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Introduction of Prediction Method of Welding Deformation by Using Laminated Beam Modeling Theory and Its Application to Railway Rolling Stock

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Abstract

The welding deformation and its prediction method at the HAZ (Heat-Affected Zone) are presented in this paper. The inherent strain method is well known as analytical method to predict welding deformation of large scale welded structure. Depend on the size of welding deformation in welding joints, the fatigue life, the stress concentration factor and the manufacturing quality of welded structure are decided. Many welded joints and its manufacturing control techniques are also required to railway rolling stock and its structural parts such as railway carbody and bogie frame. Proposed methods in this paper focus on the two different the inherent strain area at HAZ. This is main idea of proposed method and it makes more reliable result of welding deformation analysis at the HAZ.

Keywords **:** *Railway carbody, Heat affected zone*

Nomenclature

b = maximum breadth of the inherent strain region
d = maximum depth of the inherent strain region
D = deformation at the center
k_s = Spring constant of the temperature change region
k_b = Spring constant of the adjacent region
E_b = Young's modulus of the temperature change region
E_s = Young's modulus of adjacent region
h = thickness of the plate
m_y = moment on the welded line (Equivalent load)
v_b = Poisson ratio of the temperature change region
v_s = Poisson ratio of the adjacent region
Z = section modulus
α = thermal coefficient (1/)
σ_{Yb} = yield stress of the temperature change region
r = radial distance of disk
ε = total strain
ε^e = elastic strain
ε^p = plastic strain
ε^{th} = thermal strain
ε^{tr} = phase transformation strain
ε^* = inherent strain generated by the loading condition
b_1 = maximum breadth of the inherent strain region
b_2 = maximum breadth of the heat equilibrium zone
d_1 = maximum depth of the inherent strain region
d_2 = maximum depth of the heat equilibrium zone
r_1 = radial distance of the inherent strain region
r_2 = radial distance of the disk heat equilibrium zone
k_1 = spring constant of the inherent strain region
ε^*_1 = inherent strain with disk type and ring type area
ε^*_2 = inherent strain with ring type area
ε^*_2 = inherent strain with disk type area
b_{z1} = breadth of the inherent region
b_{z2} = breadth of the heat equilibrium zone
E_1 = Young's modulus of the inherent strain region
E_2 = Young's modulus of the heat equilibrium zone
E_3 = Young's modulus of the adjacent region (plate area)
m_1 = Equivalent load at the inherent region
m_2 = Equivalent load at the heat equilibrium region
V = Welding arc voltage[Volt]
I = Welding current flowing between welding rod and base plate
Q = heat input per unit length
V_s = welding speed
F_b = transverse shrinkage force of the adjacent region
F_s = transverse shrinkage force of the temperature change region
η = welding effiency

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1. Introduction

Railway carbody and bogie frame have many welded joints. These metal parts are jointed by heat and it permanently boned. Residual stresses at HAZ are caused by welding deformation. The welding deformation negatively affects the required precision and stability of structural materials. For the last twelve years, among the methods used to predict welding deformations, the equivalent loading method based on the inherent strain [1] has been successfully applied to calculate welding deformation due to its effective and reliable results.

It is important to determine the inherent strain regions. The inherent strain method does this by calculating the temperature distribution during welding [2] and converting it into equivalent loads, from which it is able to determine the deformation. Because this method independently generates a term related to the angular deformation, it can be applied very efficiently to precision deformation processes.

