Welding of Steel Structures in Service Conditions†

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Abstract

To describe the displacement behavior of the weld joint of a bridge in service, $\Delta\delta$ (the root gap opening displacement) and $\Delta\delta_v$ (vertical displacement) are measured at the weld joint. $\Delta\delta$ in service is observed as the displacement caused by the amplitude of the vibration arising from the passage of a motor vehicle and the static deflection because of the weight of the vehicle. The static deflection due to of the weight of the vehicle is the major part of the observed displacement. In the general, the frequency of $\Delta\delta$ lies between 0.2~0.3(Hz) and 4~7(Hz) and the maximum amplitude is 1(mm).

There are basically two methods based on $\Delta\delta$ for the prevention of hot cracks in service repairs. One is to lower $\Delta\delta$ itself by attaching the restraint plates to increase the mechanical restraint of the weld joint. The other is to make $\Delta\delta_{cr}$ large, which is the material properties. In order that $\Delta\delta_{cr}$ could be made large, weld cracking tests were carried out for the covered electrodes D4316 and D5816 much used in the repair work on the bridges and for the newly developed electrode D5016-MOD. $\Delta\delta_{cr}$ for D5016-MOD was 3~4 times larger compared with $\Delta\delta_{cr}$ of D4316 and D5816. By using D5016-MOD, the welding conditions in service can be largely relaxed. Successful welding in service conditions has been demonstrated through actual repair work.

KEY WORDS: (Hot Crack) (Pulsating Loads) (Prevention of Weld Crack) (Covered Electrode) (Repair) (Welding in Service Condition)

1. Introduction

A series of researches to establish welding procedures for service conditions have been carried out[1-4]. First, it was confirmed that hot cracks may occur as a result of welding in service conditions from the results of welding tests under pulsating loads[2]. Then, a prediction equation for the initiation of hot cracks was developed using as a parameter applied strain which affects the weld metal. It was proposed that relative root gap opening displacement, $\Delta\delta$, which can be easily measured before welding, should be used as a mechanical measure for the prevention of hot cracks. Thus, a practical equation to indicate the initiation of hot cracking, using $\Delta\delta$, was derived and the validity of the equation demonstrated[3, 4].

In the present study, the displacement behavior at the weld joint in a bridge in service was investigated by observing the displacement, vibration and so on. Then, a practical equation[3, 4] to indicate the initiation of hot cracking, using $\Delta\delta$, is applied to the actual work of the bridge and its validity is demonstrated.

2. Displacement Behavior of the Weld Joint in Service Conditions

Here, measuring $\Delta\delta$ and the vertical displacement, $\Delta\delta_v$, at the weld joint of a bridge in service conditions, the displacement behavior of the weld joint is elucidated.

2.1 Measurement of $\Delta\delta$ and $\Delta\delta_v$

$\Delta\delta$ and $\Delta\delta_v$ of the weld joint were observed at points A~D marked in **Fig.1**, when a motor vehicle passes over one block of the bridge in service. The weld joint is in steel deck plates of a three span continuous girder (length is 90m, span is 30m, with seven main girders.). $\Delta\delta$ was measured by clip gauge and $\Delta\delta_v$ was measured by accelerometer.

Figure 2 shows $\Delta\delta$ measured at points A~C perpendicular to the transverse direction of the bridge and at point D in the longitudinal direction of the bridge when a motor truck passes on the bridge. **Figure 3** shows the vertical displacement $\Delta\delta_v$ observed by accelerometer at point D as one example.

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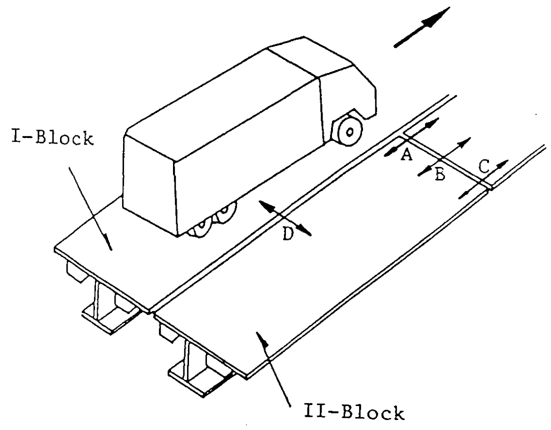

Fig.1 Measuring points of vibration and root gap opening displacement, $\Delta\delta$, at the weld joint in service condition.

