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Evaluation method for bending capacity of corroded steel girder

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Abstract

Corrosion is typical damage on steel bridges, but the evaluation method for capacity of steel member with corrosion has not been established. The estimation to repair corroded steel member is usually done on the basis of corroded area and/or corrosion depth. However, it makes the estimation more reasonable that the relationship between capacity of the member and the degree of corrosion is clear. In this study, examination of corrosion configuration using actual corroded steel member has been done, and simulation method for the configuration is discussed. Furthermore, bending capacity of I-shaped beam with corrosion on the lower flange is examined by using three-dimensional elastic-plastic finite element stress analyses.

1. Introduction

It is well known that the most typical damage in the steel bridge is the corrosion and the capacity of the member lowers with increase in corrosion. The corrosion is divided roughly into local and general one from its appearance. The general corrosion, in which whole surface of steel corrodes and its thickness decreases, is apt to occur when the steel was exposed in almost uniform corrosive environment such as atmosphere and seawater. On the other hand, local corrosion, in which partially deep hole or groove occurs, is apt to occur when corrosion reaction locally occurs. Whether corrosion damage should be repaired or not is usually assessed on the basis of the degree of the corrosion (surface area and depth of the corrosion). However, more reasonable assessment could be realized if the relationship between the capacity of the corroded member and degree of the corrosion is made clear (Japanese Society of Steel Construction 2002).

In this study, the surface configuration of the corroded steel plate taken out from actual bridges has been measured, and geometrical features and the simulation method for the configuration have been examined on the basis of the measurement results. Furthermore,

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the bending capacity of steel I-shaped beam with the general or local corrosion on the lower flange is discussed using three-dimensional elastic-plastic finite element stress analyses.

2. Investigation on the configuration of corroded steel surface

2.1 Specimen and measuring method

Specimens were obtained from 3 bridges as shown in below.

> A-bridge : This bridge was constructed in 1928, and removed in 1993. The stringer was an object.
> B-bridge : It was a arch bridge which was over the river in the inland. It was rebuilt in 1992. The test piece was collected from lateral bracing.
> C-bridge : It is a truss bridge which is located in the estuary. The lateral bracing was removed due to the remarkable corrosion is an object.

On the A-bridge, the data indicated in the report (Public Works Research Institute 1996) was utilized. The corrosion depth was measured at 5mm interval in the transverse direction of the flange and 50mm or 100mm interval in the longitudinal direction.

As for the B- and C-bridges, the specimens were mounted on the digital movable pedestal, and their surface configurations have been measured by the laser displacement gauge (measuring range: 15mm, laser spot diameter: 70μm, resolution: 3μm). The measurement was carried out at the intervals of 1.0 mm in both directions.

Table 1. Results of corrosion depth measurements on A-bridge

Specimen	Corrosion depth (mm)		Corroded cross-section area (mm^2)	
	maximum	average	maximum	average
No.1	12.88	4.82	72.12	57.39
No.2	8.13	3.37	69.68	56.26
No.3	15.68	2.63	48.89	30.29
No.4	9.59	2.07	21.63	9.61

2.2 Geometrical feature

The corrosion configuration of the A-bridge was measured on the upper flanges of 4 stringers, which had especially remarkable corrosion. Outline of measurement results on the each stringer is shown in Table 1. The corrosion on the specimen No.1 is the most remarkable, and the specimen No.2, No.3 and No.4 follows.

