Modeling of Welding Distortion in Complex Structures

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1. INTRODUCTION

1.1 General

A significant portion of the fabrication costs of large scale structures is attributable to fitting and fairing of the components. In shipbuilding, in particular, Japanese shipyards have made tremendous advances in recent years in the field of "accuracy control." Although this term is somewhat ill-defined, representing advances in initial design, cutting, forming and distortion control during welding, its implementation has reduced the costs of fitting and fairing and has increased the applicability of modular construction and welding automation in these shipyards.

Of the various aspects of accuracy control, distortion control during welding is perhaps the most intractable problem. As the structure becomes larger and more complex, the distortion problem becomes more acute. Clearly, such welding distortion can negate improvements in cutting, forming, and positioning accuracy control. In this sense, it is advisable to attack the overall accuracy control problem by starting at the end of the fabrication sequence and working backwards. Essentially, the weld distortion must be minimized, or at least predicted, before the benefits of improvements in positioning, forming, and cutting accuracy control can be realized.

Current procedures to reduce welding distortion can be divided according to the three stages at which they take place, namely:

a. Pre-welding strategies such as welding sequence, fixturing devices, etc.
b. In-process corrections such as speed adjustments, change of planned weld sequence, etc.
c. Post-welding adjustments such as flame heating.

At present, most of these strategies are based primarily on experience and are considered art rather than science. There is a missing link preventing immediate use of the existing knowledge on welding distortions for applications in the design and manufacturing process. Currently, we are not able to predict the distortions of a complex welded structure and therefore cannot interrogate the possibilities to minimize the cost associated with such distortions. As an example, consider the welding of a rectangular box. Such a box is to be constructed from five rectangular plates with an open top. A most interesting observation has to be noted regarding the different possible welding sequences. Even with the assumption of one pass per edge, having eight edges and two possible directions per edge for moving the arc, it is predicted that there are $2^8 \times 8! \simeq 10^7$ different possibilities to weld the box (these are reduced due to the symmetric nature of some combinations). If tack welds and their positions are also included, the problem of welding a rectangular box consists of practically an infinite number of different combinations. It is now clear that the number of possibilities to be investigated in the case of a complex structure is extremely large. Therefore, finding an optimal strategy and predicting the expected distortion requires an efficient tool and a good understanding of the sensitivity of the distortions to variations of the welding parameters.

Scientific approaches to the problem of weld distortion prediction have consisted primarily of two dimensional finite element modelling of simple structures. The solutions give the correct general results as compared with experimental weldments, and hence confirm that the physics of the distortion problem is understood. Unfortunately, the models are too complex and time consuming to be useful on real structures as large or as complicated as a subassembly of a ship. In most practical situations it would be cheaper and more accurate to fabricate the structure and measure its distortion than to attempt to calculate the distortion from first principles. In fact, this experimental approach is one of the primary methods used by Japanese shipyards. Distortion measurements are made on a production structure while it is being constructed. These measurements are later compared with results taken from identical or similar production structures. A huge base of experimental data is developed which can be analyzed to predict welding processes and sequences which will minimize the distortion of subsequent structures. The Japanese integrate this experimental data base on distortion into their new ship designs in order to achieve ever greater accuracy control.

It is believed that a better and a novel approach to weld distortion prediction lies somewhere between the complex finite element analyses and the statistical methods. Given the physical understanding of weld distortion demonstrated by the scientific models, it is possible to simplify the complex analyses. For example, the thermo-elastic-plastic phenomena which cause distortion are confined to a narrow region within a few centimeters of the weld line. This is called the weld region or the near field. Outside this region, the structure behaves elastically, within a meter or so of the weld line, and still further away, the structure is not distorted by the weldment. These latter two parts of the structure are considered the far field. The far field produces varying degrees of restraint on the near field depending on the geometry of the structure and on fixturing devices. One of the complications of fabrication is that this restraint in the far field varies as the welding progresses. It is believed that the distortion of complex welded assemblies can be predicted by developing generalized thermo-elastic-plastic solutions within the weld region and combining these results with a much simpler elastic model of the far field. The far field can be treated as a varying level of restraint on the near weld region. In this way, the distortion problem of a complex structure is made tractable. Any model of weld distortion requires large amounts of physical data on the material. Since much of this data is known only approximately, it is necessary to calibrate the model proposed and demonstrated herein with several experimental measurements of distortion. As the model is used and actual distortion measurements are incorporated into the knowledge base, the model will become more accurate. In this way, the model uses an experimental data base, much like the statistical approach, although requiring much less data due to the physical insight provided through the model.

1.2 Existing Methods for Distortion Prediction

A large amount of knowledge on welding distortions exists as a result of extensive research throughout the last four decades. An extensive review of this research effort has been made (Masubuchi 1980). Scientific efforts have been carried out in different parts of the world, including the U.S., Japan, U.S.S.R., the U.K. as well as other countries (Gray and Spence, 1982), (Masubuchi, 1980), (Okerblom, 1955), (Rykalin, 1947), (Ueda and Nakacho, 1982). In general, the effort to develop a model to predict distortions due to welding can be divided into several categories; namely, empirical, analytical, semi-empirical, numerical, and statistical.

Experimental effort has been carried out in many different forms, typically resulting in records of the input parameters and the output measurements. The input parameters, for example, may include the type of welding process, the type of base metal and weld metal, the arc power, a geometric description of the joint, etc. The output measurements may consist of the geometric description of the distortions, temperature readings, strain readings, etc. Many of the experimental results have been organized in the form of best fitted curves that constitute empirical formulae (Okerblom, 1955), (Watanabe and Satoh, 1961). Such formulae are to be used in a very cautious manner. They are capable of giving reliable predictions within the limitations upon which they are based; that is, any change of parameters which has not been included can lead to an error. In many cases, they may serve the purpose of predicting no more than the order of magnitude of welding distortions. However, they are not expected to be suitable for predicting distortions in large scale structures.

Some researchers have tried to understand the physics that govern the process or welding and to use this understanding to develop models that will agree with the observed results (Masubuchi, 1980), (Okerblom, 1955), and (Watanabe and Satoh, 1961). They developed semi-analytical models to suplement the purely empirical models. Unfortunately, the complexity of the process was not fully recognized until the 1970's when use of the finite element method for analysis of welding became a common practice among researchers (Masubuchi, 1980), (Ueda and Nakacho, 1982). Therefore, the somewhat intuitive semi-analytical models should be used carefully. Similar to the fully empirical models, they can give a reliable prediction only within the limitations upon which they are based. However, both empirical and semi-analytical formulas carry useful knowledge that should not be disregarded.

