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EVALUATIONS OF REMAINING STRENGTH ESTIMATION METHOD BY USING PLATE GIRDER MODELS WITH CORROSION UNDER SLEEPERS

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In steel railway bridges with open deck system, the local buckling of compressive flanges under sleepers on plate girders caused by the local corrosion of flanges leads to the collapse of bridges. The local corrosion is thought to have a substantial impact on the ultimate strength of main girders. However, past research on ultimate strength contains few inquiries into the relationship between the local corrosion of compressive flanges and the ultimate strength of main girders, and a method of evaluating the relationship has not yet been established. In this study, parameter analyses that focus on plate girders with local corrosion under sleepers have been conducted by using full-scale plate girder models subjected to bending and local loads simultaneously. Then based on these analytical values and other existing experimental values, the study verified the applicability of the separate evaluation equations that we previously proposed for remaining load bearing capacity under bending and local loads respectively, as well as the remaining strength calculation method based on the strength interaction curve of plate girders subjected to bending and local loads simultaneously to clarify that ultimate strength can be evaluated with a high degree of accuracy.

Keywords: Railway bridge, Local corrosion, Local buckling, Bending load, Local load.

1 INTRODUCTION

In Japan, many steel railway bridges with open deck system have been in use for over 60 years, and deterioration and damage due to corrosion is becoming pronounced. Partial repairs and reinforcement as well as total replacement of girders have taken place in recent years, but it cannot be said with certainty that these measures have been selected after proper, quantitative evaluations of the remaining strength of the girders. In light of recent socioeconomic conditions caused by budgetary and labor shortages, there is an even more pressing need to establish streamlined, economically viable methods for maintaining these bridges.

One phenomenon that requires maintenance is local corrosion of the upper flanges under sleepers, a type of corrosion characteristic of steel railway bridges that it shall be referred to as “corrosion under sleepers” throughout this report. The coating on upper flanges under sleepers wears more easily and is more susceptible to dampness than other parts due to the train load acting almost directly through the rails and sleepers onto the girders. Local corrosion progresses as a result. Many studies on ultimate strength of plate girders (Basler *et al*. 1961) had been conducted by experiments and analyses. However, none of them were taken account of local corrosion despite the fact that taking into account corrosion under the sleepers is vital toward accurately evaluating the remaining strength of this type of steel railway bridges. In this study, firstly FEM analyses using full-scale plate girder models subjected to bending and local loads simultaneously are conducted, then based upon these analytical results, separate evaluation equations for load bearing capacity in terms of both pure bending and local loads previously proposed by us are verified. In addition, the analyses verify the validity of the simplified remaining strength calculation method of plate girders under conditions of various load combinations based on the strength interaction curve subjected to the two loads simultaneously.

2 EVALUATING LOAD BEARING CAPACITY UNDER COMBINED LOADS

2.1 Overview of Analysis

The aim is to examine analytically that the ultimate states and load bearing capacity of girders under bending and local loads simultaneously, as is the case with actual bridges. This analysis is conducted using the analytical parameters shown in Figure 1 and Table 1, and by considering combined bending and local loads acting on main girders with corrosion in a single central location under sleepers. In addition, Figure 2 shows the analytical model and boundary conditions, and Figure 1 shows the load conditions that it is applied as a line load (local load) to the joint part between the web and the upper flange where there is corrosion under sleepers. And as shown in Figure 1, rigid elements are applied to the end plates of the girder on both supporting points and acted on by couple of forces to work as the bending moment.

