Characteristics of Distortion Generated by Welding under Static Loading

Transverse shrinkage varies according to type of load and welding length

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ABSTRACT. The basic equation describing the transverse shrinkage produced by welding under loading is derived. The validity of the basic equation is supported by results measured at a main suspension tower and a test specimen. According to the measured results of transverse shrinkage in the main tower of a suspension bridge, when the dead weight (compressive stress) increases, transverse shrinkage tends to decrease. Dead weight has a large influence on the transverse shrinkage produced by welding under loading. Based on the rearranged experimental results of Suzuki (Ref. 1), the following results were obtained. The gauge length is generally shortened when welding is done without applied load. However, when welding is done under tensile load, gauge length is elongated and, moreover, large elongation occurs because the base plate becomes plastic owing to the large applied load. Under compressive load, transverse shrinkage increases rapidly when welding length is relatively short compared to plate width. On the other hand, under tensile load, transverse shrinkage is small even if welding length is shorter than two-thirds of plate width, but it increases rapidly at welding lengths longer than two-thirds of plate width. Welding under compressive loads was more severe than welding under tensile loads.

Introduction

When repair, reinforcement, and reconstruction for functional improvement are performed on constructed structures such as bridges, welding under loading at the site is often unavoidable because it is generally impossible to transport components back to the factory. The dead weight effect on transverse weld joints such as main suspension towers increases as the steel structures become larger. Although the problems of welding deformation have been studied as main subjects in welding mechanics (Refs. 2–4), welding deformation under loading has rarely been investigated (Ref. 1).

In this paper, the basic equation describing the transverse shrinkage produced by welding under loading is derived based on assuming a one-dimensional model for the source of welding deformation. The results of transverse shrinkage, as measured in the transverse joints of the main suspension tower and in a test specimen under loading, are determined. The validity of the derived basic equation is investigated and the influences of applied load on transverse shrinkage are elucidated.

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Characteristics of Transverse Shrinkage under Loading

Using a one-dimensional model, the influence of the applied load on the transverse shrinkage produced by welding under loading and the basic characteristics are investigated. Figure 1 shows the model employed in this work. One edge of each bar is fixed and the other edge is connected to a rigid body. Each bar is free to expand, but cannot be rotated. Shrinkage is assigned positive value.

Source of Transverse Shrinkage

The source of welding deformation (transverse shrinkage) is the free shrinkage at the groove produced during the cooling stage to room temperature. The degree of deformation is controlled by in-plane stiffness. So it can be assumed (Ref. 2) that free shrinkage is the virtual displacement u_T, to which no load is applied and which can be expressed by the following equation:

KEY WORDS

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$$u_T = \alpha \cdot T_{av} \cdot L \tag{1}$$

where T_{av} is the average rise in temperature, α is the linear expansion coefficient, and L is the initial length of the bar.

When load is applied in the initial state, the edge of the bar is uniformly deformed by load P. Strain ε_{L0} and displacement u_{L0} are expressed by the following equations:

$$\varepsilon_{L0} = \frac{P}{(A_{I} + A_{II} + A_{III}) \cdot E} \tag{2}$$

$$u_{L0} = L \cdot \varepsilon_{L0} \tag{3}$$

where P is the applied load; compression (shrinkage) is assigned a positive value; A_i is the cross-sectional area of each bar (i = I – III); and E is Young's modulus.

Next, when welding is done on the broken line of bar II, bar II can be regarded as being in the state in which two bars are separated at temperature T_m (in structural steel, T_m=700°C) where the yield stress σ_Y of the material is exceeded. As bar II cannot support the applied load, the load is redistributed to bars I and III. The degree to which the edge of the bar is deformed from the initial state, u_{La}, is determined by the following equation:

$$\begin{aligned} u_{La} &= u_{L1} - u_{L0} \\ &= L \cdot \varepsilon_{L1} - L \cdot \varepsilon_{L0} \\ &= (u_{L0} \cdot A_{II}) / (A_{I} + A_{III}) \end{aligned} \tag{4}$$

where, ε_{L1} (which equals $P/\{(A_I + A_{III}) \cdot E\}$) is the strain of bar I and bar III after redistribution of loads.

