# Finite element simulation of post-buckling distortion for thin plate welding positioned by fixture

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***Abstract*****—** Thin plate welding is employed in a variety of industries, including production of automobile, ships structures and metal tanks. In the welding process, the moving electrode causes highly non-uniform temperature distribution that leads to residual stresses and different deviations, especially buckling distortions in thin plates. In order to control the deviations and increase the quality of welded plates, a fixture can be used as a practical and low cost method with high efficiency. In this study, a coupled thermo-mechanical finite element model is coded in the software ANSYS to simulate the behavior of thin plates located by 3-2-1 positioning system during the welding process. Computational results are compared with recent similar works to validate the finite element models. The agreement between the result of proposed model and other reported data proves that finite element modeling can accurately predict the behavior of welded thin plates.

***Keywords:*** Welding; Thin Plate; Buckling Distortion; Fixture Locators; Finite Element Modeling

## I. INTRODUCTION

NOWADAYS, in many industrial products such as automobiles, wagons, ships and metal tanks, large amounts of welded thin plates are used. Welding processes have several advantages over other permanent joining techniques including well sealing, high strength and weight reduction and improved performance of the final structure. However, thin plates welding may result in some geometrical deviations which, in turn, have negative impacts on assembly tolerances and product quality.

The main reasons that cause weldment deviations during welding are the moving heat source, non-uniform temperature distributions and temperature variations [1]. There are several basic types of welding distortion, which may occur on thin plates. There are several basic types of distortions which may occur during welding of plates. As shown in Fig. 1, they include transverse shrinkage, longitudinal shrinkage, angular, longitudinal bowing, rotational and buckling distortions.

For thin plates, due to low resistance against membrane stresses, buckling distortion is the dominant mode and plays an important role in distortion control strategies [2]. Furthermore, the positions of fixtures, as boundary conditions of the process, greatly affect the distortions of welded plates [3]. Therefore, using proper fixturing is an effective and low cost solution for welding distortion control.

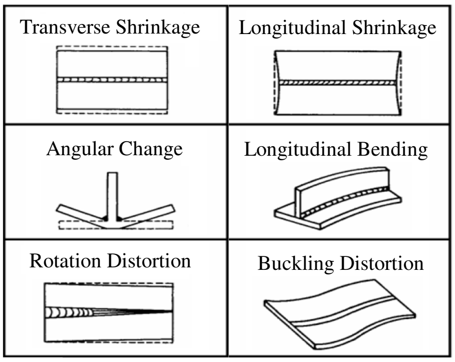

Fig. 1 Basic types of welding distortion.

Due to the high flexibility and minimal cost, numerical methods are the most widely used approach to predict welding deviations and residual stresses. Specifically, since mid 70's, Finite Element Method (FEM) is becoming more attractive to simulate various welding processes [4]. For instance, Hyde [5] simulated thin plates butt welding by a 2D and symmetric model. In several studies, the heat flux in the welding direction is ignored, but Gery [1] reveal shortcomings in this approach. As a solution, Goldak [6] considered the weld heat source has a double ellipse geometry that moves along the welding direction. Researches show that by applying this model, the results would be closer to reality [1, 4, 7]. Because the dimensional changes in welding are negligible, in most present studies the thermo-mechanical behaviors of welded plate is simulated using sequentially coupled formulation [8].

In this study, a 2D finite element model is employed to predict the post-buckling deviation in welded plates. The plate is fixed by 3-2-1 locating system, where the structure of fixture is made of two clamps and one pin. Also a mathematical Goldak's model is used to simulate the welding heat source. The finite element computations are done in two steps. First, the distribution of temperature in the plates is computed and then the temperature history is employed as a thermal load in the mechanical calculations of post-buckling distortions.

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## II. FINITE ELEMENT MODELING OF WELDING

In this study, the welding process for symmetric joining of two thin plates is modeled. As Fig. 2 illustrates, each plate has dimensions of 500×245×1 $mm^3$ and is located by a fixture including two toggle clamps and one simple pin. The material of plates is mild steel with the ST37 grade [9].

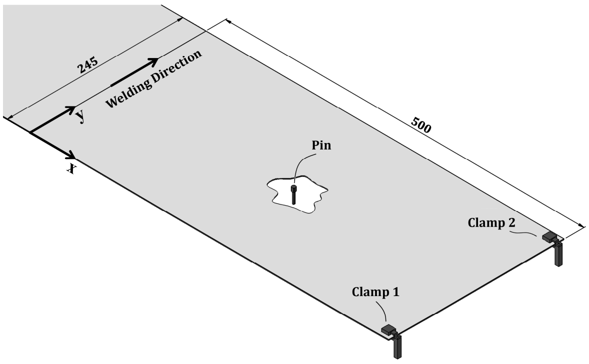

Fig. 2 Moving directions of fixture locators.

