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# STRENGTH RECOVERY OF STEEL BRIDGES WITH CORROSION NEAR BEARINGS

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A lot of steel plate girder bridges were erected during the rapid growth in the 1960s in Japan. Currently, the condition of those aging bridges has become marked and a problem in society since over 50 years have passed. Particularly, the corrosion-induced deterioration and damage in railway steel plate girder bridges, which have an open deck, is becoming prominent. Despite that, the evaluations of residual strengths and the strengthening methods of corroded bridges are not always enough. Therefore, firstly, this paper shows analytical-based evaluation results that explain how the residual shear capacities of plate girders, having corrosion near bearings, depend on the condition of the corroded surface, such as a vertical stiffener or a web. The results show the fracture mode as buckling changes as well as the residual shear capacity, according to the degree and form of corrosion. Next, this study proposes a reliable reinforcement measure to recovery the shear capacity by applying said evaluation results and analytical models. Finally, the shear capacity could be improved tremendously by simple attachments as reinforced members.

*Keywords*: Shear capacity, Web, Vertical stiffener, Local buckling, Reinforcement.

## 1 INTRODUCTION

As of 2016 in Japan, there were about 102,000 railway bridges of more than 1 m in length. Of them, the bridges with steel plate girder system are one of the oldest, and the total amount of age-induced damage is becoming more conspicuous. In this field, it has been studied that corrosion-induced damage has led to a bridge collapse (Shimozato *et al*. 2009). In recent years, partial repairs and reinforcements of girders, as well as replacements, have taken place; however, it would be difficult to say that these measures were made as a choice based on an appropriate quantitative established evaluation on the residual strength of the girders. From the point of view of recent socioeconomic circumstances raised by budget and labor crunches, there is an even more urgent need to establish rational economically sustainable ways for keeping up these bridges to increase their service life. Very few studies on simple residual strength evaluations have been conducted with analyses in order to rapidly determine the safety level of bridges faced with problems and whether to control their continuous use or not. Asao *et al*. (2016) focused on railway steel plate girders, presented an adequate understanding related to the conditions of corrosion-induced damage seen relatively near the bearings, and studied residual shear capacity and decreasing strength near bearings by analyzing with typical corrosion models. However, in that study, simple reinforcement methods had not been taken into account.

Therefore, this study proposes an applicable measure to reinforce in order to recover the strength by using and improving the analytical results and models in the past study conducted by

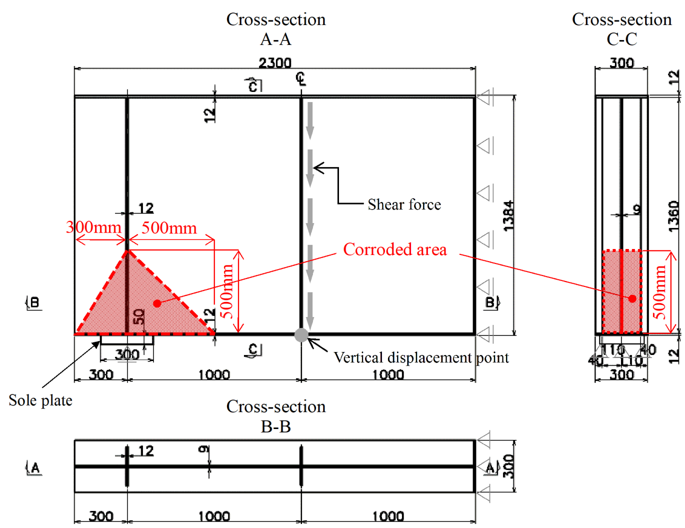
Asao *et al*. (2016). These results are shown in Section 2, which describes how the residual shear capacity of railway steel plate girders and their collapse forms change.

## 2 RESIDUAL STRENGTH EVALUATIONS

### 2.1 Analytical Models

The analysis with elastic-plastic finite displacement was conducted by applying the general-purpose analytical program NASTRAN. SS400 defined by Japanese Industrial Standards (JIS) as the steel material was used for the analytical models. This material has a yield stress of 235 MPa (tensile strength of 400-510 MPa), an elastic modulus of 200 GPa, and a Poisson ratio of 0.3. The yield criterion of von Mises with a perfectly elastic-plastic property was applied as the material constitutive law.

