Transactions of JWRI, Special Issue on WSE2011 (2011)

Study on Transient Buckling Behavior of Thin Plate Structures during Welding Process

Jiangchao WANG* and Hidekazu MURAKAWA**
* Osaka University, Yamadaoka 2-1, Suita, Osaka, 565-0871, Japan
** JWRI, Mihogaoka 11-1, Ibaraki, Osaka, 567-0047, Japan

KEY WORDS: (Thin Plate), (Transient Buckling Behavior), (Thermal Elastic Plastic), (High Strength Steel), (Welding Distortion), (Large Deformation Theory)

1. Introduction

For the fabrication utilizing welding method, welding distortion is always one of most complicated problems on welded structure. Furthermore, for the thin plate welded structure, the buckling type distortion is the most prevalent mode of welding distortion compared with other distortion modes. Considering the large deformation theory, the buckling type distortion of welded structure during and after the welding is investigated. In this study, the transient buckling behavior during the welding is studied by means of Thermal Elastic Plastic FE analysis.

In 1953, Masubuchi [1, 2] firstly presented the buckling type distortion of welded structure with experiments, where the plate may be buckled by the compressive residual stress in the plate when the plate is very thin or the length of the plate is very long compared with its breadth. Watanabe and Satoh [3] also studied this behavior deeply to propose the minimum half-wave length, below which a plate does not buckle, and maximum radius of curvature after buckling for thin steel plate due to bead-welding.

Later, Zhong, Murakawa and Ueda [4] proposed an elastic finite element approach, which bases on the elastic large deflection theory of plate, utilizing the inherent strain as an equivalent load determined by the process conditions. Deo, Michaleris and Sun [5] examined the welding-induced buckling distortion by means of employing decoupled two- and three dimensional approaches, where the investigating process can be divided into two steps, firstly determining the residual stress based on a two dimensional thermal and mechanical welding process simulation and obtaining the critical buckling stress and the buckling mode with a three-dimensional eigenvalue analysis subsequently.

2. Mechanism of buckling behavior under welding

The welding distortion is the result of the non-uniform expansion and contraction of the weld and surrounding base material, caused by the heating and cooling cycle of the welding process [6]. The heated region tries to expand but is restrained by the surrounding colder material, causing this region to yield in compression during the heating process; however, the colder material prevents the contraction of this region, causing tensile stresses, for the cooling process. The basic cause of welding distortion can be presented as the tension stresses develop around the welding line combined with simultaneously generated compression stresses in the welded structure.

2.1 Mechanical Failure Behavior of Material

Based on the theory of plate deformation under uniaxial force, it is well-known that the material will yield when the external loading F_{load} exceeds the yield stress regardless the compressive or tensile case. **Equation** (1) gives the essential mechanism of yield behavior of plastic material. On the other hand, the buckling will occur when the external compressive loading exceeds the critical stress given by **Eq**. (2), which not only depends on the material properties but also is influenced by shape of plate and thickness.

$$\text{Yield Case:}\quad \frac{F_{load}}{A} = \sigma > \sigma_Y = E\varepsilon_{total} \tag{1}$$

$$\text{Buckling Case:}\quad \frac{F_{load}}{A} = \sigma > \sigma_{cr} = \frac{k}{12}\frac{\pi^2 E}{1-\nu^2}\left(\frac{t}{b}\right)^2 \tag{2}$$

Where, σ_Y and σ_{cr} means the yield stress and critical stress for buckling; A means the area of cross section; E and ν are the material properties such as Young's modules and Poisson's ratio; t and b is the thickness and width of plate; The k is a numerical factor which determined by the aspect ratio and boundary condition.

Generally, the structure is welded by thick plate; the yield behavior and its resulting plastic deformation are the dominant issue of welding mechanics. However, when the high strength materials and its alloy are employed, the welded structure can be designed and fabricated using thin plates. In this case, the buckling behavior will become of the popular problem for the thin plate structures.