The frequency diagram of corrosion depth measured in each specimen is shown in Fig. 1(a)-(d). As for the specimen No.1 whose corrosion is the most severe, the frequency of the corrosion depth is the most remarkable where the depth is 4.0 to 5.5mm, and the histogram is similar to the normal distribution. In the specimen No.4 whose corrosion is the slightest, the frequency diagram of the corrosion depth looks the half normal

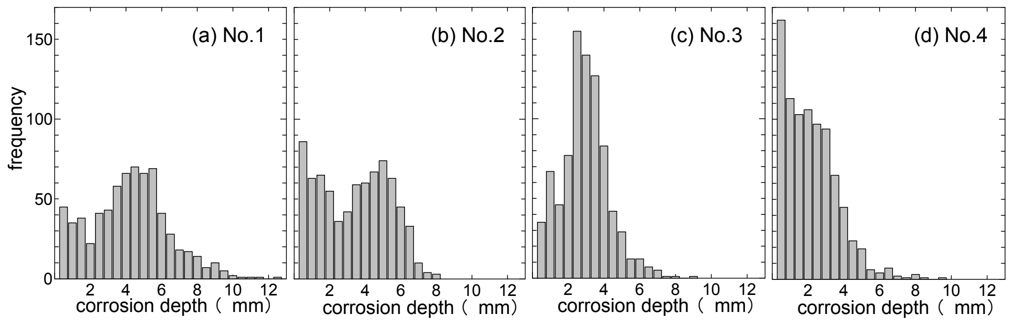

Fig.1. Distribution of corrosion depth on the upper flange of each girder (A-Bridge)

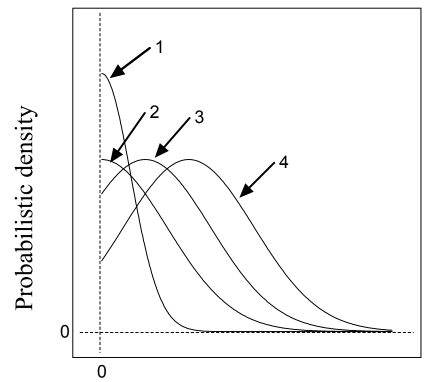

Fig.2. Model of corrosion progress

distribution whose modal value is equal to 0. On the basis of these facts, the histogram of the corrosion depth is considered to progress at the order shown in Fig.2.

Mean value, standard deviation and largest corrosion depth in each specimen measured by the laser equipment are shown in Table 2. Fig.3(a) to (c) and Fig.4(a) to (c) show the example of frequency diagram of corrosion depth, frequency diagram of corrosion depth at the point adjacent to objective point, and the relationship between maximum, average and minimum value of corrosion depth at the adjacent point and corrosion depth at the objective point. The number of adjacent points surrounding an objective point is eight.

The solid line shown in Fig.3(a) and Fig.4(a) is normal distribution obtained from measured modal value and standard deviation. Two examples shown here almost correspond with the normal distribution. Other data also corresponded with the normal distribution. From Fig.3(b) and Fig.4(b), it can be understood that corrosion depth of the adjacent point is also followed by the normal distribution whose modal value is equal to the depth at the objective point.

Fig.3(c) and Fig.4(c) indicate that the average corrosion depth of adjacent point is almost the same as that of the objective point. The maximum and minimum corrosion depth at the adjacent point is almost parallel to the average corrosion depth. This fact means that the (gradient) restriction of the corrosion depth at adjacent point to the depth of the objective point exists. That is, the corrosion depth does not change suddenly and corrosion configuration is comparatively smooth.

Table 2 Results of corrosion depth measurements of B- and C-bridge

Specimen		Average corrosion depth	Standard deviation	Maximum corrosion depth
B-bridge	No.1	1.25mm	0.45mm	2.62mm
	No.2	1.23mm	0.52mm	3.03mm
	No.3	0.58mm	0.29mm	1.88mm
C-bridge	No.1	1.44mm	0.68mm	2.69mm
	No.2	1.97mm	0.77mm	3.56mm
	No.3	1.40mm	0.66mm	3.36mm
	No.4	1.39mm	0.69mm	2.77mm

