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AN EXPERIMENTAL STUDY ON FATIGUE STRENGTH OF WEB PLATES FOR HORIZONTALLY CURVED PLATE GIRDERS

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This paper presents the fatigue strength of fillet weld joints at the web and flange plates in a horizontally curved plate girder. Firstly, an approximate formula to estimate the maximum out-of-plane bending stress in the web plate is proposed for fatigue design. Secondly, five curved plate girder models were fabricated according to the design criteria of the Japanese Specification for Highway Bridges (hereafter referred to as JSHB1)). Then, the model girders were tested up to the fatigue failure after having checked the stress distribution and displacements in the web plate through static loading tests. Finally, the fatigue strength of these fillet weld joints is examined based on the test results.

Keywords: *horizontally curved plate girders, fatigue strength, out-of-plane bending stress, fillet weld joints at the web and flange plates*

1. INTRODUCTION

In Japan due to space limitation, horizontally curved girder bridges have frequently been constructed in modern highways. However, the number of researches on the fatigue strength of horizontally curved steel girder is still very few, contrasting with several researches on straight plate girder bridges. Only in the current AASHTO2) specification, the web slenderness requirements for a curved plate girder and the corresponding design method for transverse and longitudinal stiffeners are codified according to a series of research on the ultimate strength of curved girders executed by CURT (Consortium of University Research Teams)3), as well as the fatigue tests of multiple curved plate girders conducted by Lehigh University4). The same kind of recommendation is also proposed in Ref. 5) to JSHB, but this proposition is not yet considered to evaluate the fatigue strength of the curved girder bridges.

The web plate of a horizontally curved plate girder is, generally, subjected to not only longitudinal flexural in-plane stress, but also out-of-plane bending stress. Therefore, the induced stresses in the fillet weld joints at the intersection of the web and flange plates in curved plate girder are considerably high and the weld joint of gusset plates connecting the main girder with the floor beams or sway bracings and upper or lower lateral bracings is laid in much more severe situations than in the ordinary straight plate girders.

Among these fatigue problems, this paper devotes our attention to the fundamental behavior of the out-of-plane bending of curved web plate, so-called web breathing. Then, in order to know the intensities of these stresses and the corresponding fatigue strength at the fillet weld joint of the web and flange plates,

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the following analyses and experiments were carried out :

First of all, a curved web plate subjected to in-plane bending is idealized into a strip beam model under an equivalent lateral loading and an approximate formula to estimate the out-of-plane bending stress in the web plate is derived on the basis of the elementary beam theory by comparing with the numerical results of finite displacement analysis by a finite element method using isoparametric shell elements. Then, the parametric analyses was carried out using statistical data on the geometries of actual curved plate girders and five test models of curved plate girder with out-of-plane bending stress similar to the maximum stress induced at the fillet weld joints in the actual curved girder bridge were designed and fabricated according to the design criteria of JSHB[1]. Finally, these model girders were tested up to the fatigue failure, after the examination of their static behavior. Thus, the fatigue strength of the fillet weld joints at the web and flange plates due to the out-of-plane bending was discussed in detail.

2. ESTIMATION OF OUT-OF-PLANE BENDING STRESS IN CURVED WEB PLATE

Let us now consider a simplified analytical method for estimating the out-of-plane bending stress, which will enable us to evaluate the fatigue strength of the fillet weld joints at the intersection of the flange and web plates.

(1) Analytical model for curved web plate

Fig. 1 (a) shows a web panel with the radius of curvature R, web thickness t_w, and the spacing of transverse stiffener a, in which the maximum longitudinal normal stress $\sigma_{ln\max}$, will easily be obtained by the elementary beam theory. Then, the longitudinal normal stress σ_{ln}, at an arbitrary point x, apart from the neutral axis N-N, can be obtained according to Bernoulli and Euler's hypothesis as follows.