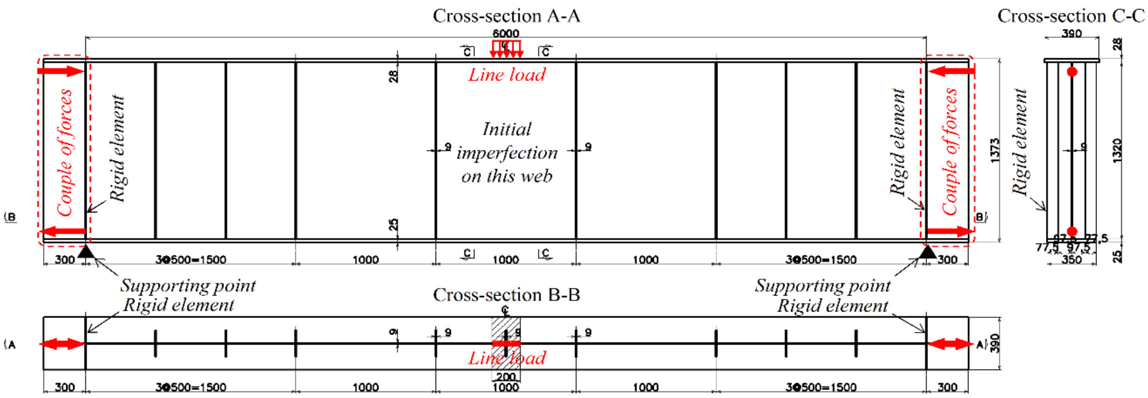


Figure 1. Configurations targeted for analysis and the load conditions.

This FEM analysis has been performed with NASTRAN, a general-purpose FEM analysis program, and focused on the full-scale railway beam of plate girders modeled as perfect elasto-plastic material using iso-parametric shell element with 4 nodal points. Material properties are given a yield stress σ_y of 235 MPa, an elastic modulus E of 200 GPa and a Poisson ratio v of 0.3.

These analytical models also take into account residual stress due to initial imperfections in the out-of-plane direction on the web between the vertical stiffeners in the middle of the span.

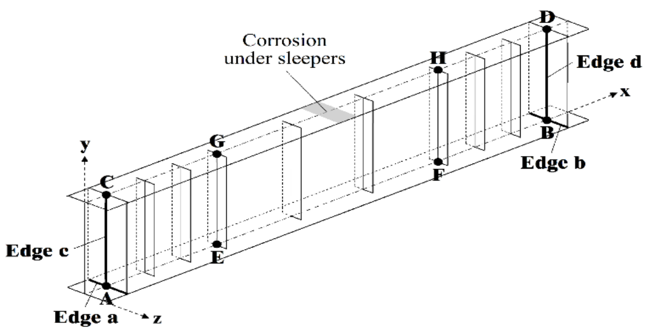
2.2 Results of Analysis

Figures 3 and 4 show the states of the deformation and von Mises stress at peak load in Case 3 for each of combined and pure bending loads. Most analyses resulted in collapse due to local buckling of the compressive flange as shown in Figure 3, but when bending is the superior force or when there is a major reduction in thickness due to corrosion under sleepers, the collapse occurs due to torsional buckling of the flange as shown in Figure 4. The stressed condition in Figure 3 demonstrates that compressive stress concentrates on the corroded part of the upper flange under sleepers and a local load increases marked local stress just on a very narrow range of the web just below the upper flange. On the other hand, Figure 4 shows that compressive stress due to pure bending concentrates not only on the corroded part of the upper flange but also on a relatively wide range of the web.

Table 1. Analytical parameters.

Analytical cases		Case 1	Case 2	Case 3	Case 4
Span length	L (mm)	6000			
Web height	h_w(mm)	1320			
Web thickness	t_w(mm)	9			
Upper flange width	b_{uf}(mm)	390			
Upper flange thickness	t_{uf}(mm)	28			
Lower flange width	b_{lf}(mm)	350			
Lower flange thickness	t_{lf}(mm)	25			
Width of vertical stiffeners	b_s(mm)	97.5			
Thickness of vertical stiffeners	t_s(mm)	9			
Thickness of corroded portion	t'_{uf}(mm)	28.0*	21.0**	14.0**	7.0**

* Case 1: Non-corroded
** Case 2 to 4: 25, 50, 75% reduction in upper flange original thickness



	x	y	z	φ_x	φ_y	φ_z
A	1	1	1	1	1	0
B	0	1	1	1	1	0
C	0	0	1	1	1	0
D	0	0	1	1	1	0
E	0	0	1	0	0	0
F	0	0	1	0	0	0
G	0	0	1	0	0	0
H	0	0	1	0	0	0
Edge a	0	1	0	1	0	0
Edge b	0	1	0	1	0	0
Edge c	0	0	1	1	1	0
Edge d	0	0	1	1	1	0

1: Fixed 0: Free

Figure 2. Boundary conditions.