Analytical work on welding analysis can be divided into two categories. The first deals with the modelling of the temperature field, whereas the second deals with the modelling of the stress-strain field. Although modelling of the temperature field is practical and reasonably accurate (Rosenthal, 1946), (Rykalin, 1960), (Moshaiov and Latorre, 1985), and (Eagar and Tsai, 1983), analysis of the thermal stresses and incompatible strains is much less satisfactory.

Early analytical modelling of the stress-strain field suffered from a lack of computational power and, therefore, was based on elastic analytical solutions (Masubuchi, 1980), (Masubuchi, 1977). The researchers of the 1960's recognized that the process is nonlinear and that the stress-strain state within the material is such that plastic strains should be introduced into the models. However, at that time extensive iterative calculations could not be carried out for the plastic strains. To overcome this difficulty, the researchers developed methods for estimating the plastic strains in simple configurations using experimental data, and employing the approximated plastic strains in their models (Masubuchi, 1980). The main physical observation that allows such an approach is that most of the plasticity is confined to a small area in the vicinity of the weldment whereas the rest of the material is elastic. Such models lack the detailed description of the weldment region, but are able to capture the near field behavior of the structure in the sense of the stress-strain and distortion fields. The main problem with this approach is estimating the plastic strains (Masubuchi, 1980).

During the 1970's a revolutionary change in the level of understanding of the thermo-elastic-plastic nature of the welding process occurred. The emerging finite element method and the availability of computers contributed to the new development. Equipped with this tool the researchers of the 70's were able to explore the physics of the process in detail. These models started from the basic principles of solid mechanics involving thermo-elastic-plastic constitutive relations. Commonly, the Prandtl-Reuss flow rule and a modified Von Mises yield criteria is useful. In addition, the finite element modelling involves a reliable field description of the joint stiffness and its dependency on the temperature. Even the role of the melting and solidification effects have found a place within such models.

The results obtained from finite element models are known to be reliable and have been verified with experiments. The degree of accuracy is strongly related to the number of degrees of freedom of the finite element model. In addition, the incremental iterative procedure that is associated with the solution has an effect on the accuracy, depending on the increment length and the convergence criteria used. The main problem lies in the fact that a detailed model is associated with large computer costs. The cost is in CPU time and the memory space required, as well as the cost of input preparation and output organization, which can be translated into dollars. A two dimensional finite element model of a weld joint can cost a few hundred dollars, whereas a crude three dimensional model may require thousands of dollars. This cost prohibits use of such analysis for distortions in a large scale welded structure. However, a substantial amount of knowledge has been and can be generated from such two-dimensional modelling, thus helping to understand the weld region behavior.

A statistical approach, oriented toward the prediction of welding distortion in large scale structures, is currently being used in Japan. Since this approach is basically empirical, it is difficult to extrapolate from one type of a geometry to another. For example, the difference between the distortion in steel versus aluminum ship hulls is known to be significant. In such a case the statistical approach will be insufficient and may be misleading unless a new data base is generated for aluminum structures. It is also conceivable that the lack of physical insight into statistical modelling reduces its reliability and effectiveness when new plate configurations are examined. In addition, the cost of collecting and assembling the extensive data base is another factor suggesting the need for a more analytical approach.

The above discussion shows that each of the currently existing methods is either too simple or too complicated and that the promising methods are very costly. In the following discussion, a new approach is sugested, believed to combine advantages of the existing methods and eliminating some of the shortcomings.

2. THE PROPOSED MODEL

2.1 General

The high costs associated with welding distortions in large scale welded structures, and the limitations of existing models, calls for a new practical approach to predict the distortions. The first question to be asked is what is requested of the model. For example, what is the needed level of accuracy? It is conceivable that in many situations involving complex structures an approximate prediction of the direction and order of magnitude of the distortion can be significant from a fabrication point of view. Therefore, the need for a detailed and costly finite element model may be relaxed. In other words, the truth lies somewhere between the detailed finite element method and the remaining available models which are less accurate and less costly. A possible model may be based on a less detailed finite element model with factors involving the empirical equations and/or the statistical data base. Another approach may be based on statistical modelling with allowances for deterministic information such as that available from a finite element model. The discussion here will concentrate on the first approach, although it should be noted that other possible approaches may be explored.

To understand the possibility of shifting the effort from a complicated detailed finite element model to a more relaxed model allowing for the integration of empirical as well as statistical knowledge, we should understand the reasons why the finite element modelling of welding is so complicated and involves prohibitive costs.

A finite element model involves a set of algebraic equations that are created and solved by the computer. These equations are in effect equilibrium equations of the structure, whereas compatibility conditions are included in the model. Presenting such equations in a matrix form we have

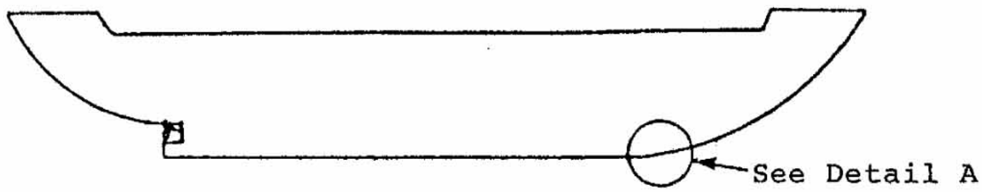
$$[K]\{U\} = \{F\} \tag{1}$$

where [K] is the stiffness matrix, {U} is a vector of nodal displacements and {F} is a vector of equivalent nodal forces. The above equations are analogous to the spring equation K x d = P where d is the extension of a spring of stiffness K due to an applied force P. In general the force vector {F} is given. Using a calculated stiffness of the given structure, the finite element solution gives the resulting nodal displacements at the free nodes. This is the general procedure in modelling elastic linear structures. The dimensions of the matrix [K] depend on how detailed the finite element mesh is. Assuming [K] is a n x n matrix, then the computer cost will be approximately proportional to n^3. In spite of the cost associated with a large mesh, such models are used to examine the elastic behavior of the entire structures of airplanes, ships, submarines, offshore platforms, etc. The main reason for the cost associated with the finite element modelling of welding distortion is not just the number of unknowns that are involved in the solution, but also the need for incrementation of the thermo-elastic-plastic problem (Masubuchi, 1980), (Moshaiov, 1985). Accurate calculation of the plastic strains produced during the process is essential for detailed modelling of the process. Such calculations require an incremental iterative solution procedure as the plasticity depends on the path of the stress-strain curve. Another complication is that the temperature field creates variations in the material behavior. Such changes in the material properties require correction of the stiffness matrix during the incremental procedure. At each increment of loading an iterative procedure is needed for calculation of the plastic strains. As an example, consider one hundred increments of loading and an average of ten iterations per increment for convergence in calculating the plastic strains. A total of one thousand calculations is needed. If a three-dimensional elastic model or a complex structure costs one thousand dollars to execute, then a similar model with thermo-elastic-plastic behavior may reach a cost of one million dollars! Luckily, some of the cost is not associated with the number of repeated calculations and therefore the last figure is somewhat exaggerated, yet it is clear that with today's computers a complete analysis of a complex welded structure is impractical. Returning to the optimization problem of the rectangular box posed in the introduction, it is clear that a detailed optimization using a regular FEM approach cannot be achieved at present.