2.2 Large Deformation Theory

According to the large deformation theory, the buckling behavior is a kind of non-linear response, which also considered as a stability problem. This behavior can be examined when the large deformation theory is applied.

The equation relating the strain and displacement is an essential equation to describe this non-linear response. If the small deformation is assumed, the strains are given as a linear function of displacements. However, the non-linear relation between strain and displacement will be considered in large deformation theory, where Green-Lagrange strain which is the second order function of the displacements will be used, the strain is given by **Eq**. (3). From the expression of this strain, the first order term represents the linear response; the second order term is essential to the non-linear behavior utilizing the large deformation theory.

$$\varepsilon_x = \frac{\partial u}{\partial x} + \frac{1}{2}\left\{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right\} \tag{3}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} + \frac{1}{2}\left\{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right\}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \left\{\left(\frac{\partial u}{\partial x}\right)\left(\frac{\partial u}{\partial y}\right) + \left(\frac{\partial v}{\partial x}\right)\left(\frac{\partial v}{\partial y}\right) + \left(\frac{\partial w}{\partial x}\right)\left(\frac{\partial w}{\partial y}\right)\right\}$$

Where, ε_x and ε_x means the strain in x and y direction; γ_{xy} means the shear strain on the x-y plane. u, v and w are the displacement in the x, y and z direction, respectively.

2.3 Thermal Elastic Plastic FEA

With the development of advanced computer and numerical technology, the Thermal Elastic Plastic FEM is widely accepted to analyze the welding problems for various typical welded joints and simple welded structures. In this study, the thermal-mechanical behavior during welding process is analyzed using thermal/mechanical uncoupled formulation. However, the uncoupled formulation considers the contribution of the transient temperature field to stresses through thermal expansion, as well as temperature-dependent thermal-physical and mechanical properties. The solution procedure consists of two steps. First, the temperature distribution history is computed using heat conduction analysis. Second, the transient temperature distribution obtained from the heat conduction analysis is employed as a thermal load in the subsequent mechanical analysis. Stresses, strains and displacements are then computed.

3. Investigation on Buckling Behavior by FEM

In this study, the bead on plate of same thickness with different material properties is examined. **Figure**.1 shows the FEM model of investigated object with dimensional information. The boundary conditions to remove the rigid body motion and 6 points to study out-of-plane welding distortion are also presented shown in **Fig**. 1.

3.1 Analysis Based on Small Deformation

Because the heat source will penetrate thin plate during welding process, there is almost no temperature gradient in thickness direction, so the out-of-plane distortion is not produced. If the large deformation theory is not employed, the buckling type welding distortion caused by compressive stress can't be predicted. **Figure** 2 shows the negligible out-of-plate welding distortion around the welding line produced by accumulation of in-plane shrinkage regardless the materials.

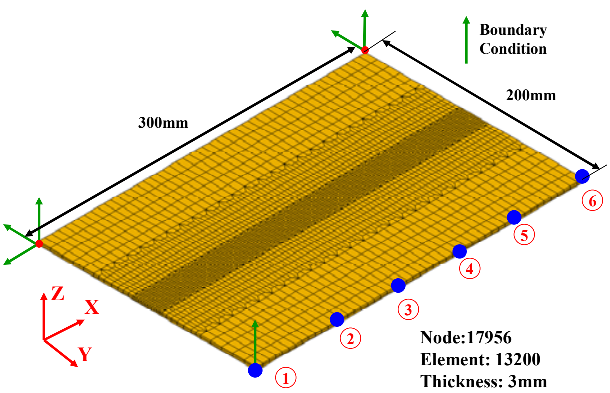


Fig.1 FEM Model of Thin Plate

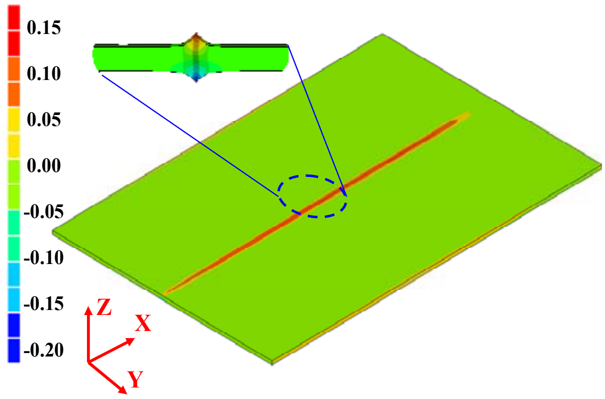


Fig. 2 In-plane Shrinkage of Thin Plate

Table 1 Welding Condition (TIG)