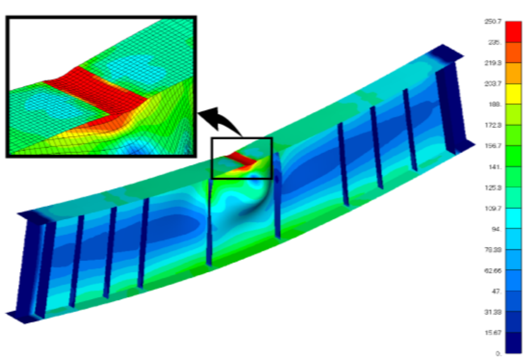


Figure 3. Case 3: 50%-corroded (for combined load).

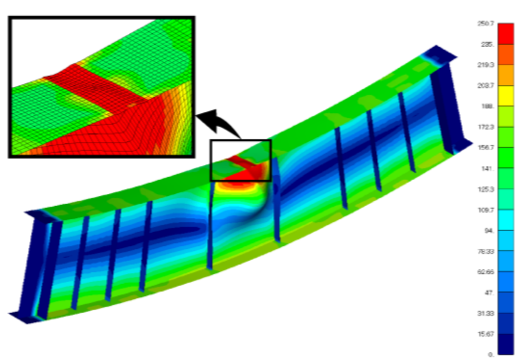


Figure 4. Case 3: 50%-corroded (for pure bending).

Figure 5 shows the results of the analysis plotted on an interactive curve. In the cases of non-corroded and 25%-corroded, the analytical values for local load and bending moment on this figure are nearly on the curve that represents Eq. (1). In the cases of 50% and 75%-corroded, as the corrosion ratio increases, the analytical values are estimated slightly on the unsafe side because they tend to be plotted into the interactive curve. However since actual steel plate girder bridges are thought to cause corrosion under sleepers of up to about 30%, Eq. (1) can be used to evaluate the load bearing capacity of girders under combined loads.

$$\left(\frac{P_u}{P_{u0}}\right)^2 + \left(\frac{M_u}{M_{u0}}\right)^2 = 1 \tag{1}$$

P_u: Local load (for combined load), M_u: Bending moment (for combined load), P_{u0}: Local load (for individual load), M_{u0}: Bending moment (for individual load).

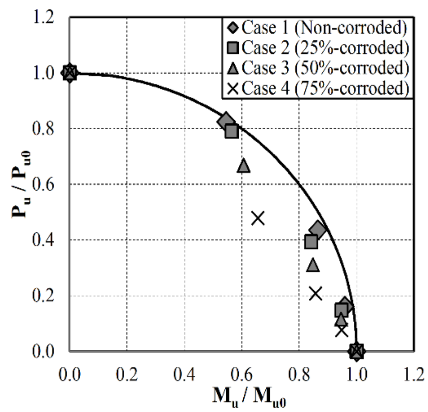


Figure 5. Interactive curve.

3 EVALUATION METHOD OF REMAINING STRENGTH

Here, for our proposed method for evaluating the remaining strength of plate girders with corrosion under sleepers, specific steps of the separate evaluation equations for load bearing capacity under pure bending and local loads respectively and the remaining strength calculation method using the strength interactive curve of plate girders subjected to bending and local loads simultaneously are shown below.