The dimensions of the main girders targeted for the analysis are shown in Figure 1, as well as the analytical cases. Since the purpose of the study was to give evaluation ways that focused on shear strength, the analytical models were set such that they take into account the symmetric property of the main girders by giving loads near bearings in order to reduce the impact of bending to a maximum extent during the analytical calculations. Additionally, shell elements with four nodal points with six degrees of freedom were applied to the analytical models, and each element was divided into an approximate 10 mm square. The boundary conditions were set in light of the symmetric property of simply supported girders. Initial imperfections were set in the out-of-plane direction on the web between the vertical stiffeners in the analytical models.




| Analytical case | | Thickness (mm) (THK reduction) Web | Vertical stiffener |
|---|---|---|---|
| I | (1) | 9 | 12 |
| II | (2) | 7 (-2) | 12 |
| | (3) | 5 (-4) | |
| | (4) | 3 (-6) | |
| III | (5) | 9 | 10 (-2) |
| | (6) | | 8 (-4) |
| | (7) | | 6 (-6) |
| IV | (8) | 7 (-2) | 10 (-2) |
| | (9) | 5 (-4) | 8 (-4) |
| | (10) | 3 (-6) | 6 (-6) |

* Above (- n) values show thickness reduction from the original thickness

Figure 1. Girder dimensions used for analyses and the analytical cases (Incl. load and corrosion conditions).

### 2.2 Results of Analysis

Figure 2 shows the relations between thickness reduction and residual strength for analytical models in which either vertical stiffeners or webs near bearings corrode and for analytical models in which both corrode. The figure indicates that corrosion on the web has the largest impact on shear capacity near girder edges. This significant strength reduction is caused most commonly by the local buckling at the corroded webs before shear force could be transferred to the diagonal tension field of the overall webs, as shown in Figure 3(a). This figure also indicates that even when only vertical stiffeners are corroded in the models and its thickness is reduced 50%, shear capacity is decreased by only around 10%. Meanwhile, when webs and vertical stiffeners are corroded in the models simultaneously, shear capacity is decreased much more seriously than in the models in which only webs corroded. This means a greater impact on shear capacity reduction than in cases where only webs or only vertical stiffeners corroded because shear force is rapidly redistributed to vertical stiffeners directly after local buckling occurs in web corroded area.