2. Inherent Strain in the HAZ

The total strain can be divided into the elastic, thermal, plastic, and phase transformation strains,

$$\varepsilon = \varepsilon^{th} + \varepsilon^{p} + \varepsilon^{tr} + \varepsilon^{e} \tag{1}$$

The inherent strain is defined as the irrecoverable strain after removing structural restraints and loads, or the sum of elastically irrecoverable strains that induce permanent deformation of the material,

$$\varepsilon^{*} = \varepsilon^{th} + \varepsilon^{p} + \varepsilon^{tr} = \varepsilon - \varepsilon^{e} \tag{2}$$

Typical inherent strains include plastic, thermal, and phase transformation strains, *i.e.*, the total strain with the exception of the elastic strain [3]. A one-dimensional (1D) bar-spring model (Fig. 1) can be used to define the welded zone and the inherent strain caused by welding [4]. The bar in Fig. 1 represents the temperature change region while the spring in represents the area of the welded zone with the exception of the temperature change region. Using a similar method, Fig. 2 uses a two-dimensional (2D) plate-spring model to describe the welded zone conditions in more detail. The 2D plate-spring model applies the coefficient and spring constant from the 1D bar spring model. The spring model simulates the elastic restraint from the surrounding area outside the disk against the disk expansion and shrinkage caused by a temperature change. During temperature changes, the spring's restraining action induces an internal stress in the bar. The inherent strain equation,

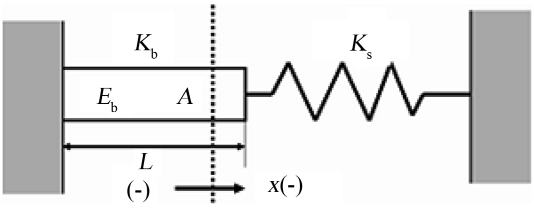

Fig. 1 Force equilibrium in bar-spring model

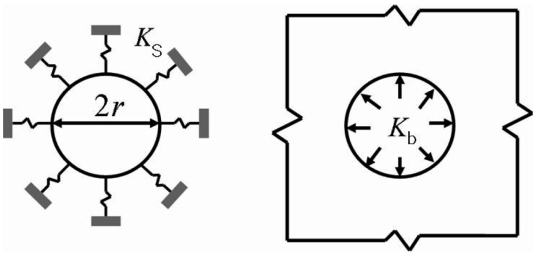

Fig. 2 Force equilibrium in disk-spring model

$$F_s = k_s \times x \tag{3}$$

$$F_b = \sigma_{yb} \times A \tag{4}$$

$$\varepsilon^{*} = \varepsilon\left(= \frac{x}{L}\right) - \varepsilon^{e}\left(= -\frac{\sigma_{yb}}{E_b}\right) \tag{5}$$

$$F_s = F_b \tag{6}$$

$$\varepsilon^{*} = \frac{\sigma_{yb}}{E_b}\left(\frac{k_s}{k_b} + 1\right) \tag{7}$$

Eq. 4 indicates the external force acting on a bar by a spring equals a material's internal force.

$$k_b = \frac{E_b}{r \times (1 - v_b)} \tag{8}$$

$$k_s = \frac{E_s}{r \times (1 - v_s)} \tag{9}$$

$$\varepsilon^{*} = \frac{\sigma_{yb}}{E_b}\left(\frac{E_s}{E_b} \times \frac{1 + v_b}{1 - v_s} + 1\right) \tag{10}$$

Based on the definition of the spring constants in Eq. 8 and Eq. 9, the 2D plate-spring model expresses the inherent strain as given by Eq. 10

3. Determining the Inherent Strain Region

The 2-D geometry of inherent strain region was introduced in Fig 3. And the result of computational heat conduction analysis was shown in Fig. 4.

Maximum temperature on the bead modeling was considered of 2300°C [6]. Any area reaching temperatures