For the evaluation of the bending load bearing capacity, according to Basler's approach (Basler *et al*. 1961), the bending collapse mode for the plate girders is mainly determined by lateral buckling and torsional buckling of compressive flanges (Figure 6). In these cases, the basic buckling lengths of girders with corrosion under sleepers are shown in Figure 6.

Based on the above, we have already analyzed and proposed the following evaluation method for bending load bearing capacity focused on compressive flanges, with lateral buckling and torsional buckling as the two types of flange buckling.

First, for the bending load bearing capacity under flange lateral buckling subjected to pure bending, Basler's proposed Eq. (2) can be applied (Figure 7). The variables for Eq. (2) are defined as follows: σ_{uh}: Bending load bearing stress under lateral buckling, σ_y: Yield stress, λ: Slenderness ratio parameter, L_h: Basic buckling length, r: Radius of gyration, E: Elastic modulus, B: Total upper flange width, t_f : Upper flange thickness for corrosion wastage, A: Upper flange cross-sectional area for corrosion wastage.

For the bending load bearing capacity under flange torsional buckling subjected to pure bending, our proposed Eq. (3) below can be applied (Figure 7).

$$\begin{cases} \dfrac{\sigma_{uh}}{\sigma_y} = 1 - \dfrac{\lambda^2}{4} & \lambda \le \sqrt{2} \\ \quad = \dfrac{1}{\lambda^2} & \sqrt{2} < \lambda \end{cases} \quad , \ \lambda = \frac{1}{\pi}\frac{L_h}{r}\sqrt{\frac{\sigma_y}{E}} \quad , \ r = \sqrt{\frac{I}{A}} = \sqrt{\frac{B^2}{12}} \quad , \ I = \frac{B^3 t_f}{12} \tag{2}$$

$$\begin{cases} \dfrac{\sigma_{ut}}{\sigma_y} = 1 & R \le 0.433 \\ \quad = \left(\dfrac{0.433}{R}\right)^{0.89} & 0.433 < R \end{cases} \quad , \ R = \frac{1}{\pi}\frac{b}{t_f}\sqrt{\frac{12\left(1-\upsilon^2\right)}{k}}\sqrt{\frac{\sigma_y}{E}} \tag{3}$$

σ_{ut}: Bending load bearing stress under torsional buckling, R: Width-thickness ratio, b: Flange half-width, v: Poisson ratio, k: Buckling coefficient [k=0.43+$(1/\alpha)^2$], α: Aspect ratio (for this analysis, L_t / b), L_t: Basic buckling length.

Based on the above, smaller value of calculated bending load bearing stresses σ_{uh} or σ_{ut} contributes to the actual state of buckling and determines the applicable bending load bearing stress σ_u for girders. This stress σ_u shall be used in beam theory Eq. (4) to calculate the load bearing bending moment M_{u0} under pure bending force.

$$M_{u0} = \frac{\sigma_u}{h} I \tag{4}$$

I: Second moment of area of corroded part, h: Distance from neutral axis to the top of upper flange of corroded part.

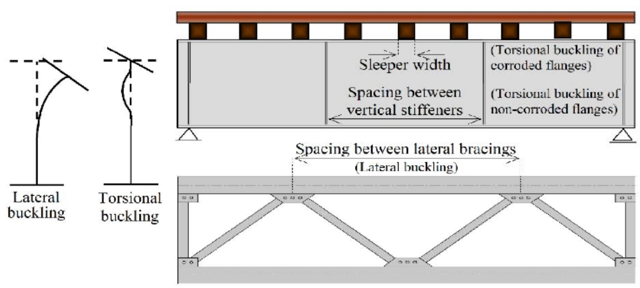


Figure 6. Buckling modes and basic buckling lengths of plate girders.