Therefore, the virtual displacement u_P under loading is obtained as the sum of u_T without load, u_{L0} at the initial state under load, and u_{La} produced by the melting of bar II.

$$\begin{aligned} u_P &= u_T - (u_{L0} + u_{La}) \\ &= u_T - u_{L1} = K_L \cdot u_T \end{aligned} \tag{5}$$

where $K_L = 1 - (u_{L1}/u_T) = 1 - \{(L \cdot \varepsilon_{L1})/(\alpha \cdot T_{av} \cdot L)\}$.

As mentioned above, the virtual dislocation u_P under loading is K_L times greater than the virtual dislocation u_T to which no load is applied. u_P decreases under compressive loads and contrarily increases under tensile loads.

Transverse Shrinkage under Loading

Transverse shrinkage S_P produced by welding under loading is obtained as the sum of u_{La} produced by the melting of bar II and the deformation of system $S(u_P)$ produced when the virtual dislocation u_P is closed. S_P is expressed by the following equation.

$$S_P = u_{La} + S(u_P) \qquad (6)$$

Equation 6 is the basic equation describing the transverse shrinkage produced by welding under loading.

Therefore, when tack welding or first pass welding is performed in the groove, the root opening cannot undergo large change under tensile loads for which plasticity or buckling are not generated. In this case, u_{L0} and u_{La} in Equation 5 can be ignored, and it is found that transverse shrinkage S_P under loading is the same as S_P in welding without applied load.

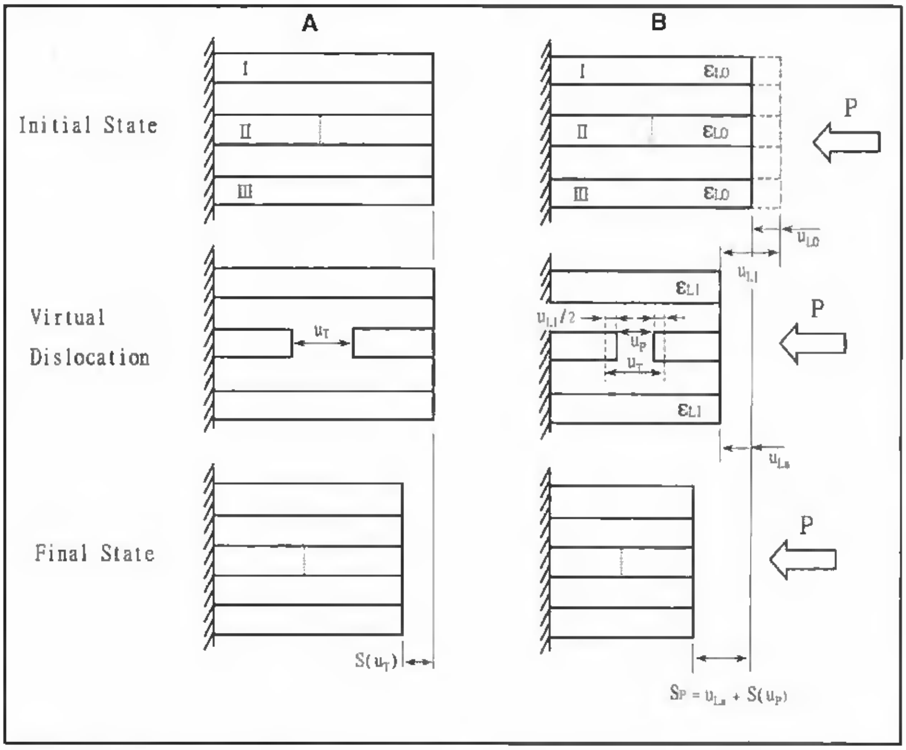

Fig. 1 — Production process of transverse shrinkage under loading: A — without loading; B — under loading.