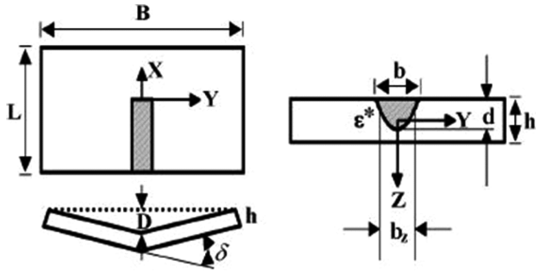

Fig. 3 Heat transfer analysis and geometry of the inherent strain region

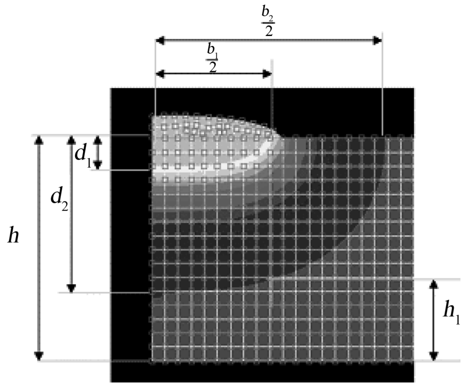

Fig. 4 Geometries of the inherent strain region

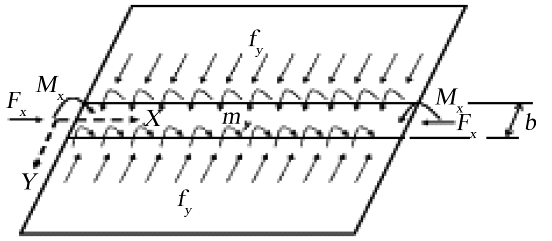

Fig. 5 Distribution of the equivalent load along the welded line equation [7]

above 700°C during the welding process was defined as part of the inherent strain region [7]. Fig. 3 shows the maximum breath (b) and maximum depth (d) of the inherent strain region.

The geometry of the inherent strain region in FEM (Finite Element Method) model is illustrated in Fig. 4.

4. Determining the Equivalent Load

Equivalent load in equation 11 was earned by substituting the geometrics values determined in Sections 3 [7]

$$m_y = \frac{1}{b}\int_{-\frac{h}{2}}^{\frac{h}{2}} E_b \varepsilon^* b_z z dz = \frac{1}{6} E_b \varepsilon^* dh\left(\frac{3\pi}{4} - 2\frac{d}{h}\right) \quad (11)$$

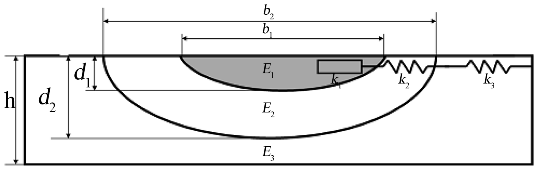

Fig. 6 Organization of springs in HAZ

5. Advanced Equivalent Loading Method

We discussed fundamental knowledge of conventional inherent strain method in section 3. It was only considered inherent strain area and other area. These areas were used to drive prediction formula of conventional welding deformation.

But the main idea of advanced inherent strain method is to define additional layer at the HAZ and applied its geometry dimensions to equivalent loading method. The additional area is defined between inherent strain and adjacent region is named heat equilibrium zone.

The advanced method is considered the heat equilibrium zone as the adjacent area based on the region in the direction of its depth and its temperature dependence material properties.

The heat equilibrium area in advanced inherent strain method is performed additional heat layer to calculate reliable inherent strain results. So three different layers existed in advanced inherent strain method such as k_1, k_2, k_3. The k_2 is core theory of this formula. k_2 is in spring constant in heat equilibrium zone is divided into ring and disk types spring constants based on the springs restrictive conditions on the level of depth in HAZ [9].

$$m_{y1} = \frac{1}{b_1}\int_{-\left(\frac{h}{2}\right)}^{-\left(\frac{h}{2}-d_1\right)} E_1 \varepsilon_1^*(z) b_{z1} z dz \quad (12)$$

$$m_{y2} = \frac{1}{b_1}\left(\int_{-\left(\frac{h}{2}-d_1\right)}^{\left(d_2-\frac{h}{2}\right)} E_2 \varepsilon^*_{2\_disk} b_{z2} z dz + \int_{-\frac{h}{2}}^{-\left(\frac{h}{2}-d_1\right)} E_2 \varepsilon^*_{2\_ring}(b_{z2}-b_{z1}) z dz\right) \quad (13)$$

Depend on definition the area of temperature changing zone at HAZ, equivalent load can be expressed as Eq. 12 and 13. The total summation of the results from Eq. 12 and Eq. 13 are total equivalent load in HAZ in advanced inherent strain method.