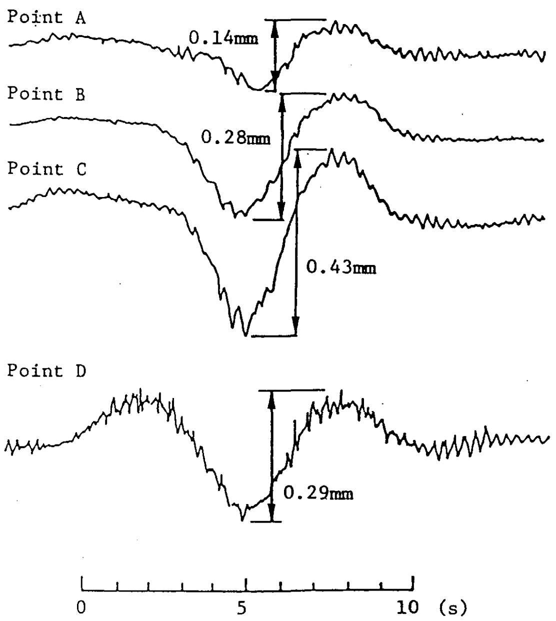

Fig.2 Results of measurement of root gap opening displacement, $\Delta\delta$, at points A~D of the weld joint in service condition.

2.2 The frequency of $\Delta\delta$ and $\Delta\delta_V$

It is found from the results of frequency analysis of $\Delta\delta$ (Fig.2) that the small amplitude waves with high frequency about 3(Hz) are superimposed on the large amplitude waves with low frequency 0.2~0.3(Hz).

As for $\Delta\delta$ at the weld joint in service, $\Delta\delta$ is observed as the displacement which the amplitude of the vibration arising from a traveling vehicle and the static deflection because of the weight of the vehicle combined. The static deflection because of the weight of traveling vehicle can be anticipated from the ratio of the traveling speed and the span. The frequency of $\Delta\delta$, because of the static deflection due to the weight the vehicle, is the period of the vehicle passing one span length of the bridge. Therefore, in Fig.2, as the travel speed of the vehicle is about 25~35(km/h) and the span length is 30(m), frequency, f, becomes 0.23~0.32(Hz). This value equals the frequency of the large wave of the low frequency.

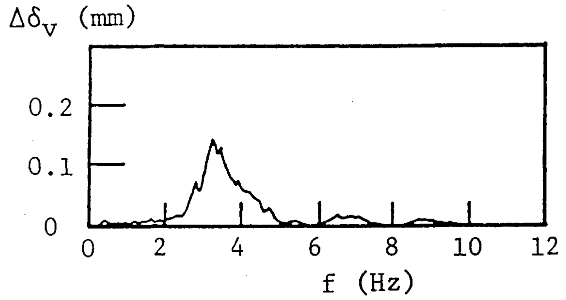

Fig.3 Vertical displacement, $\Delta\delta_V$, at point D of the weld joint in service condition.

The frequency of the vibration arising from the traveling vehicle can be estimated from the characteristic frequency of the member and the characteristic frequency of the traveling vehicle which is the origin of the forced vibration.

From the results (Fig.3) of the frequency analysis of $\Delta\delta_V$ at the weld joint, measured by accelerometer, it is known that the predominant frequency f is 3.3(Hz). It is also calculated by the transfer matrix method[5] that the characteristic frequency of this bridge is 3.2~3.3(Hz). This value corresponds to the small amplitude wave of the high frequency of $\Delta\delta$ (Fig.2).