Measured Results of Transverse Shrinkage

The transverse shrinkage measured in the transverse joints of the main suspension tower and that in the test specimen under loading are shown.

The Transverse Joints of the Main Suspension Tower

The transverse joints of the main suspension tower are provided as an example of welding under loads on large steel structures. As welding is done after the construction of each block on the top of the towers, compressive load in the range of 931–5000 kN is affected by the dead weight of the block. Figure 2 shows the composition of the typical cross sections of welded joints and a groove. Transverse shrinkage is measured by dial gauges at the points where the gauge length is 150 mm (three points on each side, for a total of 12 points).

Figure 3 shows the average values of transverse shrinkage measured at 12 points for the normal stress due to the dead weight affecting the cross section of the welded joint. According to the results, the gauge length is shrunken by 1.5–2.3 mm. As the dead weight (compressive stress) increases, transverse shrinkage tends to decrease.

It is understood that dead weight largely influences the transverse shrinkage produced by welding under loading.

Test Specimen under Loading

Figure 4 presents the experimental results (Ref. 1) under tensile load in terms of the relation between applied load (stress) and transverse shrinkage. When welding is done without applied load (stress), shrinkage occurs. However, if welding is done under 70-MPa tensile stress, gauge length is elongated and, moreover, larger elon-

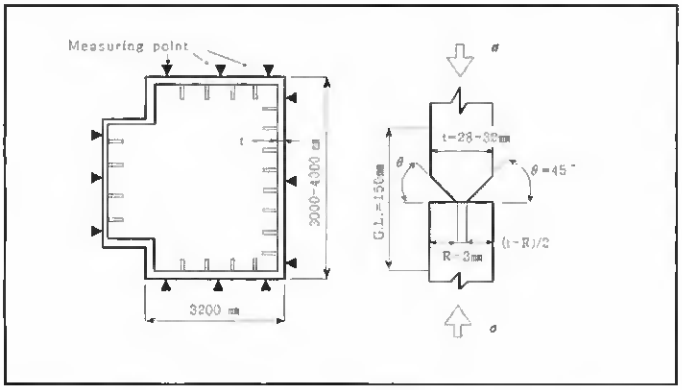

Fig. 2 — Cross section of the main suspension tower and a groove.

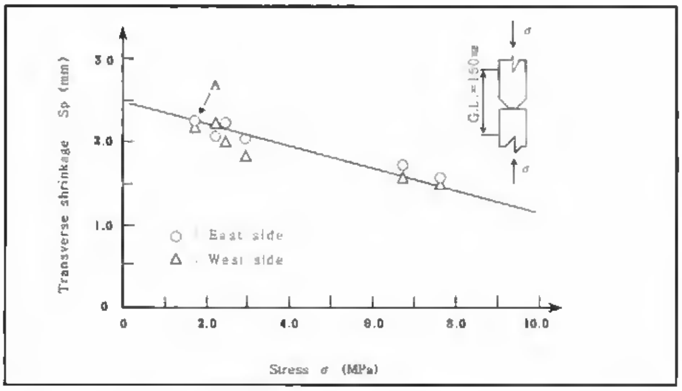

Fig. 3 — Transverse shrinkage measured in the main suspension tower.

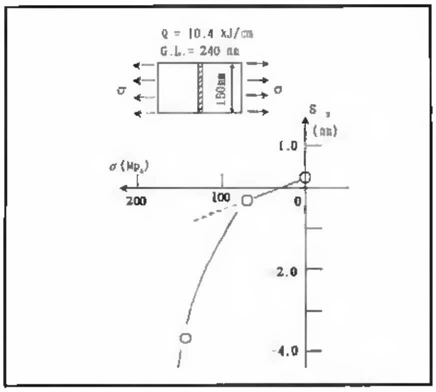

Fig. 4 — Transverse shrinkage measured in the test specimen under tensile loading (Ref. 1).