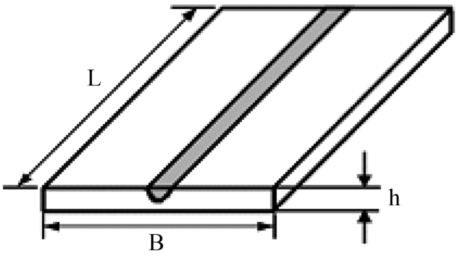

Fig. 7 test specimen model

Table 1 Welding Condition in Experimental

Plate thickness	I	V	V_s	η
cm	A	V	cm/sec	%
1.2	235	25	0.7	0.7

Table 2 Comparison of the Experimental Results with the Angular Distortion Analysis

	Angular Distortion (rad)
Experimental results (1)	0.006322
Analysis results using the proposed ε* (2)	0.0058
Analysis results using the conventional ε* (3)	0.00512
FEM (4)	0.00542

6. Application the Equivalent Load to FEM Model or Simple Beam Formula

The welding deformation of the specimen can be calculated using the elastic analysis method introduced by Jang *et al.*[1] and Nomoto *et al.*[8] It can also be calculated using a simple beam deflection formula.

7. Comparison of the Experimental Results with Advanced Inherent Strain Method

Experimental welding condition was introduced in Table 1.

$$\frac{Q}{h^2}=\frac{0.24VI\eta}{V_s h^2} \tag{14}$$

Eq. 14 indicates that calculation method in heat flux in experimental welding line.

Table 2 gives the maximum deformation results from the experiment and the analyses measured at the central point of the specimen. The results of the proposed method gave us more reliable result than conventional simple inherent strain method. Conventional inherent strain method was very limited to predict deformation at HAZ because it simply assumed inherent strain areas.

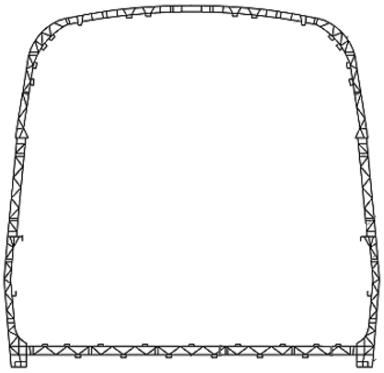

Fig. 8 All extruded aluminum carbody

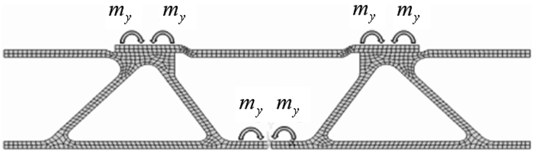

Fig. 9 Application of equivalent load to all extruded aluminum carbody

8. Application the Equivalent Load to Railway Rolling Stock

Many railway rolling stocks are manufactured by welding process. But many assembled and welded railway rolling stocks had been evaluated their structural stability by using FEM without considering post welding plastic and elastic mechanical properties of the line along welded jointed.

As shown Fig 9, equivalent load can be applied to FEM model of all extruded aluminum carbody. And equivalent load was also applicable to the line along the welded joint to verify distribution residual stress in full assembled FEM model.

9. Conclusions

We developed a new method for calculating the inherent strain by incorporating the heat equilibrium area effects into the heat transfer analysis. The following conclusions may be drawn.

1. An equivalent loading method was introduced based on the inherent strain.
2. Main as advantage of inherent strain method is not to require an elasto-plastic finite element analysis.
3. The inherent strain method that incorporated the heat equilibrium area effects produced more reliable results than the conventional method.

4. The conventional inherent strain method was only consider inherent strain area as temperature changing region but advanced method consider additional heat equilibrium area to second temperature changing region at HAZ. It provide more accrue result

Therefore, we can use the proposed inherent strain method to predict welding deformation as well as its residual stress at welding joint of railway rolling stock.

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