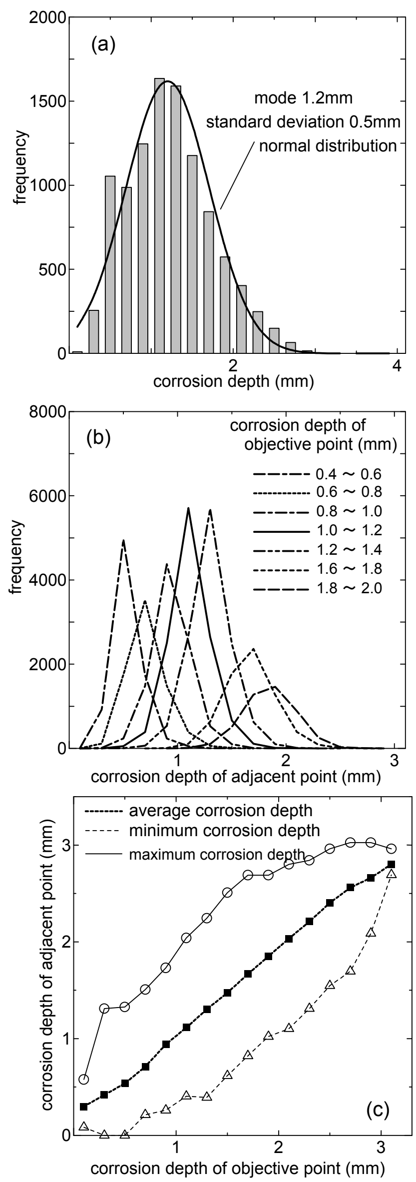

Fig.3. An example of measured results of corrosion depth in the B-bridge

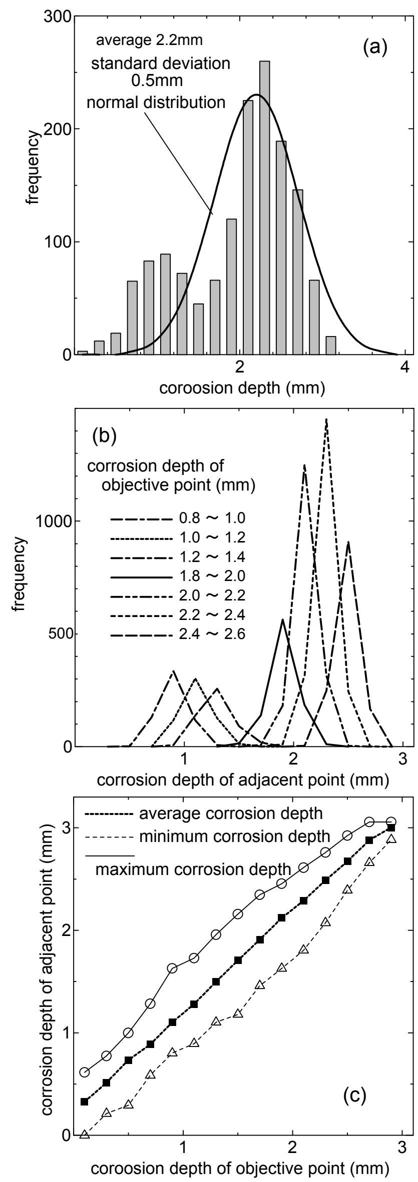

Fig.4. An example of measured results of corrosion depth in the C-bridge

2.3 Simulation of surface configuration

On the basis of results indicated in the former section, the technique to simulate the configuration of corroded steel plate surface has been developed as follows.

(a) The steel plate surface is divided into grid of perfect square, and the numbering for each node of the grid is randomly carried out using uniform random number.
(b) The permutation of corrosion depth is prepared, which follows fixed normal distribution (mode, standard deviation, maximum value, minimum value) using the normal random number.
(c) The first corrosion depth in the permutation specified in the step (b) is given to the No.1 node determined in the step (a). This corrosion depth is deleted from the permutation.
(d) Whether the No.2 node is adjacent to the No.1 node is judged. If adjacent, whether the first corrosion depth in the permutation has satisfied the condition that corrosion depth of the adjacent point follows the normal distribution with the modal value equal to the depth at the objective node is assessed. If it has been satisfied, this value is adopted as the corrosion depth at the No.2 node, and it is deleted from the permutation. When it is not satisfied, the depth satisfying the condition is searched in the order of corrosion depth in the permutation, and it is defined as the corrosion depth at No.2 node, then it is deleted from the permutation.
(e) Corrosion depth of all nodes is determined by doing repeatedly the work of the step (d).