Since the effect of dimensional changes and mechanical work done on thermal energy from the welding arc are negligible, the thermo-mechanical behavior of the welding can be simulated by sequentially coupled formulation [10]. In other words, the thermal problem is solved independently from the mechanical problem. Hence, the solution procedure consists of two steps: First, the temperature distribution and its history in the welding model are computed using a transient thermal finite elements model. The temperature history is then employed as a thermal load in the mechanical calculations of post-buckling problem. The numerical calculations of thermal and mechanical steps is coded using software ANSYS.

In order to discrete the non-linear problem, 10 sets of element size and time stepping is tested. Fig. 3 shows the convergence of distortion measure by different discretion sets. Considering a reasonable solution time, sixth settings including 5300 elements, 2800 nodes and 0.5 s for time step is used in analyses. Fig. 4 represents the applied FE model for welding simulation. The elements of surrounding the locators and welding direction are selected finest, due to stress gradient increases at these areas.

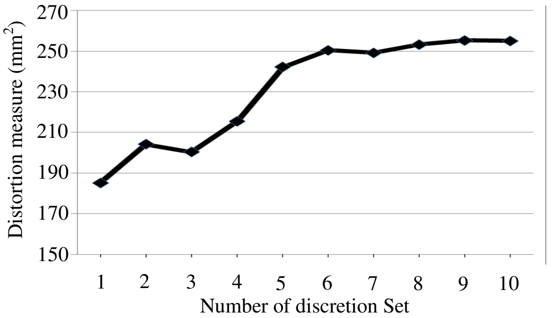

Fig. 3 Mesh sensitivity plot.

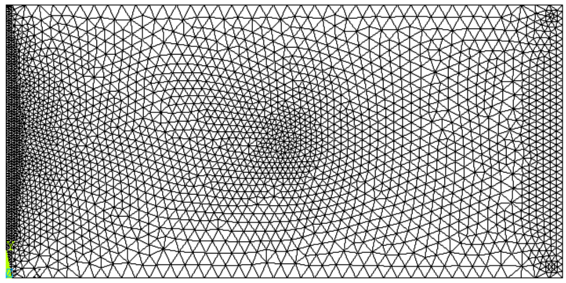

Fig. 4 Plate model used for 2D finite element analyses.

### A. Thermal analysis

In this work, a 2D double ellipse power distribution proposed by Goladk [6] is used to simulate the moving welding arc. Fig. 5 shows geometry and parameters of the double ellipse model in welding direction (y axis).

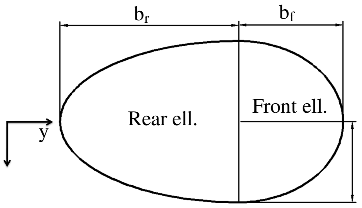

Fig. 5 Double ellipse heat source configuration.

Considering geometry of the welding pool, the heat distributions of the front and rear ellipse are obtained from (1) and (2), respectively.

$$q_f(x,y,t)=\frac{6f_f\,\eta V\,I}{a b_f\,\pi}e^{-3x^2/a^2}e^{-3(y-v\,t-y_0)^2/b_f^2} \tag{1}$$

$$q_r(x,y,t)=\frac{6f_r\,\eta V\,I}{a b_r\,\pi}e^{-3x^2/a^2}e^{-3(y-v\,t-y_0)^2/b_r^2} \tag{2}$$

Where $V$, $I$ and $\eta$ are voltage, current and heat source efficiency, respectively. In addition, distributed heat power in both ellipses is equal to the total power of welding arc ($Q = \eta\ I\ V$). Generally temperature gradient at front half of welding pool is steeper than rear half, so heat density in two ellipses distinction is given by fractions $f_f$ and $f_r$ of the heat deposited, where $f_f + f_r = 2$. In order to simulate moving heat source, a subroutine is coded in software ANSYS. Experimental measurements shows parameters $a$, $b_f$ and $b_r$ are 5, 3 and 7 mm and fractions $f_f$ and $f_r$ are 1.4 and 0.6, respectively. Also, welding speed, heat source efficiency, voltage and current are considered 4 *mm/s*, 0.8, 16 *V* and 65 *A*, respectively.