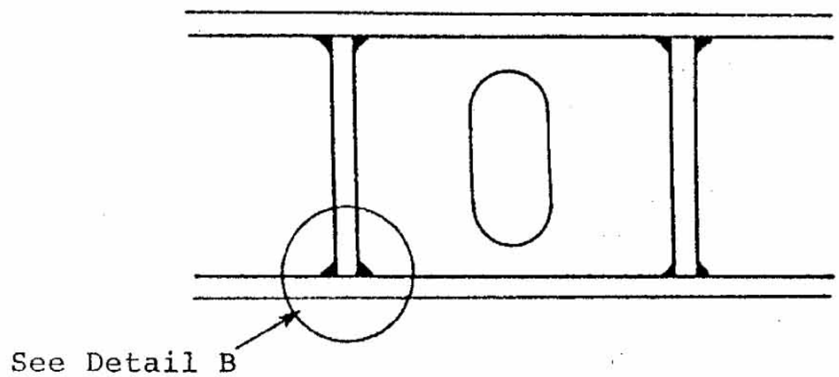
To overcome the above difficulty, a method is proposed based on the idea that we can use a modified model, overlooking the need for the expensive incremental iterative approach. This same idea is the main principle behind the early analytical works that were developed in the 1950's as discussed previously. The basic observation that justifies this concept is that the overall structure is elastic and the plasticity is confined to small areas along the welds. Therefore, the far field problem can be considered elastic, whereas the weld region involves plasticity, as illustrated in Figure 1. There is a need to match the near and the far field problems. This resembles the so-called matched asymptotic expansions that are used in some engineering problems such as the boundary layer problem. For the purpose of design and fabrication considerations, the overall distortion in a far field sense is sought. It is noted that an accurate description of the weld region behavior may not be essential for such goals. However, it appears that solving for the far field requires a description of the weld region behavior.

Far field elastic behavior can be modelled by an existing method such as the finite element, the boundary element method or finite differences (Moshaiov, 1985). It can also be solved analytically for many cases. It is most important to understand what is meant by the elastic far field. Because the effects of the welding distortion are carried to only a few plates surrounding the weldment, there is no need to model the entire structure, as illustrated in Figure 1. Obviously, a welding activity in the bow of a ship is not felt in the stern. In other words, the elastic far field should be understood as a small portion of the entire structure for any welding operations and, therefore, the far field modelling is greatly simplified.

The weld region is not solved in detail. This is the method used to make the problem tractable but it is also the source of inaccuracies. The

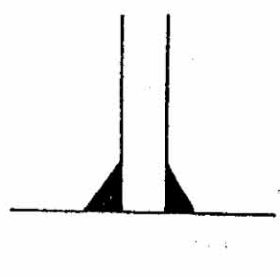


THE STRUCTURE MODEL



DETAIL A

THE FAR FIELD MODIFIED ELASTIC MODEL



DETAIL B

THE NEAR FIELD WELD REGION THERMO-PLASTIC MODEL

Figure 1 The concept of far and near fields weld region is assumed to be known to the degree that available data from the existing literature allows. This means that the residual plastic strains and stresses will be approximated. The near field solution in the weld region depends on the equivalent stiffness of the far field, as illustrated in Figure 2. To understand the effect of the weld region plasticity on the modified far field model, the plastic strains should be looked at as pseudo forces acting on the far field along its boundary, as illustrated in Figure 3. In a finite element approach, this can be represented as a modified set of equilibrium equations as follows

$$[K]\{\dot{U}\} = \{\dot{F}\} + \{\dot{P}\} \tag{2}$$

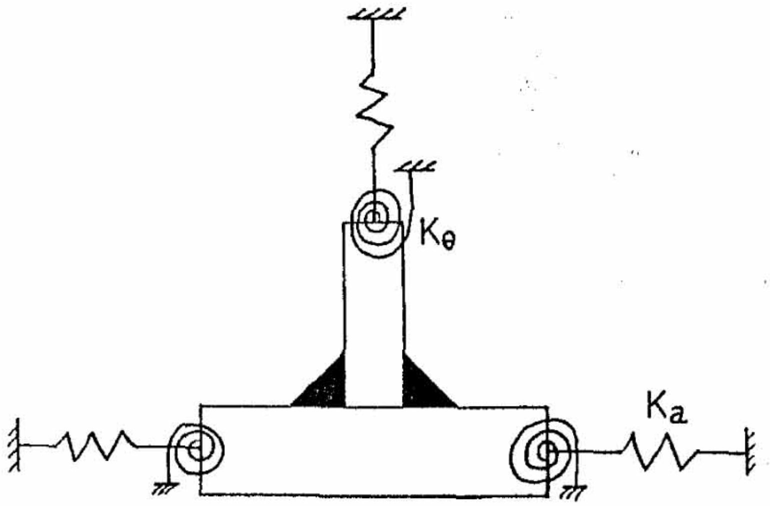
where $[K]$, $\{\dot{U}\}$ and $\{\dot{F}\}$ are as in the elastic case the stiffness matrix, the displacement increment vector and the generalized load increment vector (thermal and mechanical loads such as weight for example) $\{\dot{P}\}$ is the vector of pseudo loads resulting from the initial plastic-strain increment. Such pseudo loads due to initial strains are well known (Masubuchi, 1980), (Moshaiov, 1987), (Moshaiov, 1985).