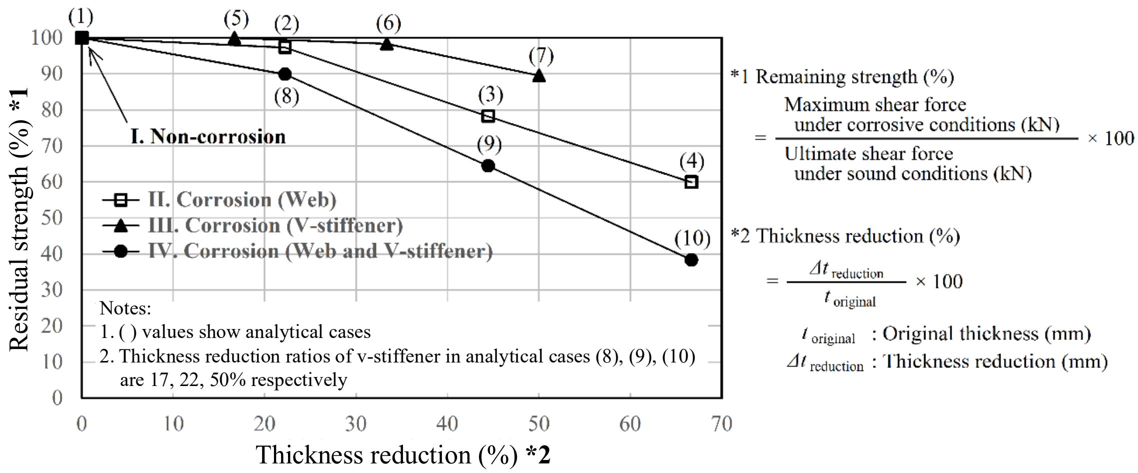
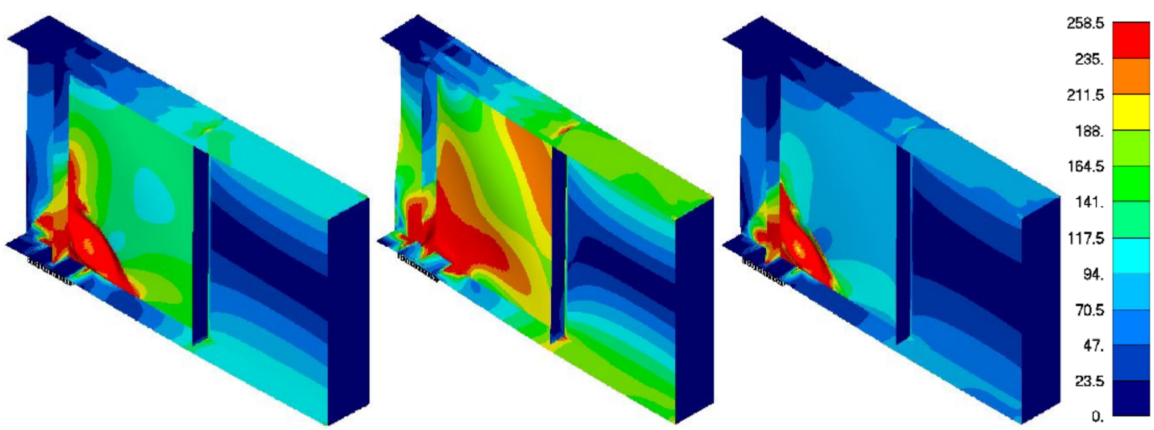



Figure 2. Shear capacity reduction due to thickness reduction.




(a) Point-(4) in Figure 2 (b) Point-(7) in Figure 2 (c) Point-(10) in Figure 2

Figure 3. Von Mises stress distribution and deformed configurations at peak shear force.

## 3 REINFORCMENT METHODS

Based on the above analytical results, this section proposes a specific reinforcement that can be conducted on railway steel plate girders, which the shear capacity has reduced in actual, taking a realistic method that can be executed without preventing train operations. The effectiveness of this reinforcement that contributed to the shear capacity is analytically evaluated below.

## 3.1 Conditions of Analysis

### 3.1.1 *Analytical models*

The prerequisites for the analytical models applied in the reinforcement method study are set as mentioned in Section 2.1.

This study targets the one case "(10)" shown in Figure 2 that showed the most apparent reduction in shear capacity and investigates and analyzes the availability of reinforcement based on those analytical models. The two analytical cases, as a target for comparison, are shown in Table 1, in which "(1)" indicates the plate girder to be in original sound condition without corrosion.

Table 1. Analytical cases (Non-corrosion and corrosion with thickness reduction).

| Analytical case | **(1)** | **(10)** |
| --- | --- | --- |
| Web (mm) | **9** | **3** (-6) |
| Vertical stiffener (mm) | **12** | **6** (-6) |
| Remarks | Non-corrosion | THK reduction |

* (- n) values in the above table show thickness reduction from the original thickness

### 3.1.2 *Reinforcement models*

A method of attaching L-shaped angle steels shall be proposed in this study. These angle steels are installed parallel and adjacent to vertical stiffeners by tightening bolts on them from both sides of the web. This reinforcement method can be finished up in a matter of hours at midnight when trains are not operating. The specifications of the angle steels are shown in Table 2. Figure 4 shows the analytical models of the reinforcement materials attached to the plate girders. Here, Figure 4(a), the "one-sided reinforcement" is where two angle steels are attached to the front and back sides of a web only on the girder center side from the vertical stiffener existing directly above the bearing. In Figure 4(b), the "two-sided reinforcement", is where two angle steels are attached at the girder end side, in addition to the state of Figure 4(a) described above.