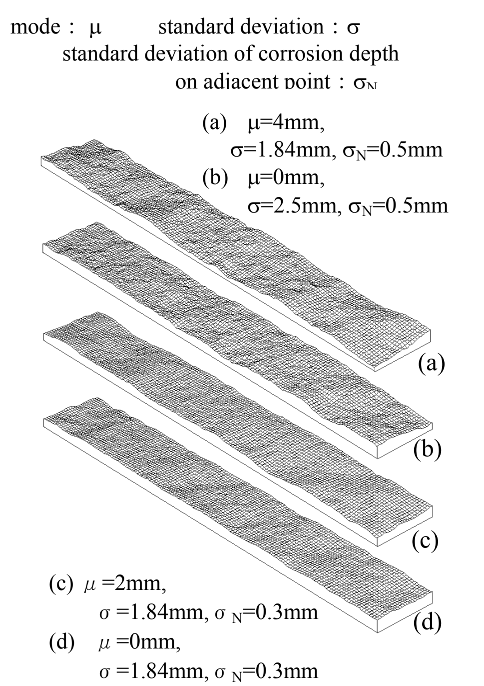

Fig.5. Examples of simulated corrosion surface

2.4 *Results of simulation*

The configuration of the corroded steel plate surface simulated using the technique described in the former section has been obtained. Some examples of simulated configurations are shown in Fig.5. The conditions of the simulation are also indicated in Fig.5.

3. **Analyses of bending capacity**

In this chapter, the bending capacity of corroded steel beam is analyzed using three-dimensional elastic-plastic finite element stress analyses, and bending capacity evaluation method is discussed.

3.1 *Analytical model*

Analytical object is the steel I-shaped beam whose cross-section is shown in Fig.6. The length of the beam is assumed to be 800mm. The existence of the general corrosion was assumed in a range of 500mm in span center on the upper surface of lower flange, and the local corrosion is assumed to exist at the span center. The configuration of general corrosion and local corrosion consists of 6 types and 6 types, respectively. In addition to the above models, the sound beam (without corrosion) was also the analytical object. The example of the finite element model is shown in Fig.7 in order to indicate the surface configuration of each corrosion model.

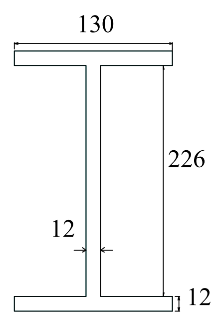

Fig.6. Cross section of beam

3.2 *General corrosion model*

Longitudinal wave (LW) model and transverse wave (TW) model simulate the corrosion configuration by sine wave, and corrosion depth of the deepest point is set at 1, 2, 4, 6 and 8mm (the minimum corrosion depth is set at 0), and the wave length is assumed to be 6 times of the depth. The double wave (DW) model simulates the corrosion configuration by double sine wave, and the wave length is set at 40mm, and the depth of the deepest point is assumed to be 2, 4, 6 and 8mm.

The uniform distribution (UD) model simulated the corrosion configuration using the uniform random number. The corrosion depth was set so that the average is equal to 1, 2, 3, 4, and 5mm (a range of random number 0-2, 0-4, 0-6, 0-8 and 0-10mm). The normal distribution (ND) model simulated the corrosion configuration using the normal random number. The modal value and the standard deviation of normal distribution is set as shown in Table 3.