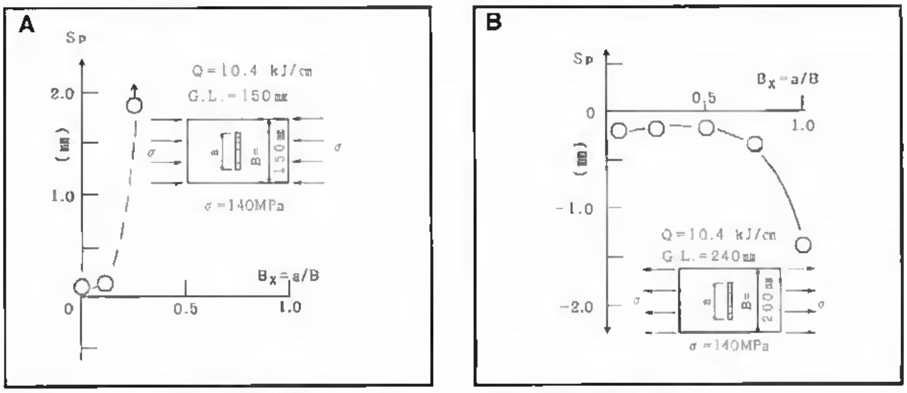

Fig. 5 — Transverse shrinkage measured in the test specimen under loading (Ref. 1): A — under compressive stress; B — under tensile stress.

gation occurs at 140 MPa, where the applying load is large. It has been reported that a cross section becomes plastic at an applied load of 140 MPa.

Figure 5 shows the experimental results (Ref. 1) in terms of the relation between transverse shrinkage and the relative welding length for the plate width, $a/B(B_x)$, in the case where the width of the specimen, B, is constant and the welding length, a, varies. As the compressive load (stress) is applied, transverse shrinkage increases rapidly at the step (Fig. 5A) when welding length is relatively short compared to plate width. On the other hand, when tensile load is applied, transverse shrinkage decreases if welding length is shorter than two-thirds of plate width, but it rapidly increases when welding length is longer than two-thirds of plate width (Fig. 5B). This result confirms that welding under compressive load should be done more carefully than welding under the tensile load.

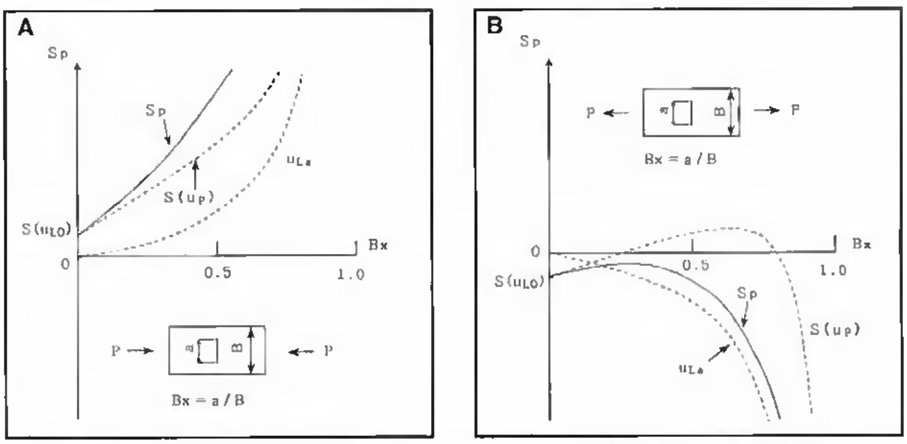

Fig. 6 — Concept diagram based on the experimental results (Ref. 1) of Figs. 4 and 5: A — under compressive loading; B — under tensile loading.