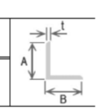
When the reinforcement members are modeled, the analytical conditions are applied as:

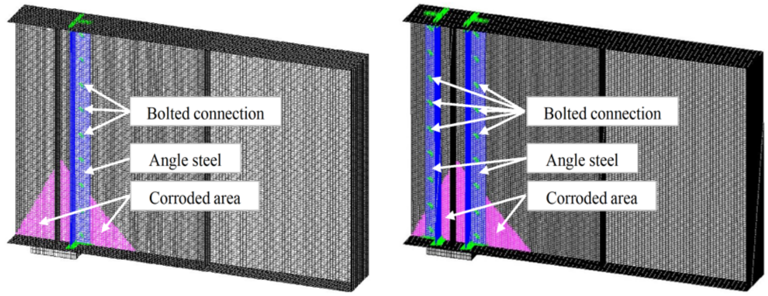
1) The connections between the webs and angle steels are used bolts modeled as rigid elements equal to $\varphi$10 mm and are installed at intervals of about 150 mm vertically, as shown in Figure 4. In fact, web plates are modeled by applying shell elements with four nodal points and are connected to the shell elements of steel angles at the same locations for bolting. These joints between the web and steel angle are modeled by applying rigid-body springs at each nodal point.

2) Figure 5 shows gap elements, which could be taken into account the contacts between the angle steels and flanges in order to prevent the upper and lower edges of the angle steels from overlapping the upper and lower flanges after the web deforms.

3) From the standpoint that the maximum reinforcing effect can be obtained by transferring conveying the stress acting on the webs to the sole plate directly, the angle steels are installed at 50 mm inward from the edges of the sole plate, as shown in Figure 5.

Table 2. Specifications of the reinforcement member.

| Material | Grade | Quality | Section size (mm) |   |
| --- | --- | --- | --- | --- |
| Angle steel | JIS G 3192 | SS400 | 10 (t)×100 (A)×100 (B) | |




(a) Reinforcement with 2 angle steels (One-sided reinforcement) (b) Reinforcement with 4 angle steels (Two-sided reinforcement)

Figure 4. Analytical models after reinforcing.

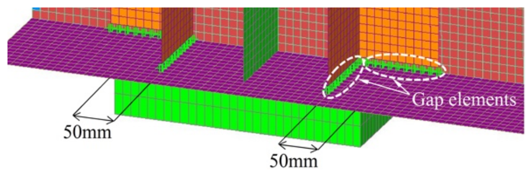



Figure 5. Modeling conditions of angle steels.

## 3.2 Results of Analysis

Table 3 indicates the analytical results conducted on the two cases listed in Table 1, which shows the maximum values of shear capacity before and after reinforcing by the angle steels. The reinforcements include "one-sided reinforcement" by the two angle steels and "two-sided reinforcement" by the four ones.

As per the results, it turned out that in the case that "one-sided reinforcement" was taken, the strength recovery degree from shear capacity with the corrosion state is limited to only around 20%, as shown by analytical case (10), which is not a huge reinforcement outcome. This is because local buckling occurs due to the stress concentration at a place where the vertical stiffener and the web at the girder end have been corroded, before the two additional reinforcing angle steels bear the load of an axial force (Figure 6(b)). The peak axial force that works on the angle steels in case (10) is shown in Table 4, and it turns out that the value remains very small. However, when "two-sided reinforcement" was applied, the shear capacity, as shown by analytical case (10), recovers to the same extent as one in analytical case (1), which is in sound condition. This is because the four angle steels bear the load of a huge axial force (Table 4), and as a result, the web is being functioned as an effective diagonal tension field (Figure 6(c)).

According to the above, in the case of severe local corrosion of the vertical stiffeners and the webs, conducting "two-sided reinforcement" applying angle steels makes a dramatic recovery of shear capacity possible, up to the soundness level when it was in the original state.