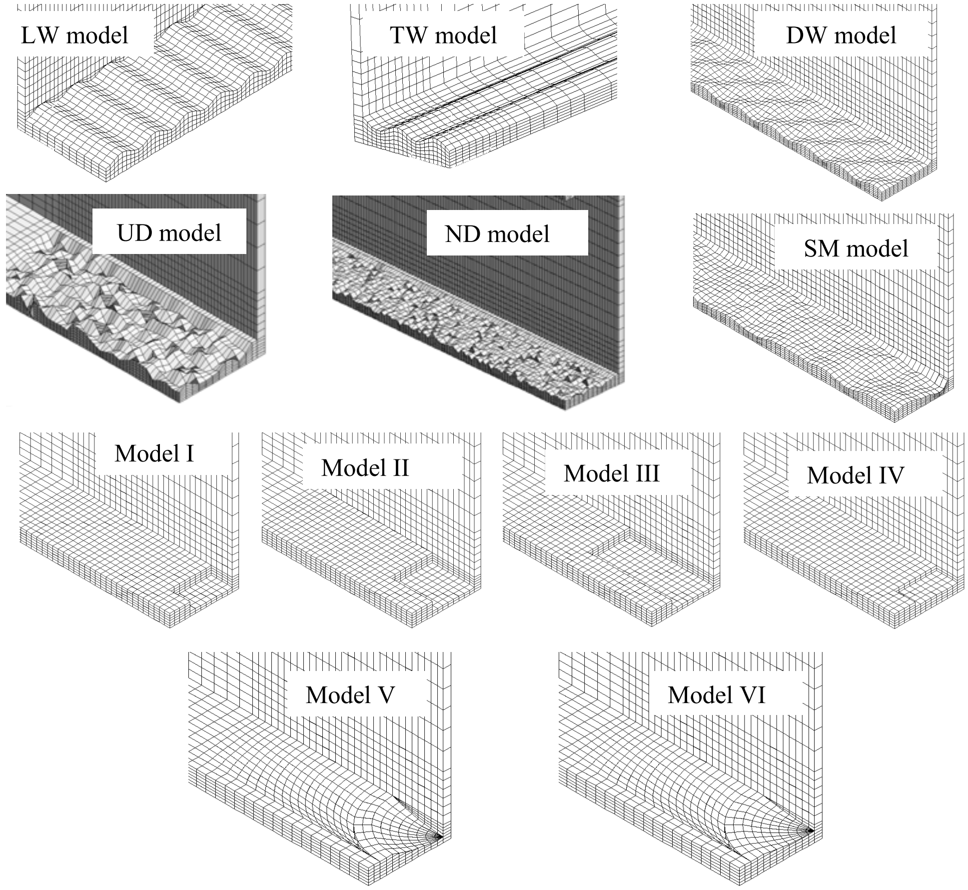

Fig.7. Finite element of each corrosion model

Table 3 Normal distribution model

ND	Mode	Standard deviation
1	0	1.84mm
2	2.0mm	1.84mm
3	4.0mm	1.84mm
4	0	1.0mm
5	0	1.5mm
6	0	2.5mm

The simulation (SM) model simulated the corrosion configuration using the method described in the former chapter. The modal value and the standard deviation of the normal distribution is set as shown in Table 4. The standard deviation of corrosion depth at the adjacent point has been set at 0.3mm or 0.5mm.

3.3 Local corrosion model

Model I to IV simulate the local corrosion by square groove. In the model I, corrosion depth is set at 2, 4, 6, 8 and 10mm, and the width and length are assumed to be 5 times of the depth. In the model II, the length and width of the groove is set at 10 times and 5 times of the depth, respectively. As for the model III and IV, the length (width) is 20 times (5 times) and 10 times (10 times) of the depth, respectively.