As an example of initial strains that act like forces, consider thermal strains. Thermal strains are known to behave as pseudo loads that cause structures to deform. In the regular iterative approach that takes place in an elastic-plastic solution, the plastic strains and, therefore, the components of the vector $\{\dot{P}\}$, are unknowns in addition to the unknown displacements $\{\dot{U}\}$ and, therefore, a costly iterative procedure is needed. Here the basic concept is that one can assume a certain nature of the plastic strains allowing for approximate values for $\{\dot{P}\}$ based on the existing weld region studies. These studies include two dimensional results and, therefore, are approximate. It is demonstrated in Section 2.3 that the use of such approximations may reduce significantly the magnitude of the degrees of freedom required. Using the approximated nature of the residual plastic strains, $\{\dot{P}\}$ is calculated and an approximate displacement field can be solved. Such an approximated displacement field should be compared with the one predicted from statistical data, empirical formulas and FEM models. In case of a deficiency, the method of calculating an approximate $\{\dot{P}\}$ can be adjusted until optimal values are obtained. These optimal values of the plastic strains should indicate the best approximation for $\{\dot{P}\}$. A set of best approximations for different generic cases can be derived from the suggested model. These generic cases, which can be verified experimentally, will become the foundations for predicting distortions in new equilibrium configurations that exist in a complex structure. It is believed that the generic data base will have a much more compact and flexible form than that of a statistical data base.

In the following, a study of a generic case of axisymmetrical residual distortions in welding ring stiffeners is given to demonstrate some of the concepts of the near field and far field, and the possibility of dramatic reductions in the computational effort involved.

2.2 Model Demonstration

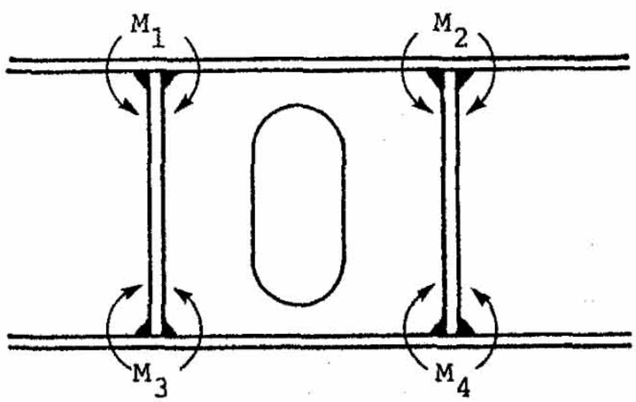
To test the suggested model, it was decided that a particular welding case should be studied. It is assumed that demonstrating the concepts of the near and the far field approximations on a particular case will eventually lead to the generalization of the method. The case of welding a ring-stiffened cylinder has been chosen. However, it should be emphasized



K_a - Effective axial stiffness

K_θ - Effective torsional stiffness

Figure 2 Effects of the far field on the near field weld region



M_1, M_2, M_3, M_4 - Pseudo moments due to plastic strains

Figure 3 Effects of the weld region on the far field that, while working on this particular problem, the research is oriented toward its general predictive merits. The primary purpose is to demonstrate the potential of the proposed distortion prediction model rather than obtaining the distortions of a realistic stiffened cylinder.

The welding of a ring stiffened cylinder has special features making it most interesting for this study. It combines theoretical and practical issues from the design, analysis and manufacturing standpoints. One important issue is the constraint imposed by the design on the allowable out-of-circularity tolerances. These restrictions are imposed to improve the buckling strength of such cylinders when subjected to hydrostatic pressure. The optimal product is a perfect circular cylinder. The manufacturing procedure will determine what level of distortions the real product has in comparison with the optimal one.

There are many possible contributers to the final out-of-circularity imperfections of a welded stiffened cylinder. Among these are:

1. Initial geometrical imperfections due to previous manufacturing processes such as cutting and bending
2. Initial distribution of residual stresses from previous manufacturing processes
3. Nonsymmetric heat loading imposed by the moving arc during welding
4. Nonsymmetric stiffness resulting from the non-symmetric cooling
5. Nonsymmetric boundary conditions such as fixturing devices and hydraulic rams
6. Nonsymmetric material properties.

The existing literature deals primarily with the study of symmetric distortions for 'pipe like' structures (Rybicki, 1979). It is believed that this is a result of the prohibitive computer costs associated with today's modelling methods. As part of an ongoing research effort at MIT, an attempt is made to predict the out-of-roundness distortions of a ring-stiffened cylinder induced by welding using the suggested modelling concept of near and far field approximations. The goal is to achieve a distortion prediction tool that will give reasonable results within a reasonable computer cost. This will help to achieve the ultimate goal of welding distortion control and optimization by interrogation of the model at a relatively low cost.

So far, the analytical effort taken at MIT has concentrated on the demonstration of the near and far field concept in conjunction with axisymmetric analysis. The results of this effort are described in the following section.

2.3. Axisymmetric Distortion Simulation

When a circular axisymmetric structure is welded circumferentially, radial distortions are expected as a result of the weld metal shrinkage during cooling. This phenomena has been investigated by many researchers considering primarily girth butt welding of pipes (Rybicki, 1979), (Ohsawa, et al., 1983), (Fugita, et al., 1981).

The most common method used to predict radial distortions of such structures is a numerical thermo-plastic analysis using a finite element code. The common assumption is that the weld metal shrinks in an axisymmetric manner as if a 'ring like' welding arc was depositing the weld metal simultaneously on the circumference. This results in a model that assumes a two dimensional behavior. Nonsymmetric effects are not included in such a model, but for small pipes the overall results are comparable with experimental results.

To evaluate the concept of the far and near field approximation, it was decided to perform such an axisymmetric analysis for a 'T' shaped ring stiffener consisting of a ring flange and a ring web welded together. Such a ring is illustrated in Figure 4. It is assumed that the top and bottom weld passes are performed simultaneously such that no tilting is allowed between the web and flange by symmetry reasoning about the web mid-plane. A simplified model based on near and far field approximations has been developed to simulate the ring stiffener welding. Furthermore, two dimensional finite element analyses have been carried out and a comparison study has been performed as described in the following.

The following assumptions are used to develop a simplified model to simulate the axisymmetric distortion of the ring stiffener. First, it is assumed that the structure and the welding process are both symmetric. Secondly, it is assumed that the whole structure can be divided into two parts, i.e., the thermo-plastic near field and the rest of the structure which is considered as an elastic far field. Furthermore, it is assumed that the hoop stresses are dominant during the process. To simplify the model as much as possible it is also assumed that the two dimensional effects can be modified into one dimensional effects reducing the problem into that of one degree of freedom. The resulting generic deformation model for the ring is therefore an equivalent system of a thermo-elastic-plastic bar-spring model which is illustrated in Figure 5. In the near field the model assumes both high temperatures and high stresses approaching the yield stress and a general thermo-elastic-plastic behavior. The far field which is assumed to be elastic imposes a restraint on the near field. The matching between the two fields is achieved by the compatibility requirement between the fields. The material behavior in the near field is strongly influenced by the temperature. In particular, Young's modulus and the yield strength are substantially reduced at higher temperatures, (Iwamura and Rybicki, 1973). The elastic far field takes into account both the axisymmetric behavior of the web and the flange and the elastic bending of the flange which are lumped into an equivalent spring representing the far field.

