measurement error. Figure 8 illustrates the measured out-of-plane distortion of a panel welded with 18.2 kJ/in. heat input and thermal tensioning. It is apparent that buckling distortion is eliminated and only angular distortion remains. Angular distortion can be minimized by applying an elastic prebending before and during welding (Ref. 10). Figure 8 illustrates a panel welded with thermal tensioning and
Implementation Sensitivity

In this section, variations of the thermal tensioning technique are investigated to determine the stability of the technique. The same weld joint, heat input and panel size are used to compare with the results of the previous section. Initially, having only the water cooling without the heating blankets is investigated. We refer to this condition as quenching only. Next, results of temperature differentials of 230°F (110°C) and 518°F (270°C) between the cooled and heated locations are presented. Finally, the effect of continued water cooling after the completion of welding is discussed.

Quenching Only

Quenching only refers to the case where the thermal blanket is not used and cooling water is running during welding. In the finite element analysis, quenching is simulated by setting the efficiency coefficient of the thermal blanket to zero.

Figure 9 shows the correlation of the computed and measured longitudinal residual stress distribution for quenching only. Good agreement is achieved. Furthermore, Fig. 9 illustrates that when quenching only is used, the residual stress at the weld zone is of yield level magnitude. However, the width of the tensile stress band is significantly reduced in comparison to that of welds with no cooling — Fig. 2. This can be attributed to the heat sink provided by the water cooling. Comparison of the quenched-only (Fig. 9) and the thermal tensioning (Fig. 7) conditions reveals that the quenched-only condition does not reduce the magnitude of the longitudinal residual stress. Furthermore, the width of the tensile residual stress is higher when only quenching is used. This is because the magnitude of the pre-tension of quenching only is negligible.

The total resulted tensile load for quenching (integration of the tensile stress at the weld zone) is approximately the same as the total tensile load for welding with heat input of 7.8 kJ/in. (comparing Figs. 9 and 3). Consequently, welding under the quenching-only condition is not expected to induce significant buckling distortion on a 24 x 48-in. panel, since the panel welded with a heat input of 7.8 kJ/in. does not buckle. The experimental test verifies this conclusion. It should be noted, however, that since welds of heat input 7.8 kJ/in. cause buckling on large panels, welds of heat input 18.2 kJ/in. and quenching only also will cause buckling on large panels.

Temperature Differentials of 230°F (110°C) and 518°F (270°C)

By changing the efficiency coefficient of the thermal blanket, the temperature differential between points A and B in Fig. 5 can be adjusted to 230°F (110°C) and 518°F (270°C). These cases correspond to lower and higher heating blanket power, respectively. Figures 10 and 11 show the computed residual stress distribution for these two temperature differentials, respectively.

The residual stress distribution of welds with a thermal tensioning differential of 230°F in Fig. 10 is qualitatively similar to that of 338°F (170°C) temperature differential (Fig. 7), with the exception that the level of the residual stress at the weld zone is a little higher. This indicates that a temperature differential of 230°F is lower than the optimal value.

However, residual stress distribution of welds with thermal tensioning differential of 518°F exhibits some new features as compared to welds with thermal tensioning differential of 338°F — Figs.
Two humps of tensile residual stress develop at the thermal blanket locations. This is because, prior to welding, with the temperature differential of 518°F, the material right above the two thermal blankets reaches its yield stress in compression and the material right above the cooling water channel reaches yield stress in tension. Upon cooling, the stress at locations that have plastified, reverses sign from compressive to tensile (or tensile to compressive). Consequently, two humps of tensile stress are formed. This result illustrates that the temperature differential of 518°F is too high for thermal tensioning of this material. Such a high temperature differential will have an adverse effect on the control of residual stresses and distortion. It is therefore reasonable to conclude that, within the elastic range, the higher the level of preset tensile stress, the better the results of controlling the welding residual stress and distortion.

Cooling Water Running Time

The effect of the time duration of the water cooling after the completion of welding also is investigated in this study. The welding simulation of thermal tensioning with a temperature differential of 230°F is modified to correspond to turning off the cooling water at zero and ten minutes after welding is completed. The resulting residual stress distribution is virtually unchanged. This indicates that the cooling water running time can be minimized, rendering the implementation of thermal tensioning more economic. A minimum cooling time also implies that a moving thermal tensioning apparatus with limited length that moves along with the welding torches may be effective.

Discussion

The finite element method is used to simulate welding under thermal tensioning. It is demonstrated that thermal tensioning can significantly reduce the longitudinal residual stress developed by welding and thus eliminate welding-induced buckling. It also is illustrated that the finite element method can be used to determine the optimum thermal tensioning conditions of a specified weld joint and heat input.

In this study, uniform heating and
Joining Center project No. 93-04. The thermal tensioning conditions. Further-thin section panels due to welding, A predictive technique for buckling analysis of devices can be designed by performing finite element simulations to determine the required heating and cooling times. welding deformation in thin-skin plate structures. However, as the sensitivity studies imply, a moving thermal tensioning apparatus with limited heating and cooling length, moving along with the welding torches, can be effective. Such devices can be designed by performing finite element simulations to determine the required heating and cooling times.

The finite element simulation of thermal tensioning can be combined with the determination of the critical buckling load of the specified panel configurations (Refs. 3, 9) to determine the optimum thermal tensioning conditions. Furthermore, numerical optimization techniques and analytic sensitivity analyses (Ref. 11) can be incorporated in the computations to automate the determination of the optimum conditions.

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References