$$\sigma_{ln}=\sigma_{ln\max}\left(\frac{2x}{h_w}\right) \qquad (1)$$

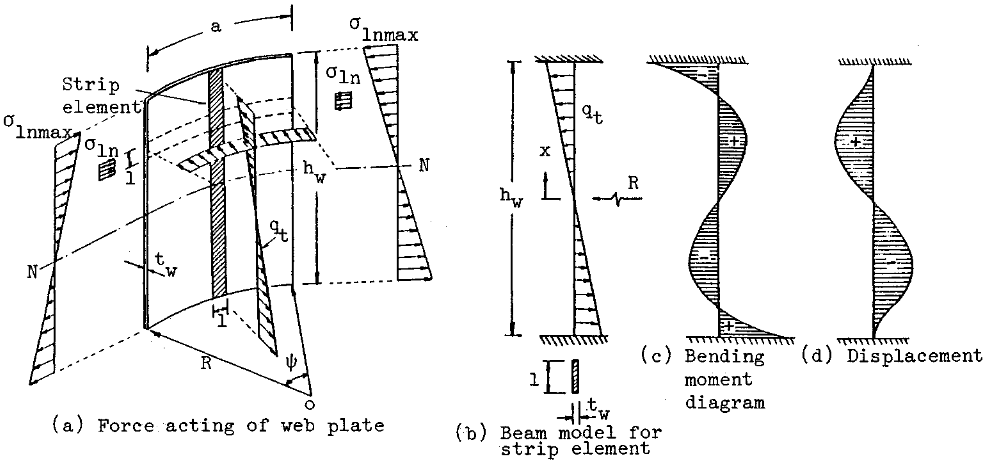
where h_w is the depth of the girder.

The out-of-plane force q_t, i. e., the resulting component force due to the curvature of the web panel in the radial direction

$$q_t=\frac{\sigma_{ln\max}}{R}A_w\left(\frac{2x}{h_w}\right) \qquad (2)$$

will be produced in a strip element with the unit width $(A_w=1\times t_w)$, as shown in Fig. 1 (a). The distribution of this force q_t, in the direction of the girder depth is also plotted in Fig. 1 (a).

Then, the out-of-plane bending stress can be approximated by the strip element as illustrated in Figs. 1



(a) Force acting of web plate (b) Beam model for strip element (c) Bending moment diagram (d) Displacement

Fig. 1 Analytical model of web plate with curvature.

(a) and 1 (b). The application of the elementary beam theory to this strip element respectively gives the out-of-plane bending stress σ_{tb}, and displacement δ_w, as shown in **Figs. 1** (c) and 1 (d), which leads to :

$$\sigma_{tb}=\frac{q_t t_w h_w^2}{240\,I}\left\{3-5\left(\frac{2x}{h_w}\right)^2\right\},\quad \delta_w=\frac{q_t h_w^4}{1\,920\,EI}\left\{\left(\frac{2x}{h_w}\right)^2-1\right\}^2 \cdots\cdots (3)_{a,b}$$

where

$$I=\frac{t_w^3}{12(1-\mu^2)}\cdots\cdots (4)$$

I : geometric moment of inertia of the strip element (cm^4)

E : Young's modulus (=2.06×10^5 MPa)

μ : Poisson's ratio (=0.3)

The maximum stress $\sigma_{tb\max}$, and displacement $\delta_{w\max}$ are respectively obtained at the location where $x=\pm h_w/2$ and $x=\pm\sqrt{5}\,h_w/10$.

$$\sigma_{tb\max}=\frac{1-\mu^2}{10}\,\sigma_{ln\max}\left(\frac{a}{R}\right)\left(\frac{h_w}{a}\right)\left(\frac{h_w}{t_w}\right),\quad \delta_{w\max}=\frac{\sqrt{5}\,(1-\mu^2)}{1\,250\,E}\left(\frac{a}{R}\right)\left(\frac{h_w}{a}\right)\left(\frac{h_w}{t_w}\right)^2\sigma_{ln\max}h_w \cdots\cdots (5)_{a,b}$$

Thus, these values are represented by a/R, h_w/a, and h_w/t_w, which are the inherent parameters of horizontally curved plate girder.

(2) Simplified analytical method

According to References 5) and 6), it is, however, pointed out that the influence of the nonlinear behavior of curved web plate as a shallow shell and the initial deflection in transverse direction of existing curved web panels should be included in the above equations $(5)_a$ and $(5)_b$.