The modeling of the far field is done by obtaining an equivalent stiffness K_{eq} that is composed of K_w, the stiffness of the web, and K_f, the stiffness of the flange (Song, 1988). In calculating the equivalent stiffness of the far field, a distinction is made between short and long flanges. In the case of a short flange, no bending is assumed, whereas for long pipes bending effects should be taken into account. K_{eq} is calculated analyatically using simple elasticity equations. The results from the model are obtained using a nondimensional coefficient Lamda such that

$$\lambda = K_{eq} L/E_o A \qquad (3)$$

where

K_{eq} effective stiffness of the far field
L length of the near field bar
E_o Young's modulus at zero temperature
A cross sectional area of the near field bar.

The near field bar model uses a uniaxial yield criterion modified for temperature dependency.

The ring structure is equivalent to the bar-spring system if the

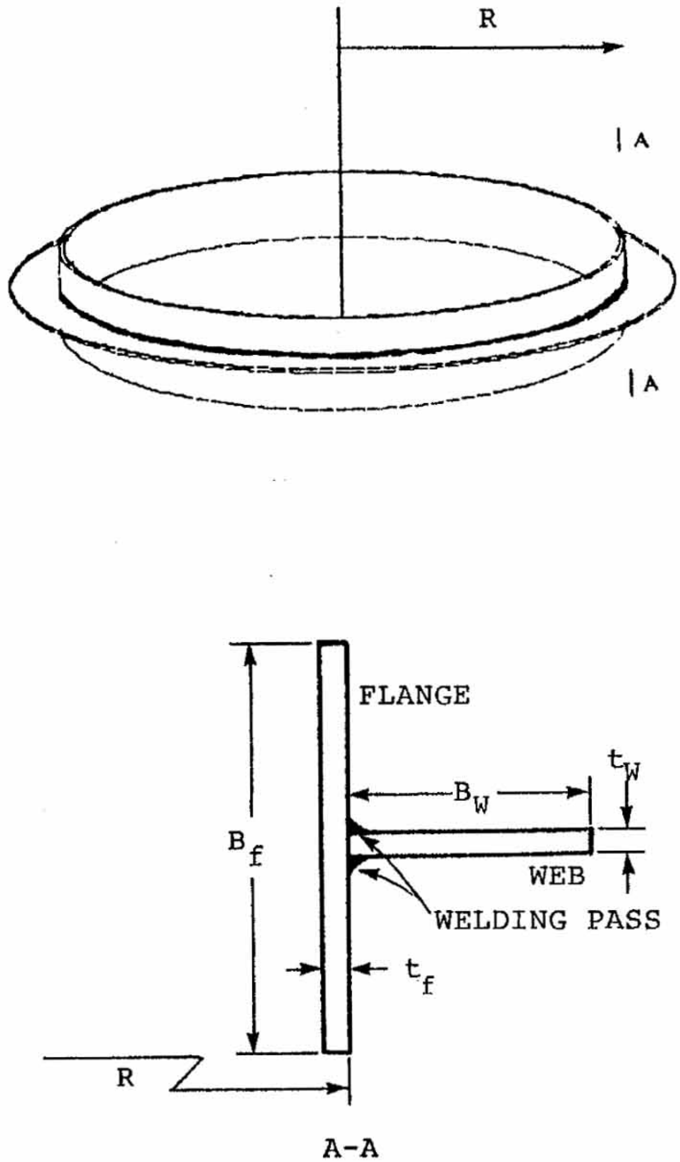


Figure 4 Ring stiffener assembly consisting of welded flange and web

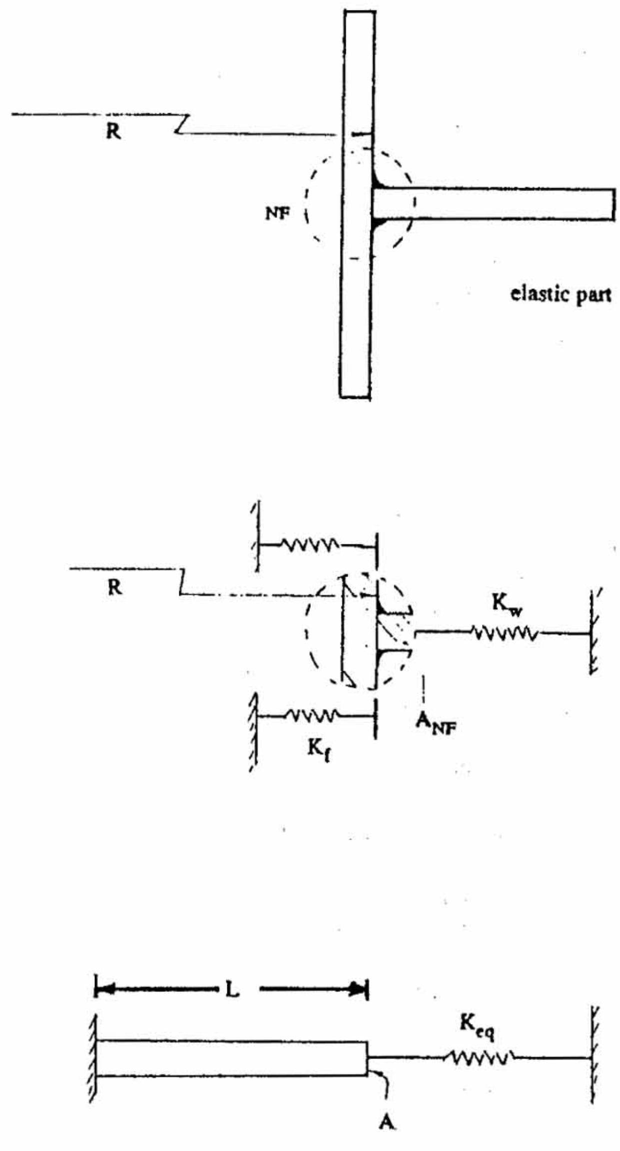


Figure 5 Simplification of ring stiffener to simple model

following conditions are satisfied:

$$L = R \text{ (radius of the ring)}$$
$$K_{eq} = K_f + K_w$$
$$A = A_{NF} \text{ (area of the near field)}$$

The last requirement poses a difficulty in determining the boundaries of the near field. The area of the near field is the area which involves thermo-plastic behavior and high temperature. While determining these boundaries a priori is somewhat arbitrary, certain rules relating to the temperature field can be established. During this research it was found that using consistent rules gives excellent results for a large variety of different cases tested. It is suggested, therefore, that by regulating the boundaries of the near field area, the model can predict the actual physical behavior and can be used for practical applications.