Current	Voltage	Velocity	Efficiency
175-185(A)	14-16(U)	3.6mm/sec	0.7-0.8

3.2 Residual Buckling Distortion

For the buckling behavior of welded structure, the welding longitudinal shrinkage [7], caused by welding tendon force, produces compressive stress in the surrounding plate fields that sometimes make welded structure to buckle after the welding process.

When the material of plate is Q345 (yield stress: 345Mpa), the residual buckling distortion will appear on the welded structure. **Figure** 3 shows the buckling type distortion of thin plate evaluated by TEP FE analysis considering the large deformation theory after the welding process. Meanwhile, **Fig.** 4 shows the buckling type distortion of same welded structure using material of HT950 (yield stress: 950Mpa). Both welded structures have large out-of-plane welding distortion (residual buckling distortion) after the welding process, which caused by compressive residual stress to balance tension around the welding line after the cooling process.

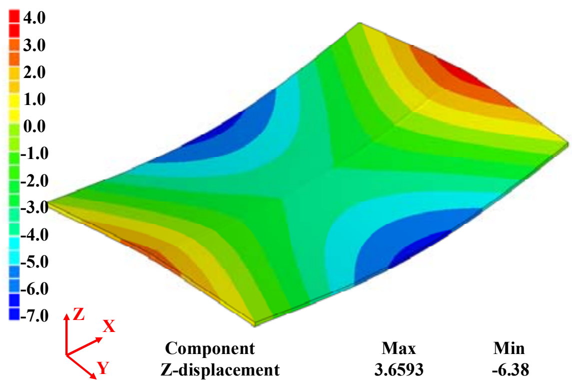


Fig. 3 Buckling Distortion (Q345)

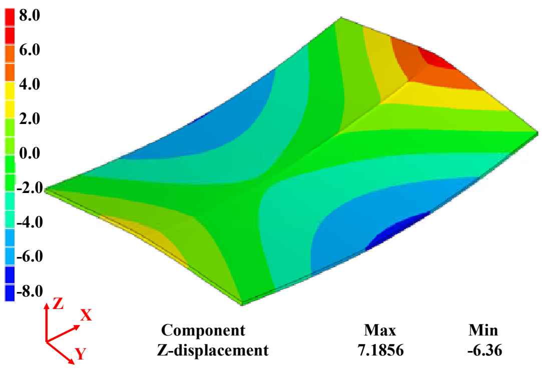


Fig. 4 Buckling Distortion (HT950)

3.3 Transient Buckling Behavior

From the above research, the same buckling behavior on welded structures made of materials with different yield stress after the welding process is indicated as shown in **Fig**. 3 and 4. However, the transient buckling behavior occurs only for the structures assembled by high strength steel during the welding process. In order to investigate this transient buckling behavior, six studied points shown in **Fig**. 1 are selected to observe the in-process out-of-plate welding distortion.

Firstly, the welded structure of Q345 is examined. **Figure** 5 illustrates the displacement of thickness direction at studied point during the welding process and subsequent cooling process. In **Fig**. 5, there is almost no out-of-plane distortion at studied points before finish of welding and relative large distortion appeared abruptly caused by compressive residual stress at edges during the cooling process.

When material of HT950 is examined, the displacements of thickness direction at studied points also are plotted in **Fig**. 6. From this result, the out-of-plane welding distortion during welding process appears. Because of no welding bending for thin plate structures, it can be summarized that the transient buckling generated large out-of-plane displacement, only on the high strength steel during the welding process. Meanwhile, the residual buckling distortion after the cooling process shown in **Fig**. 6 is indicated in opposite direction compared with transient case.