In order to simulate the temperature distribution in the welding process using ANSYS codes. The fluid flow and solidification of material in the welding pool cannot be directly considered because the coupled problem between solid and liquid is not involved in FEM software. However, the influence of fluid flow on the temperature distribution is significant. The highest temperature on the molten pool surface is approximately 1750 $^oC$. However, by neglecting the effect of fluid flow, the peak temperature would unusually increase to higher than 3000 $^oC$. This can be resolved using an artificially increased thermal conductivity in the weld pool. The thermal conductivity for temperature above the melting point is assumed to be approximately twice as large as its value of room temperature [10]. Heat losses due to convection and radiation are considered for all the surfaces. Also, a temperature-dependent film coefficient is used to make a more realistic model [8].

In this section, the thermal results of created FE model will be validated. The results of most works on welding validate by comparison with experimental tests. However, this approach is difficult, costly and time consuming. Therefore, the validation is performed by comparison with recent works such as that of Deng's [8]. For a welded plate having dimensions of 100×100×1 $mm^3$, he predicted temperature history at two points; one on the welding line and the other on the heat affected zone. The comparisons between the present work and Deng's results are schematically shown in Fig. 6 and Fig. 7. As these figures illustrate the thermal FE model can predict the welding temperature histories with good precision.

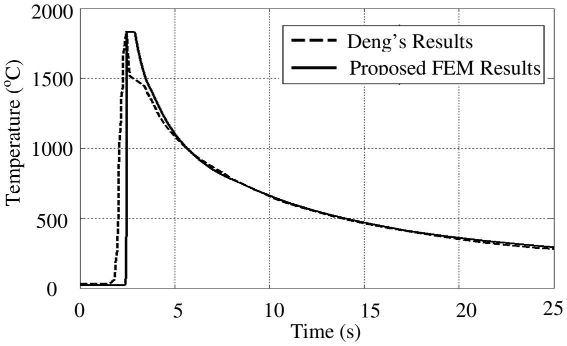

Fig. 6 Comparison of temperature histories at a point on welding line.

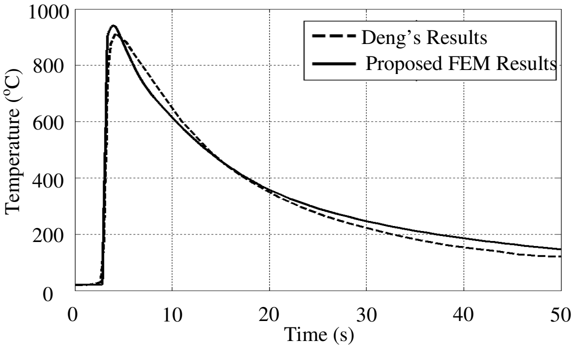

Fig. 7 Comparison of temperature histories at a point on HAZ.

By thermal simulating of welded plate, the temperature distribution can also be predicted. Fig. 8 shows the distribution of temperature, 55 second after welding starts. As shown, the peak temperature is at the tip of welding electrode and temperature gradient at the front of electrode is steeper than the rear. The temperature at different points of plate is time dependent. As the heat source gets closer, these points have peak temperature and then because of heat loses due to convection the plate will be cooled down to room temperature. Fig. 9 shows the temperature history at some points of Y 60 transverse section.

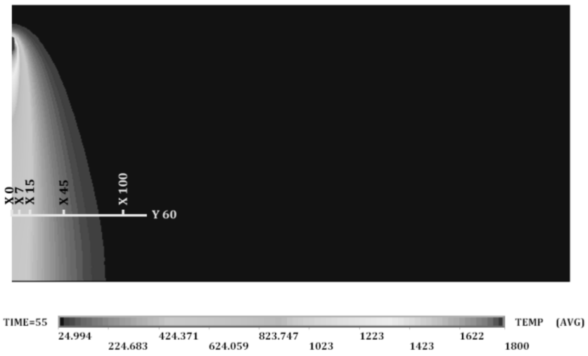

Fig. 8 Temperature distribution of half plate during welding.