2.3 The amplitude of $\Delta\delta$ and $\Delta\delta_V$

In Fig.2, the maximum $\Delta\delta$ is 0.43(mm) at point C of the bridge, and is 0.29(mm) at point D of the bridge. According to the measured results (Fig.2) of this bridge, the amplitude of the static deflection due to the weight of traveling vehicle is ten times as large as the amplitude of the vibration arising from traveling vehicles. It is suggested that the amplitude of $\Delta\delta$ is dominated by the static deflection. Therefore, to establish the amplitude of $\Delta\delta$, only the static deflection by the dead weight of traveling vehicle need be noted. By the way, the maximum $\Delta\delta_V$ is 0.15(mm) at point D (Fig.3), $\Delta\delta_V$ is a half of $\Delta\delta$ at the same point of the bridge.

On the other hand, measuring $\Delta\delta$ of the general traveling vehicle on this bridge, $\Delta\delta_{max}$ is 0.5(mm) at point D in Fig.1 even if it is measured when trucks pass on continuously. At point B, the same value is measured. $\Delta\delta_{max}$ is about 1.7 times as large as the amplitude measured when one truck passes. This is because the deadweight becomes large and the static deflection of main girder including the weld joint also becomes large owing to trucks passing continuously.

2.4 Consideration

Based on the static deflection measured at the groove of the general bridge in service, the frequency and the magnitude of $\Delta\delta$ is investigated.

Figure 4 shows the relation between the frequency f and $\Delta\delta_{max}$ measured when the large vehicle like as a truck (the weight: 200~300(kN)) passes.

The frequency of $\Delta\delta_{max}$, due to the static deflection, is notable at two positions where f is 0.2~0.3(Hz) and f is 4~7(Hz). Low frequency (0.2~0.3(Hz)), due to the static deflection, is measured in the case where the weld joint exists between the long spans as in the main girder. High frequency (4~7(Hz)) is measured in the case where the weld joint exists between short spans. From these results, although the frequency f of $\Delta\delta$ due to static deflection depends on the travel speed of the vehicle, it largely depends on the span length including the weld joint.

On the other hand, $\Delta\delta_{max}$ is 0.7(mm) in Fig.4. This amplitude occurs when the vehicle whose weight is 200~300(kN) passes. In practice, as there is the possibility of vehicles whose weight is over 400(kN) passing, $\Delta\delta_{max}$ may be 1.5 times as large as the ratio of the weight of the vehicle. So, it is sufficient to consider that $\Delta\delta_{max}$ is 1(mm).

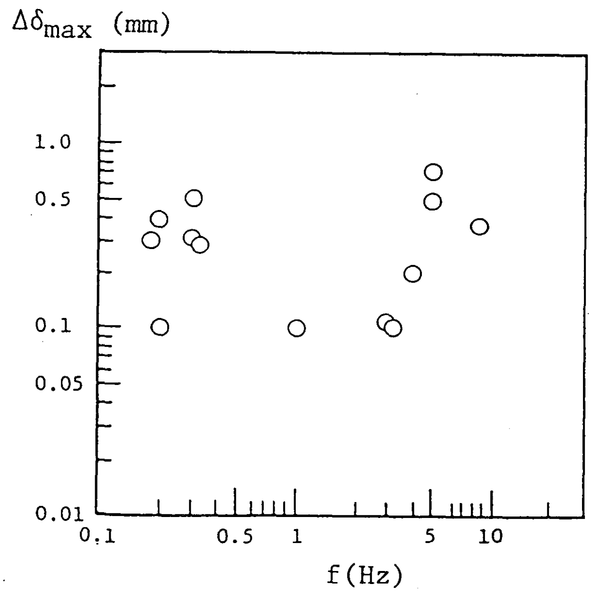

Fig.4 Maximum root gap opening displacement, $\Delta\delta_{max}$, observed when a motor vehicle passes on the bridge in service.

3. Prevention of Hot Cracking

It has been proposed that $\Delta\delta$ should be used as the practical mechanical measure for deciding the initiation of hot cracks and an evaluating equation for the hot crack initiation using $\Delta\delta$ has been derived[3, 4]. The condition in which no hot cracks occur in the welded metal can be described as follows.

$$\Delta\delta < \Delta\delta_{cr} \tag{1}$$

where,

$\Delta\delta_{cr}$:critical root gap opening displacement for crack initiation

When the actual work is taken into consideration, the above equation indicates two prevention methods of hot cracking. One is to make $\Delta\delta$ be as small as possible, and the other is to make $\Delta\delta_{cr}$, which is the material properties of the weld metal, as large as possible.

