The Effect of Welding Residual Stress on Whole Structure with T-Joint RHS

S. R. Rajesh, H. S. Bang, and H. Kim

Abstract

In the field of welding the mechanical behavior of a welded structure under consideration may be predicted via heat transfer and welding residual stress analysis. Usually such numerical analyses are limited to small regular mesh models or test specimens. Nevertheless, there is very few strength assessment of the whole structure that includes the effect of welded residual stress. The present work is based on the specialized finite element codes for the calculation of nonlinear heat transfer details and residual stress including the external load on the welded RHS (Rectangular Hollow Section) T-joint connections of the whole structure. First the thermal history of the combined fillet and butt-welded T-joint equal width cold-formed RHS are calculated using nonlinear finite element analysis (FEA) considering the quarter model of the joint. Then using this thermal history the residual stress around the joints has been evaluated. To validify the FEA result, the calculated residual stresses were compared with the available experimental results. The residual stress obtained from the quarter model is mapped to the full model and then to the whole structure model using FEM codes. The results from the FEM codes were exported to the commercial package for visualization and further analysis applying loads and boundary conditions on the whole structure. The residual stress redistribution along with the external applied load is examined computationally.

Key Words : Nonlinear heat transfer, Residual stress, Result mapping, RHS-joint, PCL.

Nomenclature

$[B]$: Strain displacement matrix
$[c]$: Heat capacity matrix
$[D]$: Material property matrix
$\{f\}$: Force vector
$[k]$: Conductance matrix
$[D^e]$: Elastic material property matrix
$[N]$: Shape function
$\{\Phi\}$: Vector of nodal temperature
α ¥á : Coefficient of linear expansion

1. Introduction

Structural joints are crucial components of many engineering design especially welded joints. Many investigators have numerically and experimentally assessed the residual stress around the welded joint to enable improvement of the manufacturing quality of the joints. The residual stress state identified at these joints greatly reduces the plastic deformation capability and hence result in brittle fracture. Nevertheless, there are very few strength assessment of the whole structure that consider weld residual stress, as this analysis considering residual stress is quiet complicated.

In this paper, a detailed investigation on residual stresses in welded T-joint cold-formed RHS as in Fig1. is presented. A welding stimulation methodology is implemented and experimentally validated to predict

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the residual stress at the combined butt and fillet-welded joint.

A specialized finite element code has been developed for calculating the welding thermal history and then evaluates residual stress distribution at the joint using this thermal history. An interface program has been developed using PCL (PATRAN Command Language) that can be compiled directly in PATRAN desktop so that PATRAN can be used as the pre and post processor for the developed code. In addition, the residual stress calculated has been applied as the initial stress at the welded joint of the whole structure and further analysis has been carried out.

An example of a simple joint between rectangular hollow section (RHS) is the T joint produced by butt and fillet welding has been considered. Also there is an on going need for applied research on the behavior and strength of such connections between rectangular hollow sections which have material properties or dimension ratios not considered in the current standards. Structural application involving arc welded T -Joint between equal width RHS are becoming more common with the increasing popularity of cold formed RHS. Due to this reason, this particular example has been considered in this paper.

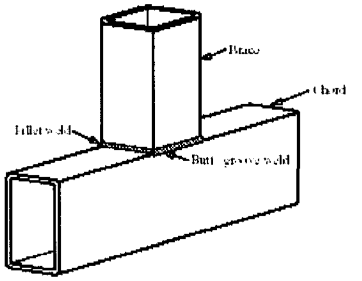
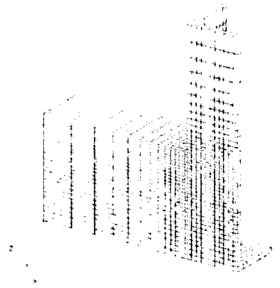