Table 4 Simulation model

SM	Mode	Standard deviation	Standard deviation*
1	0	1.0mm	0.3mm
2	0	1.5mm	0.3mm
3	0	1.8mm	0.3mm
4	0	2.5mm	0.3mm
5	2.0mm	1.8mm	0.3mm
6	4.0mm	1.8mm	0.3mm
7	0	1.0mm	0.5mm
8	0	1.5mm	0.5mm
9	0	1.8mm	0.5mm
10	0	2.5mm	0.5mm
11	2.0mm	1.8mm	0.5mm
12	4.0mm	1.8mm	0.5mm

* *adjacent point*

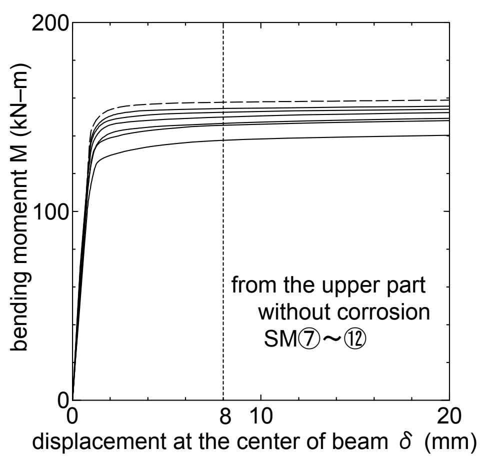

Fig.8. An example of M-δ relationship

Model V and VI simulated the corrosion configuration by a quarter ellipsoidal groove. In the model V, the corrosion depth is equal to 2, 4, 6 and 8mm and the diameter is set at 5 times of the depth. As for the model VI, the depth is 2 and 4mm, and the width and length is equal to 10 times and 20 times of the depth, respectively.

3.4 Analytical method

Steel for the model is assumed to be JIS SM400, and its yield stress is set at 294N/mm^2, Young's modulus is 2.06x10^{5}N/mm^2 and Poisson's ratio is 0.3. Considering the symmetrical shape of the analytical object, finite element elastic-plastic stress analyses have been carried out using quarter models. The element size is basically set at 5x5x2mm (2mm in thickness direction). The relationship between stress and strain is assumed to be bi-linear, and the gradient after the yield is set at 4.66×10^{-3}N/mm^2. Von-Mises criterion has been employed for assessment of yielding.

3.5 Analytical results

An example of the relationships between bending moment M and deflection δ□ at the span center, which were obtained from the analyses on SM models, is shown in Fig.8. The bending capacity was assumed to be a bending moment as the deflection reached one-hundredth of the span length (8mm).

Fig.9(a) shows the bending capacity ratio arranged by maximum corroded cross-section ratio. The bending moment ratio is the ratio of bending capacity of the beam with the corrosion to one of the beam without corrosion. The maximum corroded cross-section ratio is an amount of the loss in cross-section area due to corrosion in which the largest corrosion occurs normalized by the original flange cross-section area. The bending capacity ratio decreases as the maximum corroded cross-section ratio increases in either corrosion model. However, the lowering rate of bending capacity with increase in the maximum corroded cross-section ratio has significant difference among the corrosion model. Fig.9(b) indicates the relationship obtained from local corrosion model. The relationship also large difference among the corrosion model in this case. These facts mean that the maximum corroded cross-section ratio is not suitable parameter to arrange the bending capacity of the corroded steel member.