To ensure the validity of equations $(5)_a$ and $(5)_b$, additional calculations using a finite element method[8] with isoparametric shell element considering finite displacement behavior were conducted. In the finite element analysis, the initial deflection $h_w/250$ equivalent to the fabrication tolelance specified in JSHB is considered. Comparing the results by the approximate method using the strip element with the ones by the finite element method, the above equations were modified by introducing the initial deflection w_0, of curved web plate in addition to the meridian ordinate $a^2/8R$ (see **Fig. 2**) as follows;

$$\left.\begin{aligned}\sigma_{tb\max}&=\frac{4(1-\mu^2)}{5}\,\sigma_{ln\max}\left(\frac{h_w}{a}\right)\left(\frac{h_w}{t_w}\right)\left(\frac{a}{8R}+\frac{h_w}{a}\frac{w_0}{h_w}\right)\\ \delta_{w\max}&=\frac{4\sqrt{5}\,(1-\mu^2)}{625\,E}\,\sigma_{ln\max}h_w\left(\frac{h_w}{a}\right)\left(\frac{h_w}{t_w}\right)^2\left(\frac{a}{8R}+\frac{h_w}{a}\frac{w_0}{h_w}\right)\end{aligned}\right\}\cdots\cdots (6)_{a,b}$$

where $(a/8R)$ is the term corresponding to the meridian ordinate of the curved web panel and $(h_w/a)(w_0/h_w)$ corresponds to an imaginary initial deflection w_0.

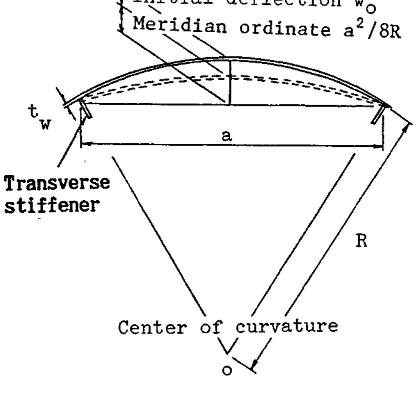
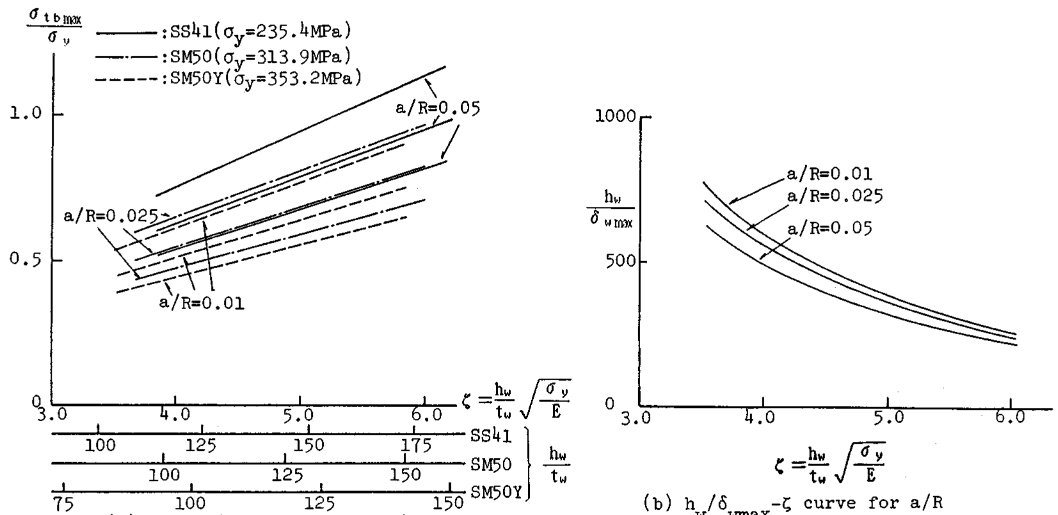


Fig. 2 Meridian ordinate $a^2/8R$ and initial deflection w_0 of curved web panel.