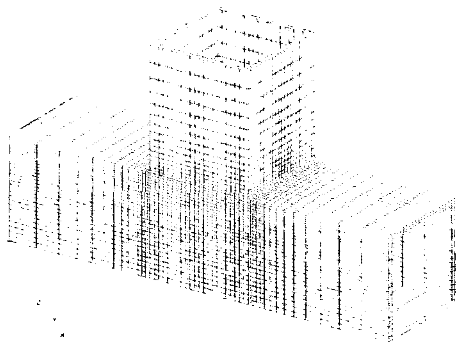
Fig 1. RHS. T-joint

2. FEA : Model and Assumptions

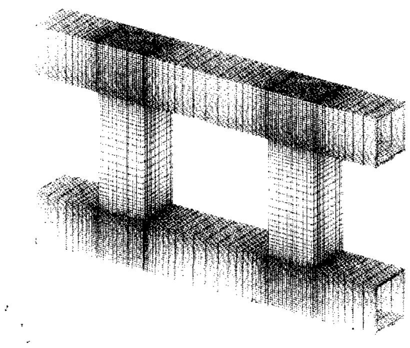
Arc welding is a material joining technology based on fusion process. By applying intense heat, metal at the joint between two parts got melted and caused to intermix-directly, or more commonly, with intermediate molten filler metal [1]. During the welding process, expansion and shrinkage of the material occurs due to thermal cycles and thus result in residual stress on cooling. In this paper, the residual stresses at the T-joint of cold-formed RHS were analyzed numerically and compared with the available experimental result from literature.



(a) Quarter model of the T-joint RHS



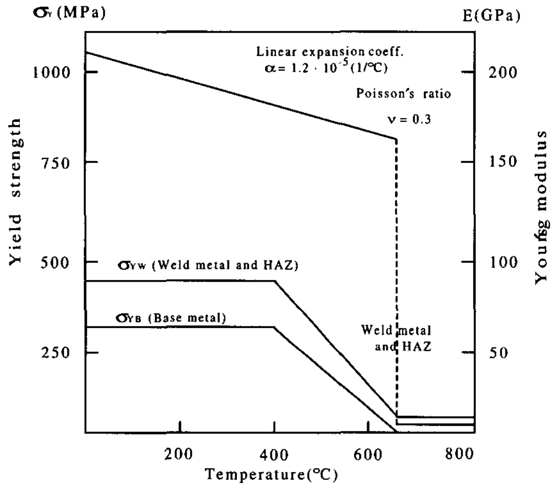
(b) Full model of the T-joint RHS



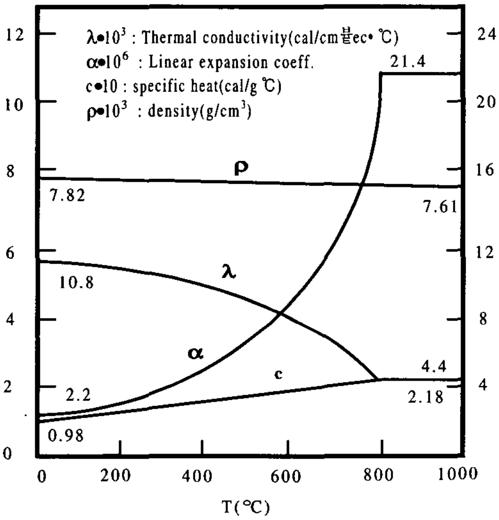
(c) Whole structure model

Fig 2. 3-D FEA model for welding residual stress analysis

Due to symmetry of the joint, a quarter portion of the 3-D FEA model of the T-joint of RHS using solid brick element as shown in Fig 2 is modeled and result obtained from the numerical analysis are mapped on the full model and then to the whole structural arrangement. The total number of elements and nodes of the quarter model are 1602 and 3256, full model 6408 and 12540 and for the whole structure model are 25632 and 49394 respectively. A sufficiently fine mesh at the welded zone was generated to obtain more accurate result. The temperature dependent material property applied in the FEA is as shown in Fig 3.



(a) Mechanical properties



(b) Thermal properties.