Table 3. Maximum shear capacity before and after reinforcing.

| Analytical case | Maximum shear capacity (kN) | | | Remarks |
|---|---|---|---|---|
| | Before reinforcement | After reinforcement | | |
| | | One-sided reinforcement | Two-sided reinforcement | |
| (1) | 1440 | — | — | Non-corrosion |
| (10) | 553 | 639 | 1454 | THK reduction |

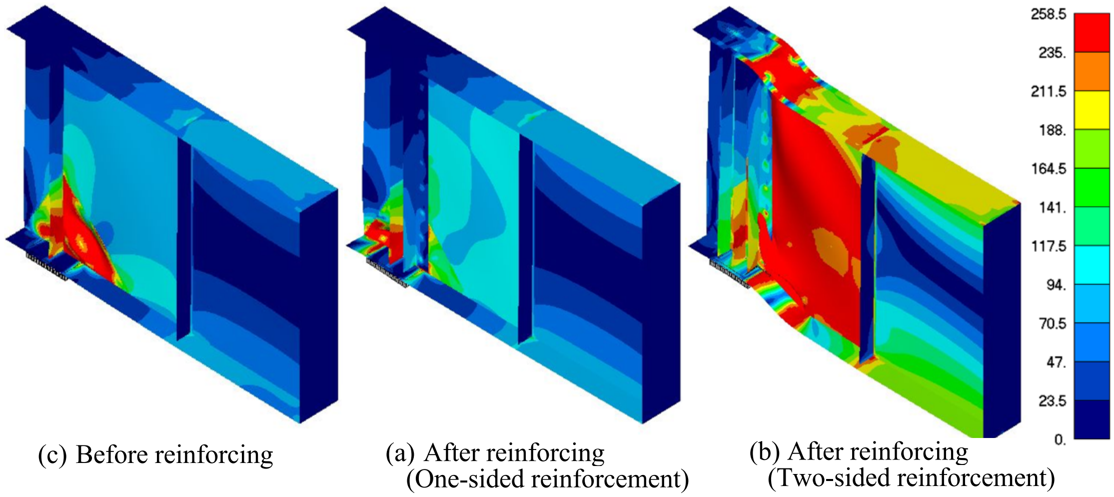
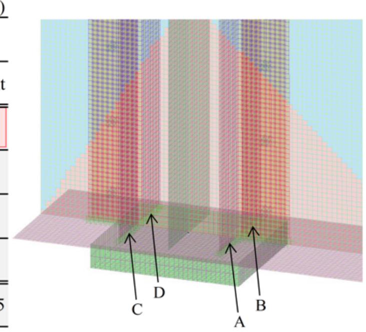



Figure 6. Von Mises stress distribution and deformed configurations at peak shearing force: Case (10).

Table 4. Peak axial forces working on reinforcing angle steels: Case (10).

(Compression: +, Unit: kN)

| Analytical case | Location of angle steel | Peak axial force | |
|---|---|---|---|
| | | One-sided reinforcement | Two-sided reinforcement |
| (10) | A | 104 | 288 |
| | B | 90 | 254 |
| | C | — | 241 |
| | D | — | 242 |
| | Total | 194 | 1025 |




Note: The axial force that acts on an angle steel is calculated using the membrane stresses in the vertical direction on the elements at the lower end of the angle steel.

## 4 CONCLUSION

In the case of severe local corrosion on the vertical stiffeners and webs, two-sided reinforcing system using angle steels makes the shear strength restoration possible to the extent of the strength of beams being in sound state. Additionally, this method contributes to the simplified and brief work on-site and is more economical than other ways. In short, developing and establishing simplified analytical methods and reinforcement ones, like in this study, could make a lot of future aged bridges evaluate speedy and suitably, and keep them in use for much more than each design service life.

### References

Asao, N., Fujii, K., Fukuda, and H., Yokota, R., *Remaining Strength Evaluation of Plate Girders with Corrosion near Support*, Proceedings of the Third Australasia and South-East Asia Structural Engineering and Construction Conference, ASEA-SEC-3, Kuching, Sarawak, Malaysia. doi: 10.14455/ISEC.res.2016.156. Oct 31-Nov 4, 2016.

Shimozato, T., Murakoshi, J., Tamaki, Y., and Takahashi, M., *Real Time Monitoring of Bridge Collapse due to Intense Corrosion*, Bridge and Foundation Engineering, 43, 55-60, 2009.