Two important methods of solution were investigated. The first involves numerical integration using incremental loading which allows updating of the material properties. The second method of solution used was analytical integration using approximated material properties such that:

$$E = E_o(1 - T/T_M)$$

and

$$\sigma_y = \sigma_{yo}(1 - T/T_m)$$

where T_m is the melting temperature, E_o and σ_{yo} are Young's modulus and the yield stress at zero temperature.

Using the above methods of integration, a curve representing the residual axisymmetric radial shrinkage, δ_r , was obtained as a function of the ring geometry, the area of the near field and the material properties. For all practical cases the difference between the numerical integration and the analytical integration was found to be negligable.

The simplified model effectively reduced the problem from two dimensions into one of one degree of freedom reducing the computational effort tremendously. To check the validity of the results obtained from the simple model, finite element analyses have been carried out. The finite element model consists of a detailed two dimensional axisymmetric mesh as illustrated in Figure 6. In Figure 6 the radial direction corresponds to the y direction. The temperature field immediately after the deposition of the weld metal is given in Figure 7. A typical residual stress field is described in Figure 8 which clearly shows that the hoop stresses are dominant and are relatively uniformly distributed in two regions. These two regions are simulated by the near and far field approximations in the simplified model.

2.4 Discussion of Results

The residual radial deformation from both the simplified model and the finite element model is given in Figure 9. The results are shown as a function of the coefficient lambda of Eq. 3 which takes into account the geometry. In Figure 9 the curves were created by the simplified model and the data points by the detailed finite element models. The results are of different geometries including cases of essentially welding just a web or just a flange as well as different stiffened rings. It is clear from