(a) σ_{tbmax}/σ_y-ζ curve for a/R

(b) h_w/δ_{wmax}-ζ curve for a/R

Item a/R	σ_{tbmax}/σ_y			h_w/δ_{wmax}		
	Eq. (6)a	F. E. M.	w_0	Eq. (6)b	F. E. M.	w_0
0.050	0.969	0.917	h_w/∞	303	319	$h_w/3000$
0.025	0.807	0.807	$h_w/700$	340	340	$h_w/500$
0.010	0.696	0.707	$h_w/450$	361	364	$h_w/325$

(c) Analytical values for slenderness ratio $\zeta=5.14$, $h_w/a=0.7$ and initial deflection w_0

Fig. 3 Variations of the out-of-plane bending stress σ_{tbmax} and displacement δ_{wmax}.

Accordingly, the relationships among the maximum out-of-plane bending stress non-dimensionalized by the yield stress σ_{tbmax}/σ_y, the curvature parameter a/R, and web slenderness ratio $\zeta(=h_w/t_w\sqrt{\sigma_y/E})$ can be shown in Fig. 3(a) by using Eq. 6(a) where σ_{tbmax} is taken as σ_y. Also plotted in Fig. 3(b) are the relationships between the maximum out-of-plane deflection h_w/δ_{wmax}, a/R, and ζ, when $\sigma_{tbmax}=\sigma_y$.

In Fig. 3(c), the values σ_{tbmax}/σ_y and h_w/δ_{wmax} obtained respectively by the approximate method and F. E. M. analysis are summarized : For the web slenderness ratio $\zeta=5.14$ and steel grade SS 41, the imaginary initial deflections of web plate are listed together.

From these figures, it seems that the approximate method for calculating the out-of-plane stress and displacement can be applicable to the fatigue design of the horizontally curved plate girders.

3. TEST GIRDERS AND EXPERIMENTAL METHOD

The parametric analyses for the maximum out-of-plane bending stress σ_{tbmax}, were carried out by using the approximate method mentioned above.

In the most severe condition in actual curved plate girders, the intensity of σ_{tbmax} in the web plate is nearly equal to the maximum longitudinal normal stress σ_{lnmax}, i. e., $\sigma_{tbmax}=\sigma_{lnmax}$. The geometrical parameters in the test girders are decided so as to satisfy this condition and the dimensions of test girders were designed according to JSHB as shown in Fig. 4 with the exception that the thickness of the web plate t_w, is taken to be equal to 3.2 mm due to the capacity of our testing machine. Cross-sectional properties and parameters of test specimens according to actual measurements are shown in Table 1.

The fillet welding at the intersection of flange and web plates was automatically carried out with the electrode of $\phi=1.2$ mm, size of welding of 4 mm, voltage of 20 V, electric 32 A and velocity of 450 mm/min.

The test girders were simply supported at both ends and two point loads $P/2$, were applied to the test

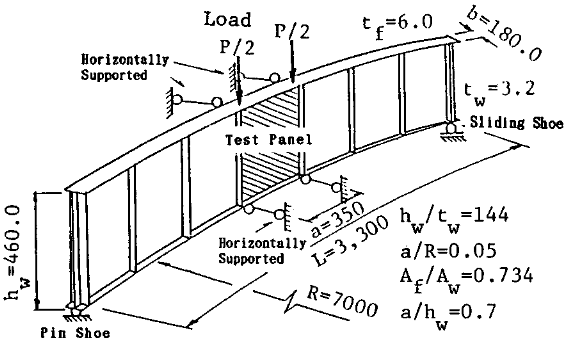


Fig. 4 Outline of the test girder (Dimension : mm).

Table 1 Cross-sectional properties and parameters of test girders.