Considerations

The Transverse Joints of the Main Suspension Tower

The coefficient K_L in Equation 5 is estimated. It is considered that when L is equivalent to the region where thermal stress produced by welding is uniform, L is 1.5–2.0 times as long as the width (Ref. 5) from the weld interface according to the St. Venant principle. Therefore, L is about 9 m long. The average rise in temperature of the base plate over the 9 m is 12°C. If the linear expansion coefficient is 1.2×10^{-5} (1 /°C) and the applied load is 10 MPa, K_L is described as $K_L = 1 - \{(L \cdot \varepsilon_{L1}) / (\alpha \cdot T_{av} \cdot L)\} = 0.67$. This evaluation indicates that when the applied stress increases 10 MPa, transverse shrinkage decreases 0.67% of transverse shrinkage without load. The solid line in Fig. 3 expresses the straight line applying the measuring point A in the figure, and has good coincidence with the measured results in both towers.

It has been elucidated that the influence of the applied load on transverse shrinkage is large even when the applied load is as small as less than 10 MPa, as the allowable stress of steel (SM520) is about 200 MPa.

Test Specimen under Loading

The reason for the occurrence of the large transverse shrinkage under tensile load is considered. Slot welding is performed under tensile load, so the cross section of base plate at the groove is smaller than the full base plate cross section. When the displacement produced by applied tensile load is larger than shrinkage due to slot welding, the groove is elongated. In this experiment, as the cross section at the groove becomes plastic, the elongation is seen to rapidly increase — Fig. 4.

The case where the applied load, P, and width of specimen, B, are constant and welding length, a, varies is demonstrated in Fig. 5. In this case, as welding length and average rise in temperature, T_{av}, has a proportional relationship, u_p and u_{La} are described by Equations 7 and 8, derived from Equations 4 and 5. Transverse shrinkage under loading becomes Equation 9.

$$u_{La} = \frac{u_{L0} \cdot A_{II}}{A_I + A_{III}} = \frac{u_{L0} \cdot B_x}{1 - B_x} \qquad (7)$$

$$u_P = u_T - u_{L1} = (\beta \cdot B_x) - \frac{u_{L0}}{1 - B_x} \qquad (8)$$

$$S_P = u_{La} + S(u_p) = \frac{u_{L0} \cdot B_x}{1 - B_x} + \left[S \cdot \left\{ (\beta \cdot B_x) - \frac{u_{L0}}{1 - B_x} \right\} \right] \qquad (9)$$

where, β is a proportional constant and B_x ($= a/B$) is the ratio of welding length, a, and plate width, B.

S_P in Equation 9 is shown schematically by the expression of the solid line in Fig. 6A under compressive load and in Fig. 6B under tensile load. As shown in the figure, as welding length increases, in-plane welding deformation (transverse shrinkage) rapidly increases. This is particularly notable under compressive load. Under tensile load, the in-plane welding deformation has the tendency to increase rapidly when the welding length becomes relatively long.

As mentioned above, the validity of the basic concept is supported by the experimental results, which were used to elucidate the basic characteristics of in-plane welding deformation produced by welding under loading.

Conclusions

1) The basic equation describing the transverse shrinkage produced by welding under loading is derived. The validity of the basic equation is supported by results measured at the main suspension tower and the test specimen.

2) Owing to the measured results of transverse shrinkage in the main tower of a suspension bridge, when the dead weight (compressive stress) increases, transverse shrinkage tends to decrease. Dead weight has a large influence on the transverse shrinkage produced by welding under loading.

Based on the rearranged experimental results of Suzuki (Ref. 1), the following results were obtained.

3) The gauge length is generally shortened when welding is done without applied load. However, when welding under tensile load, gauge length is elongated and, moreover, the elongation is large because the base plate becomes plastic owing to the large applied load.

4) Under compressive load, transverse shrinkage increases rapidly when welding length is relatively short compared to plate width. On the contrary, under tensile load, transverse shrinkage is small when welding length is shorter than two-thirds of plate width but rapidly increases when welding length is longer than two-thirds of plate width.

5) Weld distortion, when welding under compressive loads, is more severe than when welding under tensile loads.

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