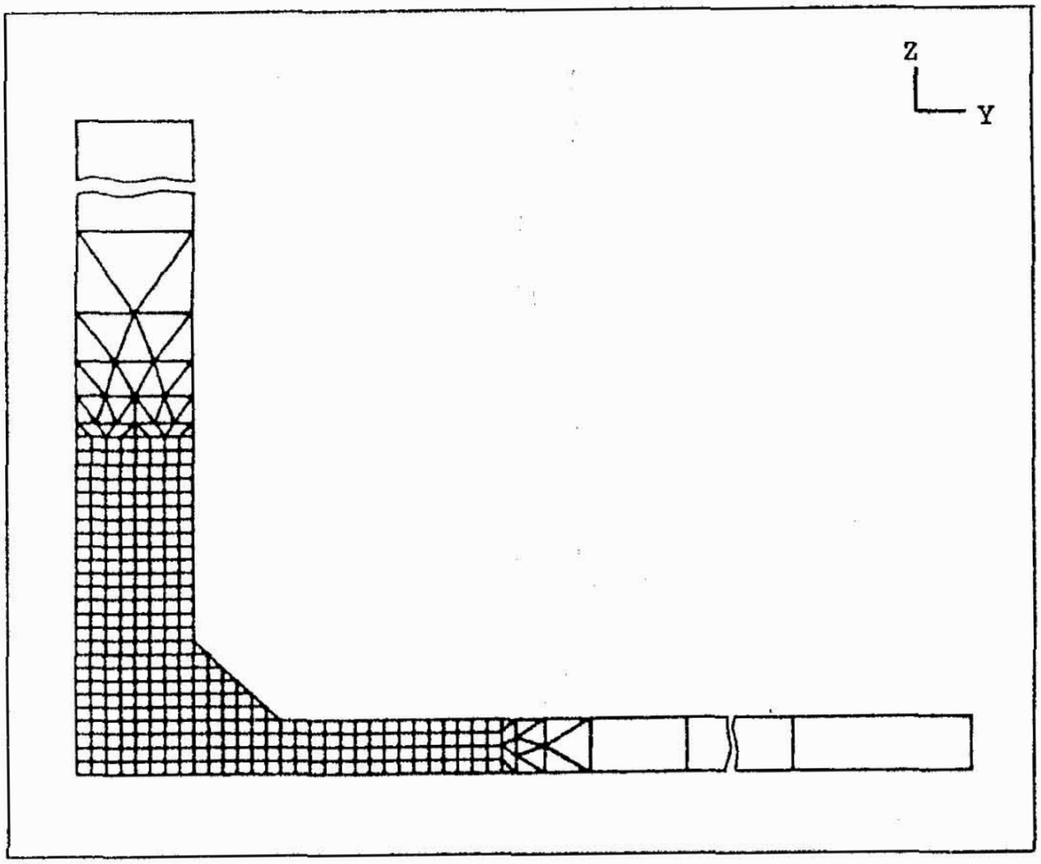


Figure 6 Axisymmetric finite element model

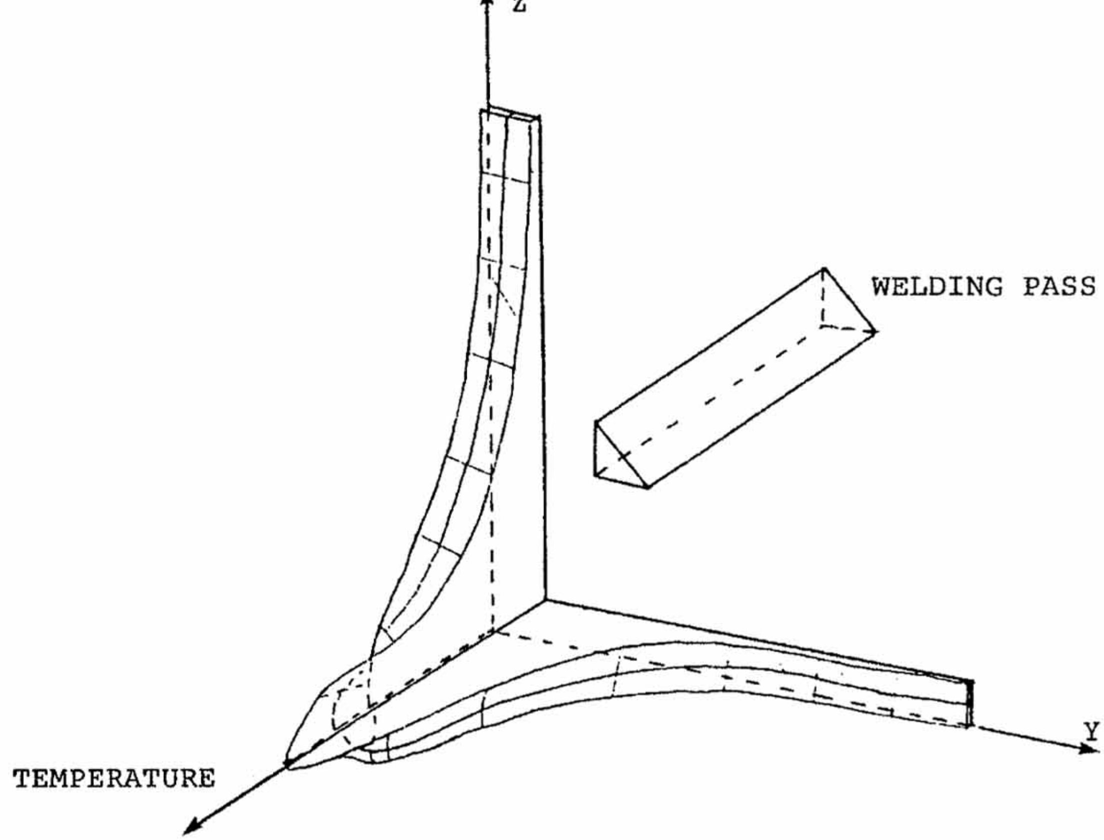


Figure 7 Temperature distribution when weld material is applied

STRESS DISTRIBUTIONS
Along an axial line

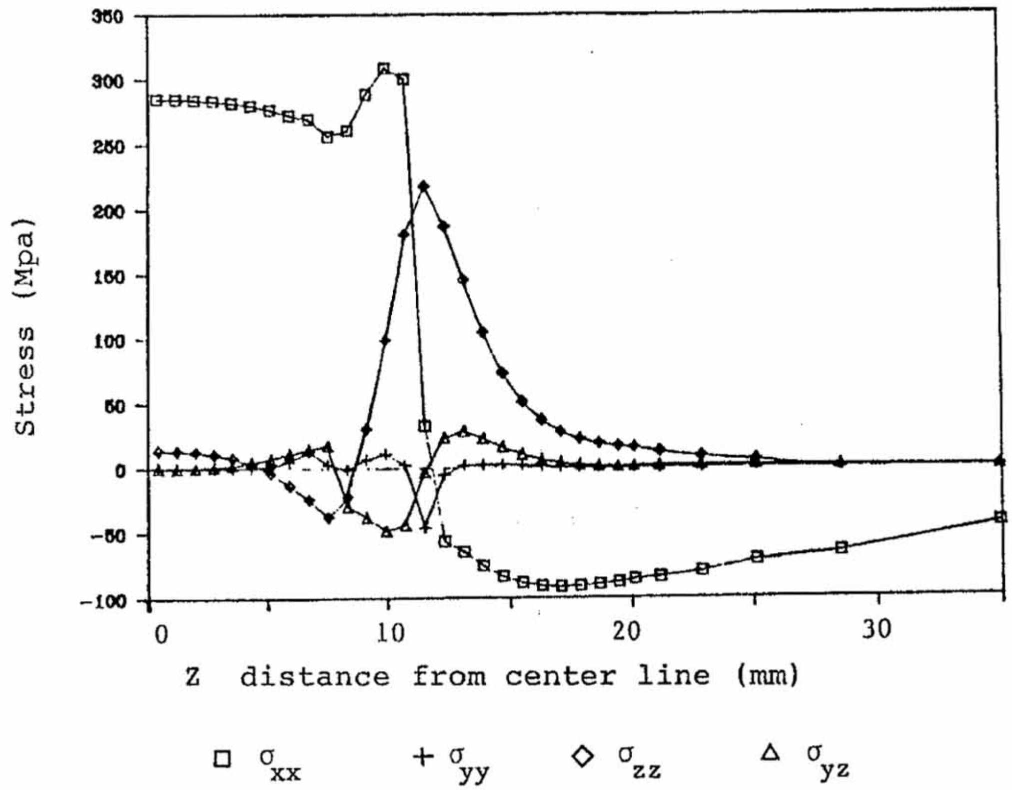


Figure 8 Stress distribution in the flange and web

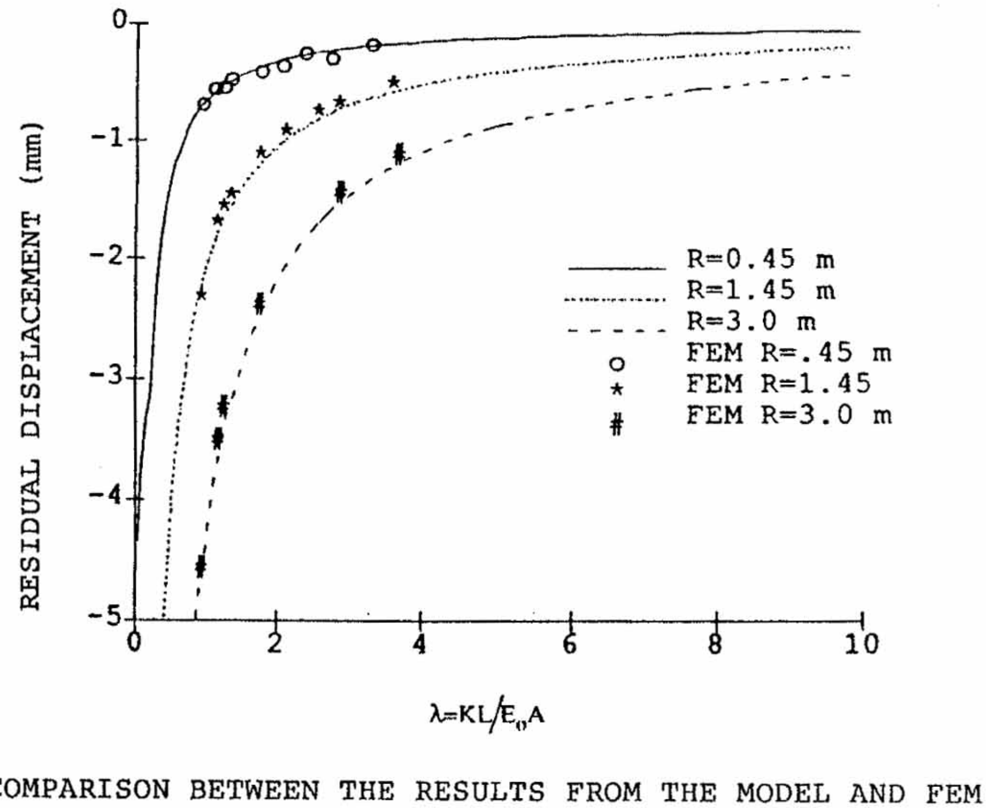


Figure 9 Comparison between simple model and FEM

Figure 9 that as the system becomes stiffer (increasing lambda) the final residual displacement is smaller. The excellent agreement between the simple model results and those of the detailed finite element model suggest that the axioms of our research can be justified at least for this relatively simple case. As part of this research, similar simplified models are explored for the more complicated situations.