Fig 3. Temperature-dependent material properties employed in nonlinear FEA

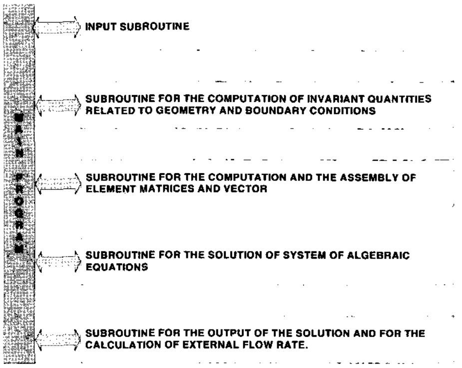
The numerical analysis procedure for determining the welding residual stress consists of two parts: Non-Linear Heat Transfer Analysis and Mechanical Analysis. The block diagrams of the sub-routines for the both are as shown in Fig 4. The main governing equations based on which the in-house solver has been developed are:

Heat transfer analysis [2,3]:

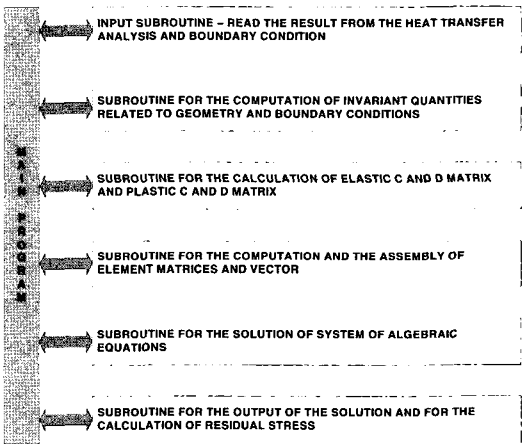
$$[k]\{\Phi\} + \left[c\left\{\frac{\partial \Phi}{\partial t}\right\}\right] = \{f\} \qquad (1)$$

Residual stress analysis [4]:

$$\{d\sigma\} = [D^e]\{d\varepsilon\} - [D^e]\left\{\frac{\partial f}{\partial \sigma}\right\}\lambda - [D^e]\{\alpha\}dT + \frac{d[D^e]}{dT}[D^e]^{-1}\{\sigma\}dT \qquad (2)$$



(a) Structure of the Heat transfer analysis program



(b) Structure of the Residual stress analysis program

Fig 4. Block diagram of the subroutines of in-house solvers

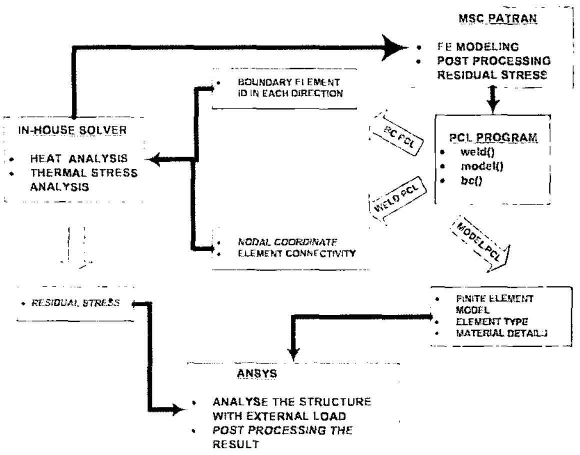


Fig 5. Typical Architecture of the data transferring

3. Data transferring details

PATRAN Command Language (PCL) that can be compiled directly from the PATRAN desktop was used for making a basic interface between the in-house solver and commercial package [5]. Three PCL programs were developed. First is WELD.pcl, used to transfer coordinate and connectivity details of the model developed in PATRAN to in-house solver. Second is BC.pcl, used to transfer the details of the surface elements to in-house solver and the last one is MODEL.pcl, used to export the results (residual stresses) from the in-house solver to commercial package for further analysis with the external load. The block diagram for this data transferring between the in-house solver and commercial packages is shown in Fig 5.