3.1 Decrease of $\Delta\delta$

In the case of the bridge, and the reduction of $\Delta\delta$, there are two possible methods.

(1) As the main source of $\Delta\delta$ is the traveling vehicle (especially large vehicle like as a truck), the traffic control becomes the effective means decreasing of $\Delta\delta$.

(2) The mechanical restraint of the weld joint is increased.

Here, the second demand is considered.

$\Delta\delta$ is measured in the case where restraint length l_R is made to change by attaching restraint plates in front of and behind of points B and D. **Figure 5** shows the results plotting $\Delta\delta_{max}$ against the inverse of l_R.

$\Delta\delta_{max}$ has a tendency to decrease if l_R is made short. If l_R is 1(m), $\Delta\delta_{max}$ is less than 0.1(mm) at

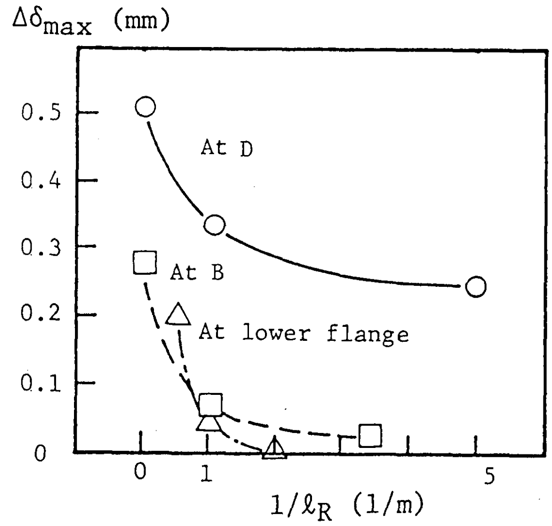

Fig.5 Effects of restraint distance on maximum root gap opening displacement, $\Delta\delta_{max}$.

Table 1 Chemical compositions of covered electrodes

Grade	Size mm	Chemical compositions (%)							Mn/S	Mn/Si
		C	Si	Mn	P	S	Ni	Mo		
D5016-MOD	ϕ4	.03	.22	1.44	.008	.001	-	-	1440	6.5
D5816		.06	.52	1.10	.014	.007	.62	.23	157	2.1
D4316		.04	.42	0.03	.002	.004	-	-	12	0.1

D5016-MOD : Newly developed welding electrode

point B and 0.35(mm) at point D although it is 0.28(mm) and 0.5(mm) respectively when there is no restraint. In the case where the member is attached to the lower flange of the transverse girder, $\Delta\delta$ is reduced from 0.2(mm) to 0.03(mm) if l_R decreases from 2(m) to 1(m). Moreover, if l_R becomes 0.5(m), $\Delta\delta_{max}$ can be ignored.

As mentioned above, $\Delta\delta_{max}$ can be largely decreased by shortening l_R, that is, mechanical restraint is increased.

3.2 $\Delta\delta_{cr}$ for hot crack initiation

$\Delta\delta_{cr}$, reflecting material properties, depends on the chemical compositions of the weld metal, welding condition and the stiffness of inner plate. Trans-Varestraint tests were carried out and the influence of the chemical compositions on hot cracking when the external load was applied once, were investigated. It was found that the susceptibility to hot cracking became small if the ratio of Mn/S and of Mn/Si was made high. Therefore, an electrode for hot crack resistance was developed by way of trial and error lowering C, Si, P, and S and making the ratio of Mn/S, Mn/Si high[6]. The newly developed electrode D5016-MOD corresponds to the low hydrogen electrode D5016. **Table 1** shows the chemical compositions of D5016-MOD.