It is important to note that the computational effort in calculating the residual radial distortion by the simple model is three orders of magnitude less than that required by the FEM model. The accuracy when compared with experiments is equivalent to the more complicated method. These features give hope for the use of the concept of far and near fields for analyzing large complex welded structures.

An important question to be raised is what has made the results from the FEM model and from the simple model so similar? Answering this question may give clues necessary for extending the ideas developed here to more complicated situations such as the nonsymmetric distortions of welded rings. Several observations can help in answering the above question, and it may shed some light on future research needs and developments.

The first observation is the nature of the stress distribution as given in Figure 8. Clearly the yield is effected primarily by the hoop stresses, and therefore the near field solution can be approximated by a uniaxial bar. In other cases a clear understanding of the nature of the stress distribution may suggest a bi-axial consideration of the near field.

The second observation is the distribution of the hoop stress which is approximately uniform within the near field. The simple model uses a uniform stress assumption which is therefore in agreement with the "actual" case. A fundamental principle of solid mechanics, namely the Saint Venant principle, states that two different force systems which are statically equivalent acting on a small portion of the surface of an elastic body produce the same stress distribution at distances large in comparison with the dimension of the portion of the surface on which they act. In view of this principle, and recognizing the near field as a producer of some stress resultants acting on the elastic far field, it can be said that, when designing an equivalent near field, attention should be given to the nature of the stress distribution within the weld region such that its resultants can be simulated by the simple model. It is most important to realize that such a distribution may become complicated in particular for a multi-pass weldment. However, the distortions will be effected primarily by the integral of the stresses rather than by their exact distribution.

The third observation involves the number of degrees of freedom. The actual axisymmetric case involves a two dimensional continuous stress/strain field. The FEM model simply uses a discretization of the two-dimensional field. However, the simple model uses the minimum number of degrees of freedom necessary for describing the primary distortion yet keeping a reasonable description of the process mechanics (in this case, one degree of freedom). This observation leads to some suggestions regarding more complicated situations. For example, when considering the nonsymmetric distortion of a welded ring, two sets of minimum degrees of freedom may exist. The first is the minimum number required for a sufficient geometric description of the distortion, and the second is the minimum number required for a sufficient presentation of the mechanics. Furthermore, several questions could be raised regarding the mechanical degrees of freedom in view of the near and far field approximations. For example, what is the minimum number of degrees of freedom required for the near field presentation versus those required for the far field presentation? Also, in cases where the near field model is complicated it may prove to be important to investigate the type of coupling between the different degrees of freedom. Two types of coupling may exist, elastic and thermo-plastic, depending on the geometry and the load history.

The issue of reducing the mechanical degrees of freedom which is related to the last three observations is not a trivial one. When Euler, Bernulli, and other scientists contributed to the simple beam model they in effect reduced a three dimensional problem into a one dimensional case. Their physical observations, intuition, and ingenuity led to this historical accomplishment. Unfortunately, intuition is not trivial when dealing with thermo-elastic-plastic phenomena and we are bound to use any available modern techniques as discussed in the following fourth observation.

The fourth observation is the use of the FEM model as an experimental tool to validate the simple model. The availability of such a powerful tool as the FEM, and the use of supercomputers allow complicated three dimensional thermo-plastic analyses. These can serve as a laboratory achieving a better understanding of complex welding situations that have never been explored before. Physical insight and simplified methods can then be used to develop simple models that can capture the nature of the process yet reduce the computational effort to a level that may become of practical use, especially for manufacturing purposes such as discussed in the introduction.

The fifth observation has to do with the relationship between the direction of the moving welding arc and the direction of the chosen degree of freedom. In the simple model presented here, the above directions are perpendicular and the interest is in out-of-plane distortions. Therefore, the model is taken perpendicular to the weld pass. This kind of model is also used when dealing with multipass welding analysis, (Ueda and Nakacho, 1982). In some cases however, such as the analysis of butt welding of thin plates, the model is taken as an in-plane model assuming no variations take place through the thickness direction. When viewed as such, the modeling effort may be complicated by the effects from the moving arc and nonuniform far field effects. A good example is a recent study on in-process reduction of root gap changes during butt welding (Chang, 1988). The keys to simplified models given in this paper are believed to be suitable for such complicated problems. Researchers at MIT are currently exploring the use of near and far field approximations for modeling the moving arc effects in conjunction with the nonsymmetric distortions of ring stiffeners.

3. SUMMARY

The increasing need for accuracy in fabricating complex welded structures will not be met without predicting and minimizing welding distortions. Unfortunately, existing methods for simulating the mechanics of welding are impractical for use in the design/manufacturing process. Currently, we are not able to predict the welding induced distortions of a complex welded structure and therefore cannot interrogate the possibilities to minimize the cost associated with such distortions.

The key problem with existing methods is that they are either too complicated or too simplified. Moreover, the use of the FEM method which is most promising in analyzing the complex thermo-plastic mechanics of the welding process requires impractical CPU time and memory when a complex structure is considered. Yet, the nature of the mechanical process that takes place during welding may allow some simplification using a near and a far field approach. This is based on the fact that only a small portion of the structure near the welding arc undergoes a thermo-elastic-plastic behavior whereas the rest of the structure behaves elastically and may at most have some thermo-elastic effects.

Using an example of a welded ring stiffener, it is demonstrated that such approximations could well prove to be practical both in terms of computational efforts and accuracy of the results. Furthermore, the example is used to highlight some of the characteristics of the suggested method in view of future use for more complicated situations. It is suggested that the FEM will be used as an experimental tool to help understand the nature of the mechanics in complicated situations and simplified models such as described here will follow, based on the guidelines given in conjunction with the far and near field approximations.

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