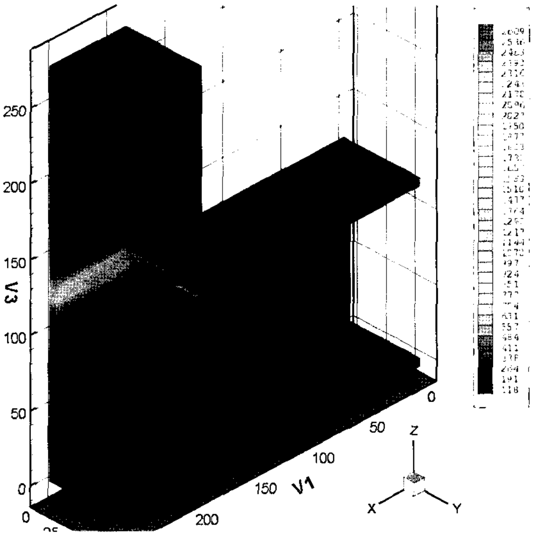
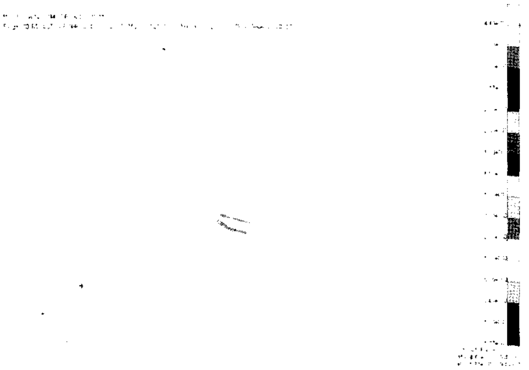
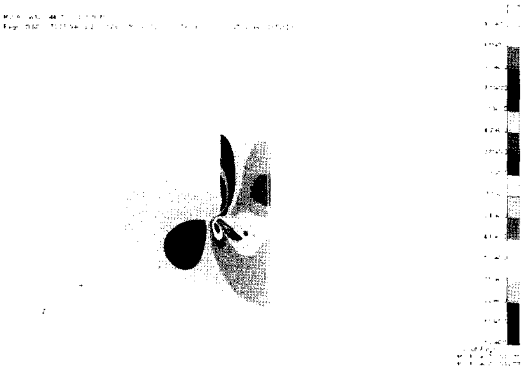


Fig 6. Temperature distribution on the weld joint

(a) σ_{XX} distribution



b) σ_{YY} distribution



c) σ_{ZZ} distribution

Fig 7. Welding residual stress distribution for the Quarter model

4. Numerical residual stress analysis results

A 3D model is generated in PATRAN with the graded meshing near the weld zone. The nodal coordinate, the element connectivity and surface element details are transferred to in-house solver and nonlinear heat transfer and residual stress analysis are carried out and the results from the in-house solver is transferred back to PATRAN for post processing. The temperature history near the weld zone of the T-joint of the quarter model is obtained as the shown in Fig 6.

The peak temperature was around 2600℃ at the nugget center and 851-777℃ around the weld zone. The residual stress distributions calculated from this thermal history for the quarter model are as shown in Fig.7.

Calculated residual stress value was around 62 MPa. The results of the quarter model are mapped to the full model. This residual stress values are then transferred to the whole structural model and then exporting the model with the residual stress details to commercial package, analysis has been carried out with the application of external load and boundary conditions on the model as shown in Fig.8.