After carrying out the weld cracking test[2] under pulsating loads, **Fig.6** shows the results arranged according to the relation between stiffness of the inner plate (restraint intensity[7]) and $\Delta\delta_{cr}$ for three kinds of electrode (Table 1). $\Delta\delta_{cr}$ of D5016-MOD is three times as large as $\Delta\delta_{cr}$ of usual electrodes D4316 and D5816. This means that welding in service conditions can be conducted more successfully.

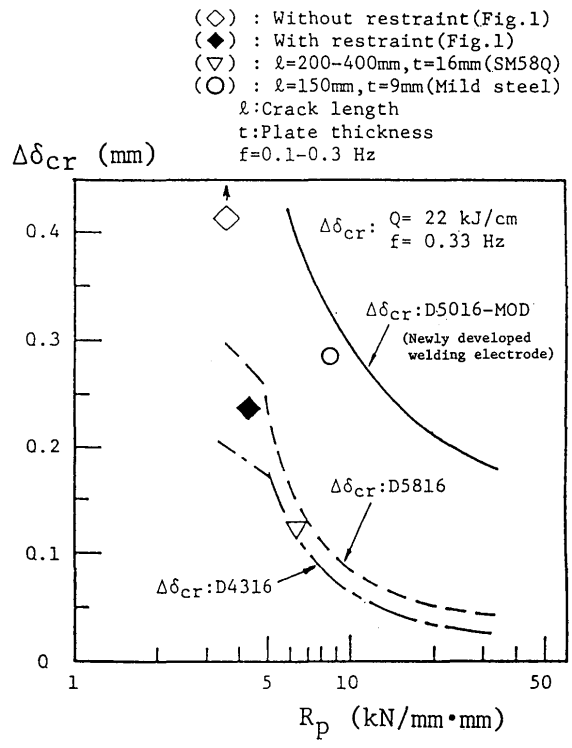

Fig.6 Critical root gap opening displacement, $\Delta\delta_{cr}$, for three kinds covered electrode and judging the advisability of welding in service.

4. Welding in Service Conditions and Its Validity

Here, the welding procedure to obtain a joint without hot cracking is defined and its validity is investigated using actual repair work on the bridge in service an example.

4.1 Welding in service conditions in the bridge

The welding procedure for the actual work of repair, reinforcement and so on, of the bridges in service condition becomes as follows.

Considering the actual welding construction yard, it is necessary to know the behavior of the bridge because there is a possibility that the welding defects may occur and welding can not be done if the vibration (acceleration) becomes too large. Therefore, measuring the vibration of the bridge by accelerometer, it is necessary to confirm that the bridge is within the limits where defect-free welding work can be done.

Next, the frequency and the amplitude of $\Delta\delta$ at the weld joint are measured (**Fig.7**). If necessary, $\Delta\delta$ must

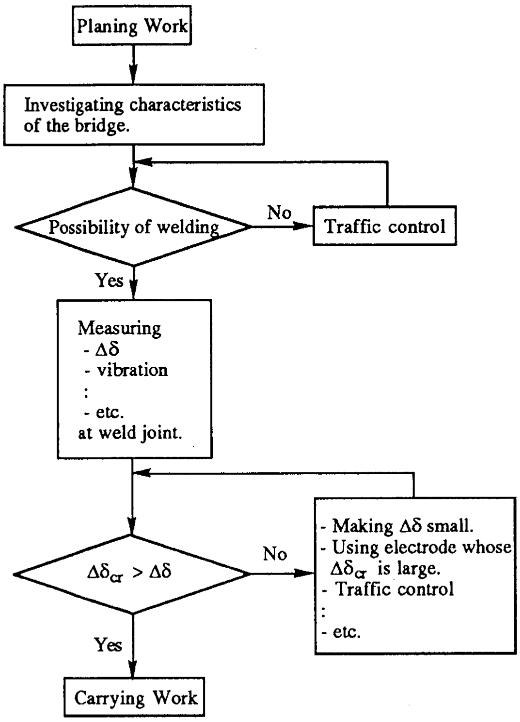

Fig.7 Flow chart for deciding the sequence of welding of the joint in service.

be reduced by attaching restraint plates, or by using the electrode producing a large $\Delta\delta_{cr}$ so as to satisfy the equation for the initiation of the hot cracking (Eq.(1)).