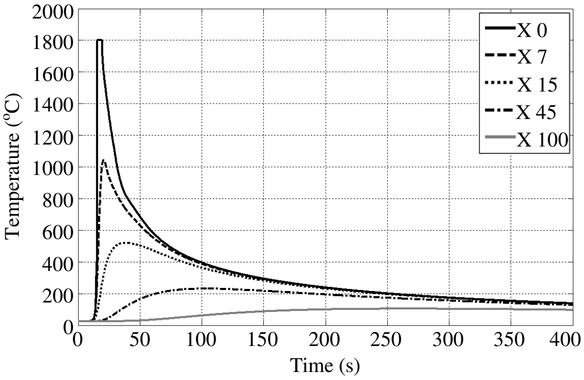

Fig. 9 Temperature histories at points of Y 60 transverse section.

### *B. Mechanical analysis*

In order to create mechanical finite element model, only the element type of thermal model should be changed. The thermal simulation can provide temperature history of welded thin plate. The temperature distribution is considered as thermal load in mechanical simulation. Generally, fixture structure can be assumed rigid in comparison with the plates. So, in order to simulate the fixture, nodes degree of freedom at locator positions restrain from displacement.

As mentioned above, the buckling distortion is the dominant mode of thin plate deviations during welding. The buckling problem can be solved by Eigenvalue and nonlinear (large deformation) methods. Eigenvalue buckling analysis predicts the critical buckling strength and shape mode of distortion. But using the nonlinear buckling analysis, the measure of distortion can be computed. In this way, the fabrication tolerance and quality of welded plates may be predictable. In this study, the nonlinear buckling analysis is used to predict behavior of weldment.

For the mild steel, influence of phase transformation on welding residual stresses and the distortion is insignificant. The total strain can therefore be decomposed into just three components as follows [8]:

$$\varepsilon_{ij} = \varepsilon_{ij}^{th} + \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \quad (1)$$

Where $\varepsilon_{ij}^{th}$, $\varepsilon_{ij}^{e}$ and $\varepsilon_{ij}^{p}$ are thermal, elastic and plastic strain, respectively.

The results of our mechanical analysis are then compared with similar recent works in the literature. In this regard, Raju's [11] case is simulated by proposed finite element model. He analyzed thermal post-buckling behavior of warmed square plate with simply supported edges using Rayleigh-Ritz method. In order to validate, two cases with uniform and non-uniform temperature distributions, are investigated applying Raju's equations and the proposed FE model. Computational results of two cases are shown in Fig. 10 and Fig. 11. As illustrated, the finite element method has been able to approximate buckling and post-buckling behavior of plates in both cases.

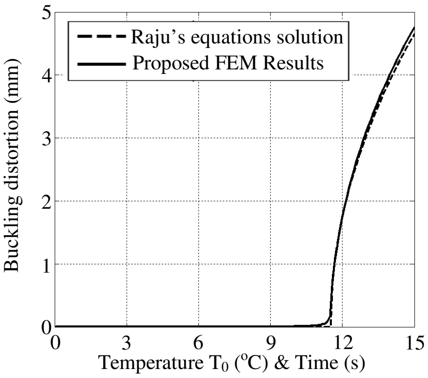

Fig. 10 Validation case with uniform temperature distribution ($T(x,y)=T_0$).

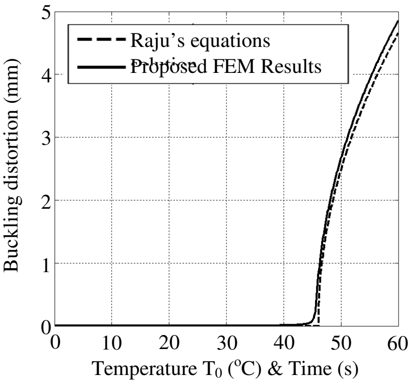

Fig. 11 Validation case with non-uniform temperature distribution ($T(x,y)=T_0(a-x)(a-y)/a^2$).

By applying the second simulation step, the mechanical behavior of welded can also be predicted. Fig. 12 shows that the measure of distortion at two areas between welding line and pin and between three locators is more than other areas.

Fig. 13 and Fig. 14 shows buckling will certainly occur at these areas. As these figures illustrate, the points close to welding line have been buckled immediately, but buckling occurs at the farther points in later times. Nevertheless, thermal strains at some points have been less than the critical values. For example, in Fig 14 a point at coordinate of (250, 60) positioned in the transverse direction of pin, is still stable.