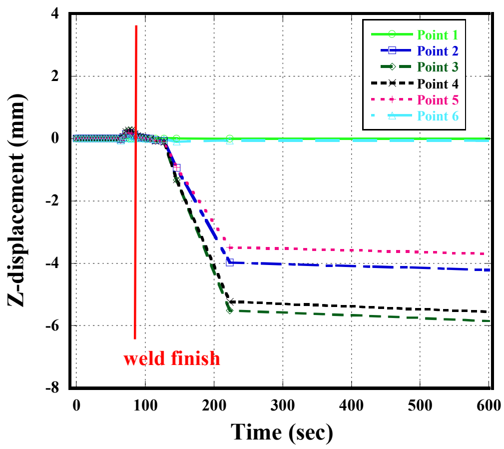


Fig. 5 Z-displacement of Studied Points during Welding (Q345)

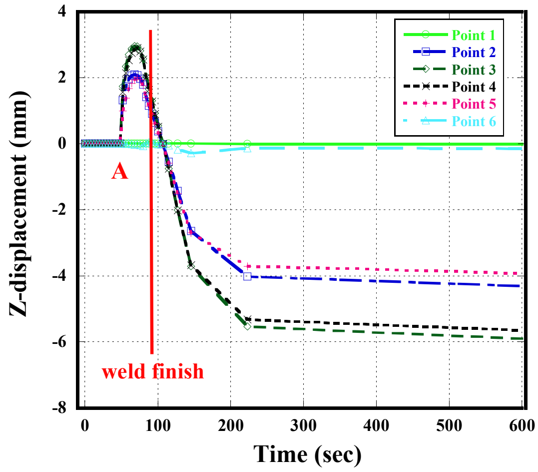


Fig. 6 Z-displacement of Studied Points during Welding (HT950)

In **Fig**. 7, the distributions of out-of-plane distortion at different moment of welding process are shown. The reason of this behavior can be explained as the response to changing of distributed internal compressive stress in welded structure. Furthermore, the temperature field, longitudinal internal compressive stress field and out-of-plane displacement field at the time when transient buckling occur during welding process are computed by thermal-mechanical FE analysis are shown in **Fig**. 8.

To closely examine the stress distribution just before the buckling starts to develop, the stress distribution at point A in Fig. 6 are compared between HT950 and Q345 plate. Figure 9 shows the distribution of the stress component in welding direction along the transverse direction at the moment when the welding torch is passing the center of the plate (point A in Fig. 6). As seen from the case of HT950, larger compressive stress is observed in the