Following to this procedure, it can be decided whether the welding work in service condition is possible or not. If Eq.(1) can not be satisfied, it is necessary that the traffic control on the bridge should be introduced either partly or wholly. This means that welding is performed under the static load.

4.2 Applied to the actual work

Vibration in three actual bridge repair works, using the accelerometer, measured below 0.1G in all cases. This value is within the limits where no welding defects, caused by the vibration of the bridge, will occur[8]. So, $\Delta\delta$ at the weld joint is noted.

Figure 6 shows $\Delta\delta_{max}$ measured in each case with symbols. The frequency of $\Delta\delta$ ranges from 0.1~0.3(Hz).

Example A is the case mentioned in Fig.1.

The welding length is long and the restraint is weak. In this case, $\Delta\delta_{max}$ (symbol ◊) is larger than $\Delta\delta_{cr}$ of D4316 and D5816, so it is necessary that $\Delta\delta_{max}$ is decreased by attaching restraint plates and using the restraint jig or an electrode for which $\Delta\delta_{cr}$ becomes larger than $\Delta\delta_{max}$. Here, decreasing $\Delta\delta_{max}$ to 0.24(mm) (symbol ◆) by using the restraint jig, enabled welding to be performed in service condition using D5816. As a result, a good welded joint could be obtained without hot cracks in the weld metal. Using the newly developed electrode D5016-MOD, it is possible to obtain a good welded joint even without using the restraint jig.

Example B is the case in which the repair of fatigue cracks is the object.

In this case, $\Delta\delta_{max}$ (symbol ∇) is slightly larger than $\Delta\delta_{cr}$ of D4316 and is smaller than $\Delta\delta_{cr}$ of D5816. Therefore, it can be naturally anticipated, that cracks occurred if D4316 was used. However performing welding in service using D5816, a good welded joint could be obtained.

Example C is also the case in which the repair of fatigue cracks is the object.

In this case, $\Delta\delta_{max}$ (symbol ○) is larger than $\Delta\delta_{cr}$ of D4316 and D5816. Here, welding was performed in service condition using D5016-MOD and a good welded joint could be obtained.

5. Conclusions

The displacement behavior of the weld joint in a bridge in service was investigated by observing the displacement, vibration and so on at the weld groove. Then, welding in service employing the parameter $\Delta\delta$ is shown. Welding is applied to the actual repair work for a bridge in service and its validity demonstrated.

The results obtained are as follows.

(1) The displacement behavior of a weld joint of a bridge in service can be described by $\Delta\delta$ (root gap opening displacement) and $\Delta\delta_v$ (vertical displacement).

1) $\Delta\delta$ in service is described as the displacement caused by the amplitude of vibration arising from motor vehicle passage and the static deflection due to the weight of the vehicle.

2) The magnitude of $\Delta\delta$ is dominated by static deflection due to the weight of traveling vehicle. Amplitude of $\Delta\delta_v$ is smaller than $\Delta\delta$ at the same weld joint of the bridge.

3) In the general the frequency of $\Delta\delta$ lies between 0.2~0.3(Hz) and 4~7(Hz) and the maximum amplitude is 1(mm).

(2) Two methods based on $\Delta\delta$ are proposed for the prevention of hot cracks in service. One is to make $\Delta\delta$ itself low by attaching the restraint plates to increase the mechanical restraint of the joint. The other is to make $\Delta\delta_{cr}$ large, which is the material properties. In order that $\Delta\delta_{cr}$ could be made large:

(a) Weld cracking tests were carried out for the covered electrodes D4316 and D5816 much used in the repair work of bridges and the newly developed electrode D5016-MOD. $\Delta\delta_{cr}$ for D5016-MOD was found to be 3~4 times larger compared with $\Delta\delta_{cr}$ of D4316 and D5816.

(b) By using D5016-MOD, welding conditions in service are largely relaxed.

(c) Welding in service conditions was confirmed by applying it to the actual repair work.

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