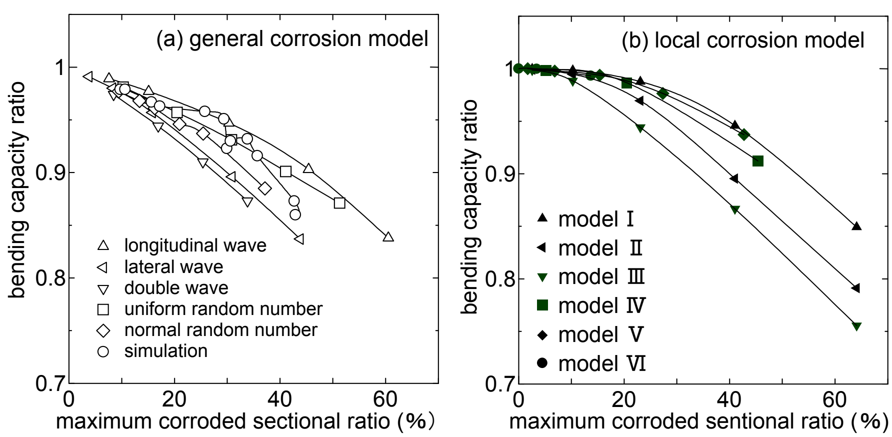

Fig.9. Bending capacity ratio arranged by maximum corroded sectional ratio

Bending capacity ratio of the beam with general corrosion has been tried to be arranged by the average corroded cross-section ratio. The average corroded cross-section ratio is the average ratio in all cross-sections with the corrosion, and it is equal to the volume defect ratio in the objective part. The results are shown in Fig.10. The difference of bending capacity ratio due to corrosion model also exits in the case that the average corroded cross-section ratio is utilized.

3.6 Estimation of bending capacity using modified corroded cross-section ratio

The bending capacity can be defined as a bending moment when a cross-section receives large plastic deformation. Such plastic deformation does not occur in the whole region of the beam, and it is considered to occur in some part of the beam. If this region (length) can be defined, the average corroded cross-section ratio in the region may be powerful parameter to arrange the bending capacity. Here, the length (F_L) being 0.5, 1.0 and 1.5 times of the flange width (F_W) is taken up in the direction of longitudinal axis of the beam, the average corroded cross-section ratio is regularly calculated in each region, and the bending capacity is tried to be arranged by the largest one of the average corroded cross-section ratio calculated. This average corroded cross-section ratio is called the modified corroded cross-section ratio.

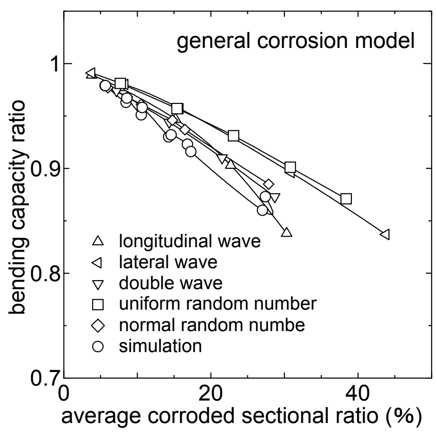

Fig.10 Bending capacity ratio arranged by average corroded sectional ratio

Fig.11(a) to (c) shows the bending capacity ratio arranged by the modified corroded cross-section ratio in case of F_L=0.5F_W, F_L=1.0F_W and F_L=1.5F_W. As for the general corrosion model, the bending capacity ratio is well arranged by the modified corroded cross-section ratio regardless of corrosion model in each value of F_L. In the local corrosion model, the bending capacity is also arranged well by the modified corroded cross-section ratio regardless of corrosion model in each value of F_L. However, the bending capacity of the local corrosion model is higher than one of the general corrosion model in case of F_L=0.5F_W and lower in case of F_L=1.5F_W. When F_L is assumed to be equal to 1.0F_W, the bending capacity is not influenced by corrosion type. Therefore, the modified corroded cross-section ratio in a region of F_L=1.0F_W is considered to be adequate parameter to evaluate the bending capacity of the beam with corrosion.

3.7 Estimation method of bending capacity

Bending capacity of corroded beam is tried to be evaluated by plastic moment (Mp) which can be obtained from simple calculation. In order to obtain the value of Mp of corroded beam, thickness of flange with corrosion is uniformly reduced by the modified corroded cross-section ratio. The value of Mp can be calculated by following equation using the symbols shown in Fig.12.

$$M_p = \sigma_{ys}\left(\int_{y_2}^{y_1} w_l y \cdot dy + \int_0^{y_2} t_w y \cdot dy - \int_{-y_3}^{0} t_w y \cdot dy - \int_{-y_4}^{-y_3} w_u y \cdot dy\right) \quad (1)$$

Solid line in Fig.11 indicates the relationship between bending capacity ratio and the corroded cross-section ratio, which was obtained from Eq.(1). This line has represented well the data shown in Fig.11(b).