Item / Specimen	Cross-sectional area (cm^2)			Moment of inertia (cm^4) I	Radius of gyration(cm) r	Curvature a/R	Aspect ratio a/h_w	Cross-sectional area ratio A_f/A_w	Web plate Slenderness ζ
	A_f	A_w	A						
CF-1	10.723	14.297	35.743	14211	19.94	0.05	0.761	0.750	5.58
CF-2	11.140	14.371	36.651	14655	19.99		0.762	0.775	5.59
CF-3	10.017	14.535	36.569	13498	19.76		0.760	0.689	5.30
CF-4	10.022	14.538	36.583	13510	19.77		0.760	0.689	5.30
CF-5	11.134	14.368	36.636	14641	19.99		0.762	0.775	5.59

girder indicated by the shaded portion in Fig. 4 of which horizontal displacements were completely restrained by the special shoes with roller bearing to permit the vertical deflection of the test girder. Thus, the test panel was subjected to pure bending.

In order to investigate the effect of out-of-plane bending stress on the fatigue strength of the fillet weld joint in curved plate girders, the pulsating force was taken so as to make the out-of-plane bending stress σ_{tb}, equal to the allowable stress $\sigma_a=137.3$ MPa of steel grade SS 41 in the fatigue test, although this pulsating force is comparatively large from the practical point of view.

4. EXPERIMENTAL STUDIES

(1) Residual stress distributions

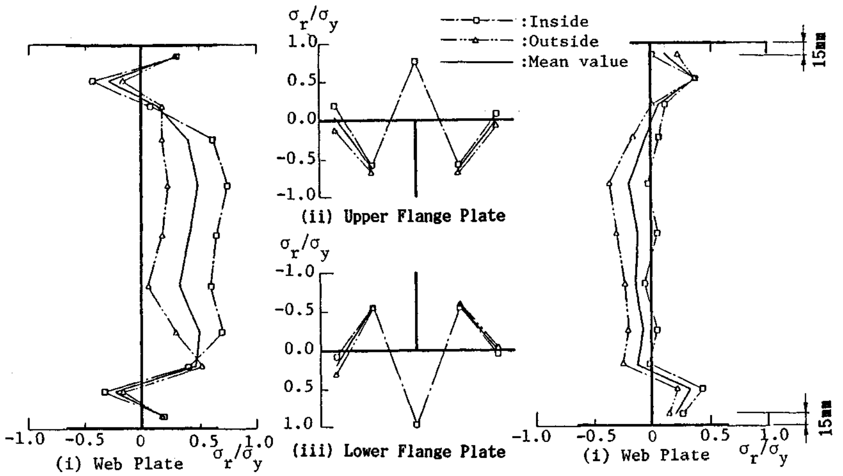
Using the test specimen (CF-2) after the fatigue test, the residual stress distribution were measured as shown in Fig. 5.

The residual stress distributions in the flange plates were similar to those of previously reported, but those in the web plate were very scattered. It is considered that this distribution of the web plate due to welding had been removed by the spot heatings. The residual stress in the transverse direction at the fillet weld joints of the web and flange plates is nearly equal to zero.

(2) Stress distribution

Analytical and measured in-plane and out-of-plane bending stress distributions is the cross section at the mid-span are shown in Figs. 6 (a) and 6 (b), where these stresses are non-dimensionalized by the allowable stress $\sigma_a=137.3$ MPa. The maximum values of the out-of-plane bending stress in the tension and compression sides of the web plate, predicted by means of the least squares method, are also listed in Table 2 together with analytical ones by the finite element method and Eq. $(6)_a$.

It is clear from this figure and table that the longitudinal normal stress distribution indicates a non-linearity in the same manner as, the analytical one presented by the finite element method in the test



(a)Longitudinal residual stresses (b) Transverse residual stress

Fig. 5 Measured residual stress distributions in the test girder.