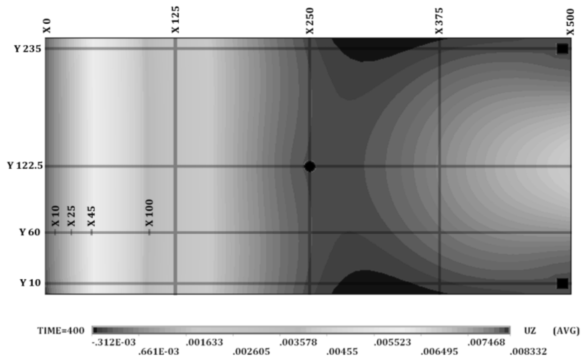

Fig. 12 Post-buckling distortion of one plate during welding.

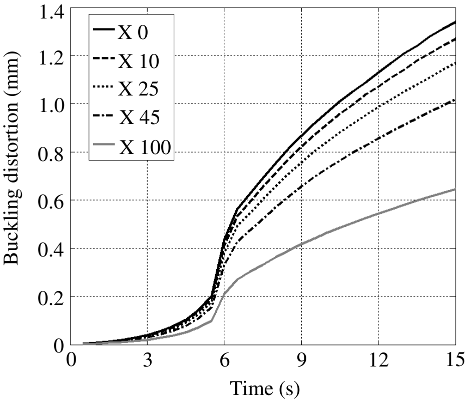

Fig. 13 Distortion histories at points close to welding line on Y 60 transverse section.

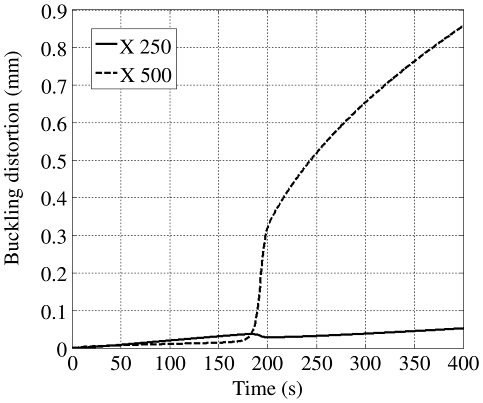

Fig. 14 Distortion histories at points far from welding line on Y 60 transverse section.

The buckling mode shape of longitudinal and transverse directions is shown in Fig. 15 and Fig. 16, respectively. It can be seen that because of the large ratio of plate length to width, the buckling occurs only in the longitudinal path at the area between the welding line and the pin. In addition, the pin has been effective in controlling buckling distortion.

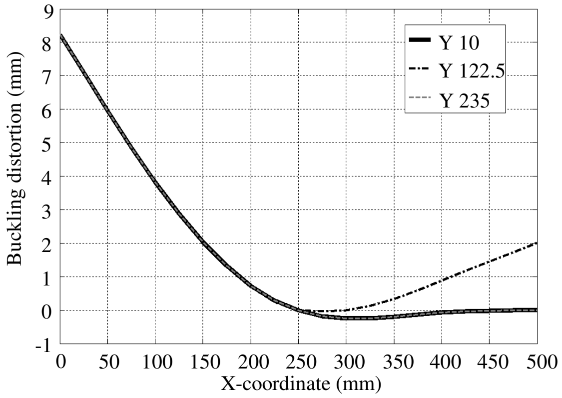

Fig. 15 Longidunial buckling mode shape of plate in different paths.

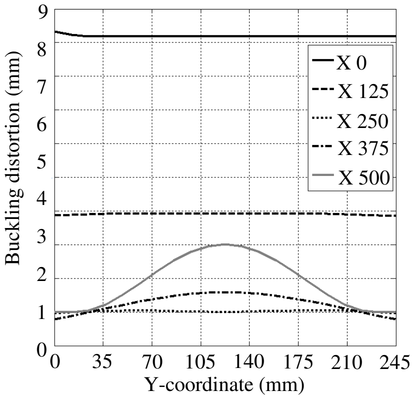

Fig. 16 Transverse buckling mode shape of plate in different paths.

## III. CONCLUSION

Welding distortions may cause geometrical and dimensional inaccuracies in the weldments. In this study, a thermo-elastic-plastic finite element model is used to predict the behavior of welded thin plate during butt welding. The proposed finite element model is close to actual welding process and has few realistic assumptions. In order to validate computational results of the finite element model, comparisons are performed with recently published thermal post-buckling and welding works. Computational results show that the proposed welding simulation can accurately predict temperature history as well as thermal buckling and post-buckling behaviors in a thin plate during the welding process. In addition, it is shown that proper fixture positions can control the welding distortions with great efficiency.

## ACKNOWLEDGEMENT

We highly appreciate Khorasan Razavi Gas Co. for their technical and financial support of this research.

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