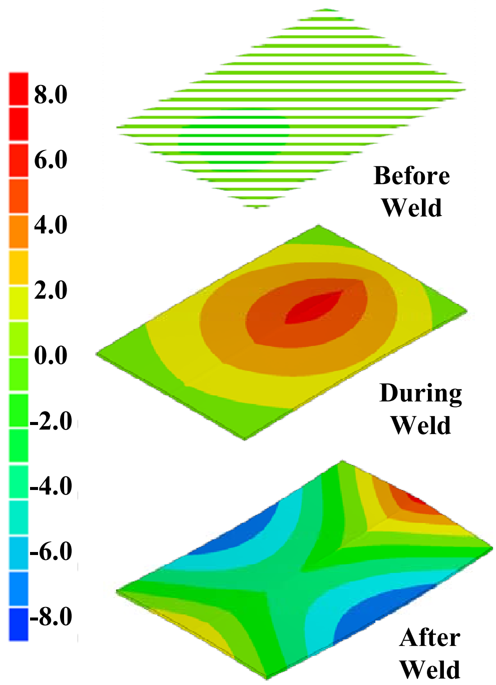
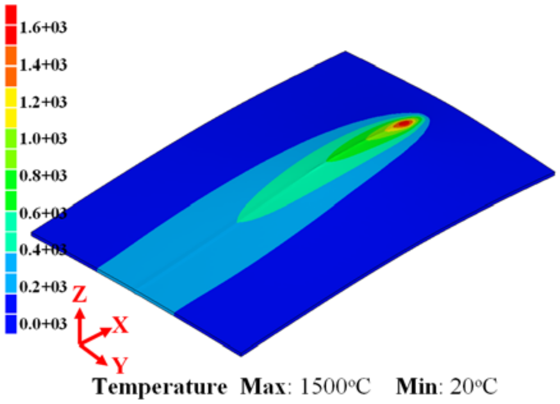
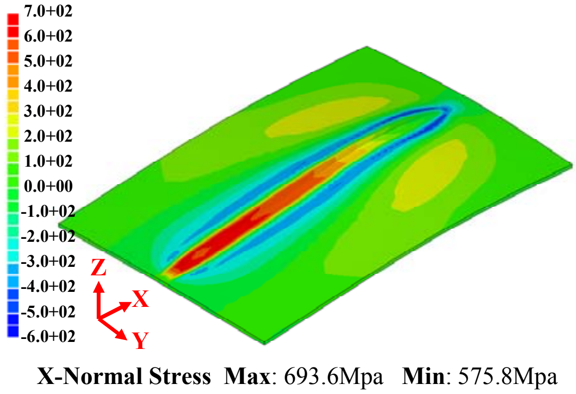


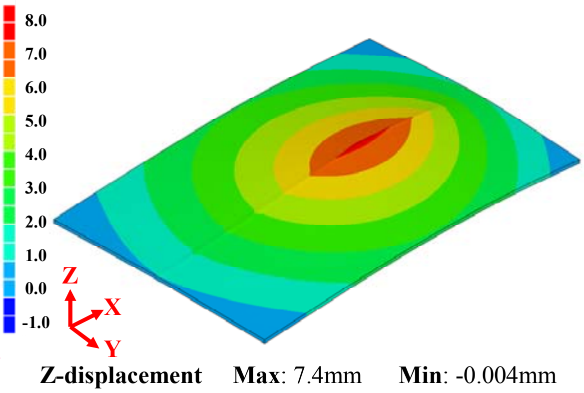
Fig. 7 Buckling Behavior Caused by Welding



(a) Temperature Field



(b) Longitudinal Internal Stress Field



(c) Out-of-plane Displacement

Fig. 8 Thermal-Mechanical Analysis during Welding

area just beside the welding line compared to the case of Q345. This explains that the buckling during the heating stage is likely to occur when the yield stress of the material is high.

4. Conclusions

From the above investigated results, the following conclusions can be drawn.

(1) When structures are designed, both yielding and buckling are considered as the major failure modes. Similarly yielding and buckling must be taken into account to predict the welding distortion in thin structures.

(2) The buckling type distortion, caused by welding on thin plate structures, can be predicted using Thermal Elastic Plastic FEA in which the large deformation theory is considered

(3) When welded structure is assembled by thin plate, the buckling type distortion will become of critical importance. Buckling type distortion can be produced not only in the cooling process but also produced during heating process when the yield stress is high.

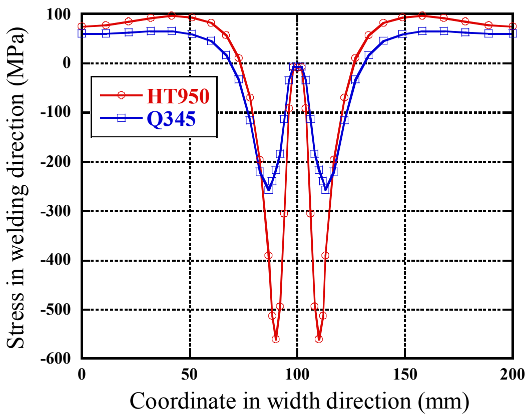


Fig. 9 Distribution of Stress for Different material before Buckling occur

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