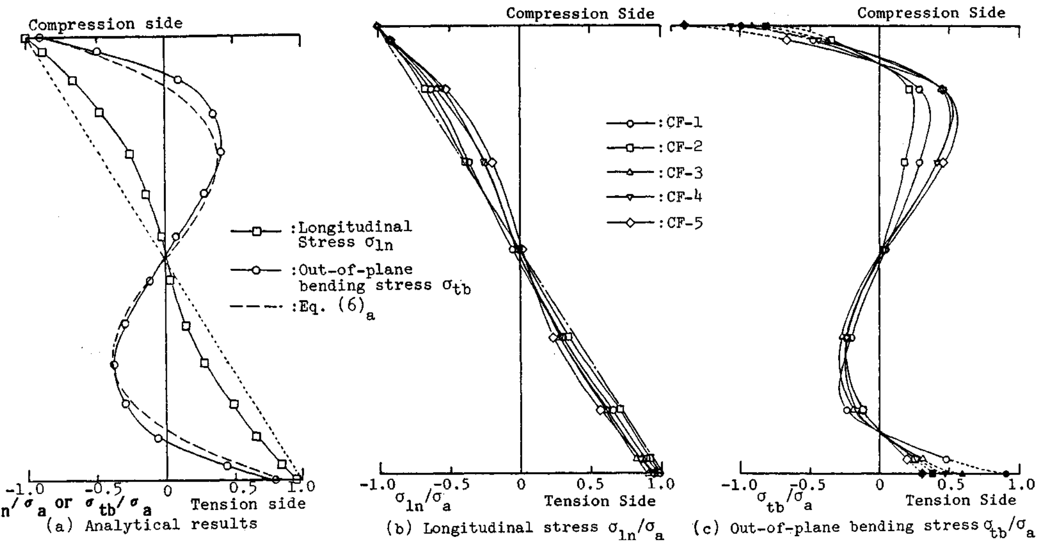


Fig. 6 Analytical and measured stress distributions σ_{ln}/σ_a and σ_{tb}/σ_a in cross-section at midspan.

Table 2 Maximum out-of-plane bending stress and initial deflection.

Item / Specimen	Out-of-plane bending stress		Initial
	Tens. Side ($\times\sigma_a$)	Comp. Side ($\times\sigma_a$)	Deflection ($\times h_w$)
CF-1	0.944	-1.044	1/920
CF-2	0.394	-0.845	-1/3067
CF-3	0.618	-0.945	1/279
CF-4	0.478	-1.056	-1/1314
CF-5	0.316	-1.393	1/836
F.E.M.	0.839	-0.924	1/250
Eq. (6)$_a$	0.860	-0.860	1/∞

girder CF-3~5, whereas a symmetry in test girders CF-1 and CF-2 was observed.

The maximum bending stress in the test girder CF-2 is somewhat small, whereas that of CF-5 is large. These out-of-plane bending stress distributions have various patterns because of the accuracy of fabrication of each test girders, in particular difference of magnitude and mode of the initial deformation of each web plate.

(3) Out-of-plane deflection of web plate

The relationships between the out-of-plane deflection δ_w, and the bending moment M/M_a, are shown in Fig. 7, where δ_w is the deflection of web plate at $0.23\,h_w$ (at the point of the maximum out-of-plane deflection in reference 8) away from the compression flange, and applied bending moment M, is non-dimensionalized by the allowable bending moment M_a, which induces the longitudinal normal stress σ_{in}, is equal to the allowable stress σ_a. Analytical results by Eq. $(6)_b$ and F. E. M. are also plotted in Fig. 7.

From this figure, it is clear that the test results of CF-1 and CF-2 are somewhat small compared with the analytical results, while those of the other test girders are almost similar to the analytical result by the approximate method. It seems that the out-of-plane deflections are also influenced by the magnitude and mode of the initial deformation of web plate[8].

(4) Fatigue tests

Test girders CF-1~CF-5, were subjected to pulsating more than $N=2.0\times10^6$ cycles, but no fatigue crack was observed along the fillet weld joints of the web and flange plates. All the fatigue failures were due to the initiation of fatigue cracks in other places.

In the test girders CF-1 and CF-2, the fatigue cracks were propagated at the junction of the compression flange and the transverse striffeners under the loading points. The cracks proceeded to the web plate at $N=1.6\times10^6$ cycles. These cracks are caused by the stress concentration at the locations near the loading points.

In the test girder, CF-3, the fatigue cracks occurred at the tension flange attaching the horizontally supported device to prevent the lateral displacement of test girder as is shown in Fig. 3, and then thus the test girder reduced to the fatigue failure occurred at $N=5.6\times10^6$ cycles. In the test girder CF-4, no fatigue cracks were observed.