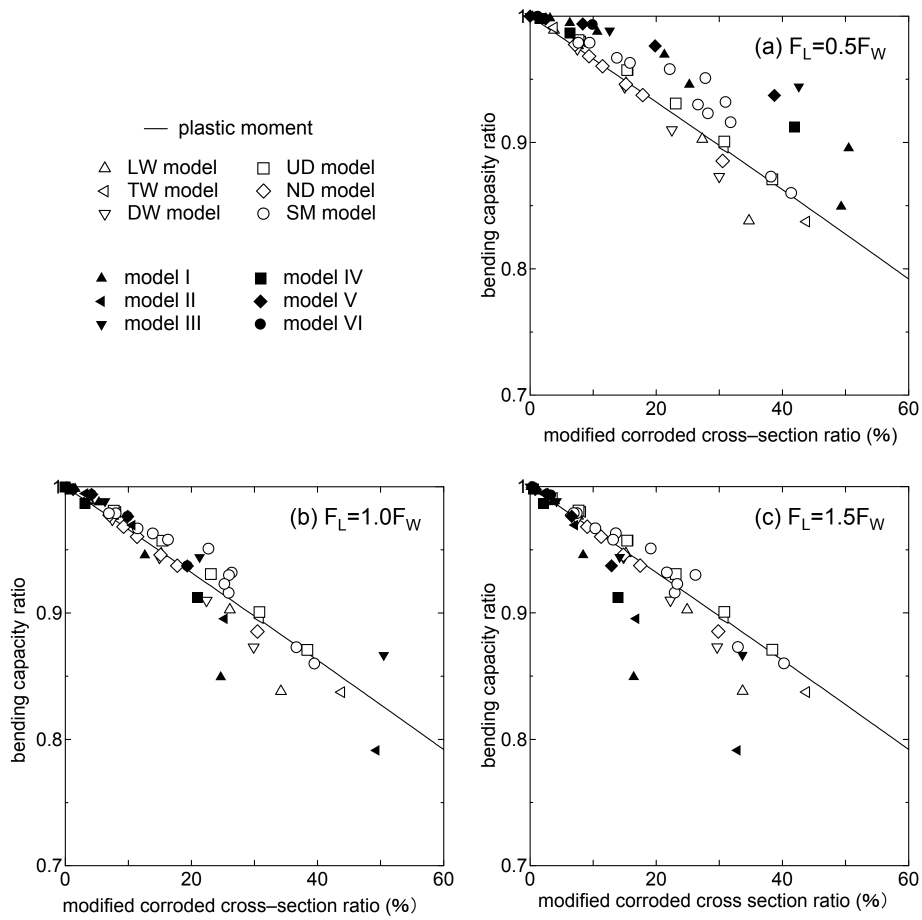

Fig.11. Bending capacity ratio arranged by modified corroded cross-section ratio

4. Conclusions

(1) The corrosion depth of corroded steel plate follows the normal distribution.

(2) The corrosion depth of the adjacent point to the objective point follows the normal distribution whose modal value is equal to the corrosion depth of the objective point.

(3) The method for simulating the configuration of corroded steel plate surface has been proposed using the conclusions (1) and (2).

(4) The bending capacity of steel I-shaped beam with corrosion in the lower flange can be arranged by the maximum value of volume defect ratio due to corrosion in a region where length of flange is equal to flange width (modified corroded cross-section ratio).

(5) The bending capacity of steel I-shaped beam with corrosion in the lower flange can be evaluated by plastic moments of the beam in which the thickness of the lower flange is uniformly reduced by the modified corroded cross-section ratio.

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