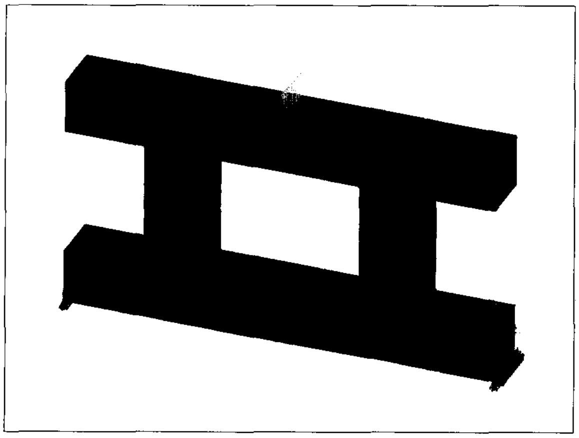
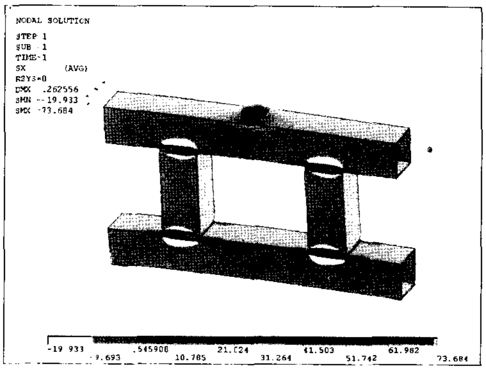
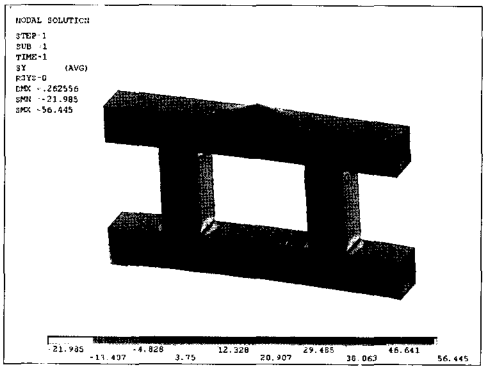


Fig 8. Full model exported to commercial package and with external load and boundary conditions

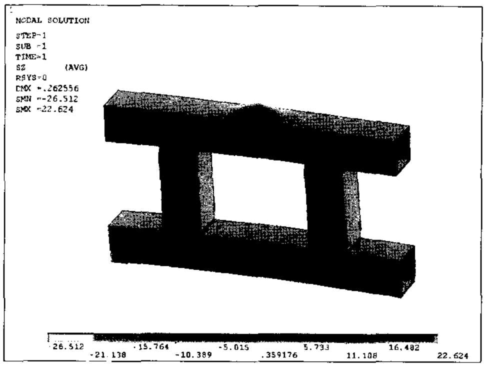
The stress distribution obtained due to the combined effect of the residual stress at the weld zone and external loading and boundary conditions are as shown in Fig 9.



(a) σ_{XX} distribution



(b) σ_{YY} distribution



(c) σ_{ZZ} distribution

Fig. 9 Stress distribution for the whole model obtained for the analysis considering external load and residual stress.

5. Conclusion

Specialized Finite element codes of heat-transfer analysis and residual stress analysis are presented and developed. Related the in-house solver to MSC PATRAN by PCL for pre and post processing. Fracture in the welded T-joint occurred at a similar level where the residual stress obtained in the numerical analysis is maximum$^{6)}$. This because the residual stress directly affected the development of the crack-tip opening stress with increase in load. Thus the accuracy of the finite element models is evaluated based on experimental results and the results of the analytical solution. Transferring the residual stress values calculated from the in-house solver to commercial package and further analysis with external loads that address realistic issues in industrial based welding application has been made applicable.

References

1. Lincoln electric company : Arc welding fundamentals, *www.lincolneletrics.com*, (1994)
2. R. W. Lewis, K. Morgan, H. R. Thomas, and K. N. Seetharamu : The finite element method in heat transfer analysis, *John Wiley & Sons*, (1996)
3. G. Comini, S. D. Giudice, and C. Nonino : Finite element analysis in heat transfer, *Taylor & Francis*, (1994)
4. J. Ueda, J. Wang, H. Murakawa, M. G. Juan : Three dimensional numerical stimulation of various thermo-mechanical processes by FEM (Report I), *Trans. of JWRI*, Vol. 21, No. 2(1992), pp. 111-117
5. MSC Institute of technology : PAT 304 customization course notes, *The MacNeal-Schwendler Corporation*, (1994), p. 3
6. L. H. Kim and J. R. Rasmussen : Strength of welded T-joint Truss connections between equal width cold-formed RHS, *NSW*, Sydney, (2006).