Test results on the fillet welded joints of the web and flange plates due to out-of-plane bending stress are plotted in Fig. 8. Also plotted in this figure is the S-N curve proposed one by Maeda and Ohkura[7] for the fatigue tests using T-shaped specimens subjected to bending.

It is clear from this figure that the fillet welded joints at the web and flange plates are safe for fatigue strength with $N=2.0\times10^6$, because the repeating out-of-plane bending stress of the intensity of 137 MPa (1 400 kgf/cm^2) due to the live load rarely occurs even in the severe case of actual horizontally curved plate girder bridges in which the out-of-plane bending stress equal to the maximum in-plane bending stress may

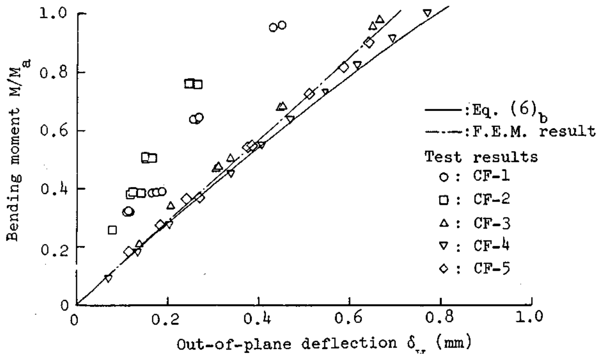


Fig. 7 Relationship between bending moment M/M_a and maximum out-of-plane deflection δ_w.

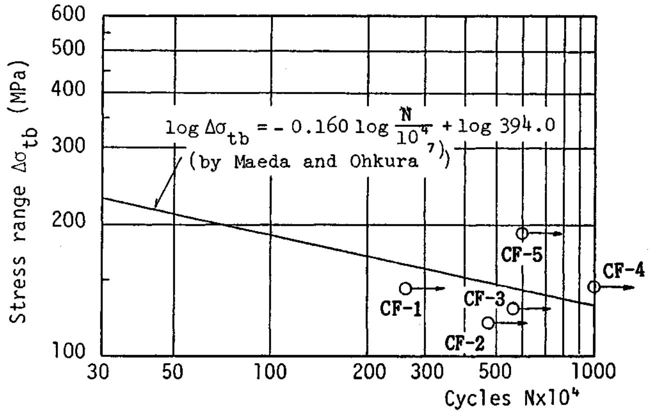


Fig. 8 S-N curve for out-of-plane bending stress.

be induced.

5. CONCLUSION

This paper presents an approximate formula for evaluating the out-of-plane bending stress of web plates in curved plate girder bridges. The fatigue strength of the fillet weld joints at the intersection of the web and flange plates is investigated through fatigue tests using five test girders designed by this analysis. The major points of this paper can be summarized as follows :

(1) An approximate formula for estimating the maximum out-of-plane bending stress $\sigma_{tb\max}$, and deflection $\delta_{w\max}$, of a curved web plate is proposed by idealizing the web plate into a strip beam model subjected to lateral loading.

(2) The maximum out-of-plane bending stress in curved web plate $\sigma_{tb\max}$, is nearly equal to the maximum longitudinal normal stress $\sigma_{ln\max}$, due to the in-plane bending in the severe case of actual curved plate girder bridges.

(3) No fatigue cracks were observed in the fillet weld joints at the web and flange plates of the test girders, in spite of the application of pulsating force of more than $N=2.0\times10^6$ cycles. However the fatigue cracks propagated at the intersection between transverse stiffener and compression flange plates or at the tension flange plate attaching the horizontally supported device to prevent the lateral displacement of test girder.

(4) The fatigue strength of the fillet welded joints of the web and flange plates in the test girder are safe for fatigue strength with $N=2.0\times10^6$.

(5) It is considered that the fillet weld joint of the web and flange plate in the horizontally curved plate girder bridge designed by JSHB have no problems in fatigue strength.

(6) In horizontally curved plate girder bridges, it is, however, still one of the important problems to be investigated in the fatigue strength of the fillet weld joint at the intersection of web plate and transverse or longitudinal stiffeners as well as gusset plates connecting main girder with floor beams and lateral bracings.

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