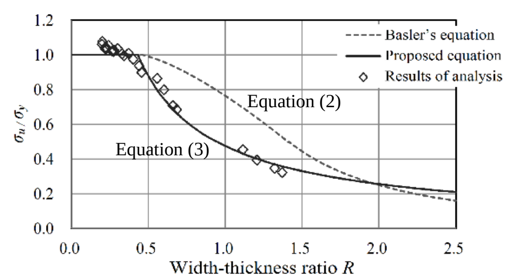


Figure 7. Load bearing capacity curve

Next, the load bearing capacity P_{u0} of girders only under local load can be calculated by using Eq. (5) below, which is further simplified based on Takimoto's equation (Yoshikazu *et al*. 1988).

$$P_{u0} = \left(25 t_w^{\,2} \sigma_w + 4 t_w t_f \sigma_f\right) \cdot \left(1 + \frac{a + 2t_f}{2h_w}\right) \tag{5}$$

t_w: Web plate thickness, σ_w: Web yield stress, σ_f : Upper flange yield stress, a: Width on which local load acts, h_w: Web height.

Finally, by using the values of M_{u0} and P_{u0} that are calculated above, and the value of bending moment M_u or local load P_u which acts on actual girders, above Evaluation Equation, Eq. (1), can be used to estimate the remaining load bearing capacity of girders under combined loads.

4 APPLICABILITY OF PROPOSED EVALUATION METHOD

Figures 8 and 9 show comparisons between the analytical values and the respective evaluation values for bending moment M_u and local load P_u calculated using Eq. (1). The evaluation results are well accorded with the analytical ones.

To compare the values obtained from the evaluation equation proposed by our study, circles representing the results of experiments from reference materials (Taishi *et al*. 2010) are plotted on the graphs. These results also demonstrate that our proposed evaluation method and equation are well accorded with the values obtained from experiments.

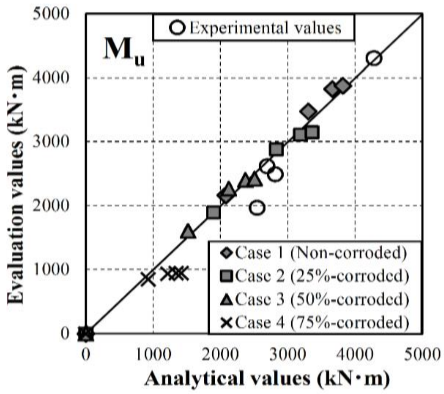


Figure 8. Comparison of analytical and evaluation values (Bending moment M_u).

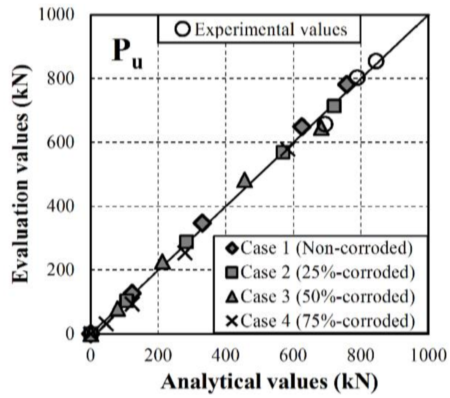


Figure 9. Comparison of analytical and evaluation values (Local load P_u).

5 CONCLUSIONS

As this study aimed at properly evaluating our proposed remaining strength calculation method for plate girders with corrosion under sleepers, elastoplastic non-linear FEM analysis has been conducted by using full-scale plate girder's beam models subjected to various bending and local loads simultaneously to investigate the remaining load bearing capacity for each analytical case. Then given these results, this study clarified an interactive curve for plate girders with corrosion under sleepers under combined loads. These analytical results showed that Basler's proposed equation for lateral buckling and our proposed evaluation equation for torsional buckling are effective respectively. Furthermore, the analysis also showed that the bending load bearing capacity obtained from the evaluation equation can depict bending load bearing capacity obtained from past experiments with accuracy.

In fact, examining and comparing the values obtained from this evaluation method with the FEM analysis results in this study could verify that this method is an applicable simplified way to estimate the remaining strength of plate girders with corrosion of upper flanges under sleepers.

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