EVALUATION OF CORROSION STATE OF GUSSET PLATE CONNECTIONS OF STEEL TRUSS BRIDGE

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ABSTRACT A huge number of steel bridges were constructed in Japan during the period of high economic growth from the 1950s to the 1970s. As these bridges age, deterioration and damage resulting from heavy traffic and the effects of the natural environment are also increasing rapidly. Improved techniques related to inspection, diagnosis, repair, reinforcement and appropriate maintenance of such bridges are urgently needed. In the case of steel truss bridges, serious corrosion damage has been reported recently, especially on diagonal members and at gusset plate connections. In this study, detailed corrosion profiles of four gusset plate connections removed from a dismantled steel truss bridge are obtained using laser measurement equipment. The corrosion state of the connections is evaluated on the basis of the corrosion depth distribution over their surfaces.

Key words: 腐食, レーザー変位計測装置, 鋼トラス橋, 格点部
Corrosion, laser measurement device, steel truss bridge, gusset plate connection

1. INTRODUCTION
Many steel bridges were built in Japan during the period of high economic growth from the 1950s to the 1970s, so the number of aging bridges in the country is now increasing rapidly. With this rising number of bridges over 50 years old, there have been reports of serious corrosion damage, including the cases of the Kiso river bridge on National Highway Route 23 and the Honjo bridge on National Highway Route 7 in 2007. Around the same time, the Minneapolis I-35W truss bridge[1, 2] suddenly collapsed.

Steel truss bridges are prone to damage affecting the truss members and the connections between them. Corrosion has a particularly severe effect on truss bridges and can lead to significant sectional loss of truss members which may lead to loss of structural integrity. In order to verify the integrity of an entire bridge system, there is a need for an inspection and maintenance regime that evaluates the impact of such corrosion efficiently and properly.

In this study, the targeted bridge is the Choshi bridge, a five-span cantilever steel truss bridge, that crossed the estuary of Tone river. This bridge was removed in accordance with the opening of new bridge in 2009 after approximately 50 years of service. Due to the influence of salt, the corrosion damage occurred
severely on every members of this bridge even the repainting was carried out several times in its service life. Moreover, during its service life, the diagonal members, the gusset plate connections, floor beams were reinforced and the lateral bracing was replaced. Besides, the corrosion also occurred severely at the transition area and the bolt area because of stagnant water and the lack of coating thickness, respectively. The load carrying capacity and the earthquake resistance of the bridge also were decreased due to the corrosion damage on superstructure and concrete spall on the RC piers because of severe corrosion of reinforcement. Because of the degree of damage, the structure was dismantled in 2009, with several parts (connections and diagonal members) removed for corrosion research purposes.

In detailed, four connections (2 upper, 2 lower) were cut out from an aging steel truss bridge and the pattern of corrosion at these connections was measured in detail. More specifically, both the inner and outer surfaces of chord members, diagonal members and gusset plates were profiled using laser surface measurement equipment[3, 4]. The results of these measurements clarify how corrosion actually proceeds on these gusset plate connections and reinforcement area[5-7].

2. GUSSET PLATE CONNECTIONS

The four connections studied were removed from the Choshi bridge, as shown in Figure 1. The four connections studied here consisted of one top connection from the second span on the downstream side of the bridge and three connections from the fifth span, one top and two bottom. On of the bottom connections, P72u, had been reinforced in 2002 by attaching additional plates with high-strength bolts due to loading carrying capacity requirements. The specific locations, dimensions and materials of these connections are indicated in Figure 1.
3. CORROSION MEASUREMENT METHOD

3.1 Laser measurement equipment

The laser measurement equipment, shown in Photo 1, comprises:

1. Clamp stand to support specimens for measurement
2. Laser meter
3. Stepper motor for Y direction
4. A-D converter
5. Measurement-control equipment
6. Fixing device

The specifications of the laser measurement equipment and clamp stand are given in Table 5. In taking measurements, the measurement grid is selected from 1-3mm depending on the actual corrosion condition of the specimen so as to gain understanding of its corrosion state.

3.2 Outer surface measurement

In order to measure the corroded profile of the outer surface, the specimen was set up vertically and parallel to the laser measurement equipment. The equipment has a limited 1m x 1m measurement range, so for measurements of the outer surface directly from the large specimens, the surface was divided into segments for measurement.

The normal set-up for measuring the surface corrosion profile of a specimen’s outer surface was carried out as follows:

1. The surface of the specimen to be measured was set up parallel to the axes of the laser measurement equipment. The distance of the laser measurement equipment from the specimen is output by the A-D converter, allowing verification that the two planes are parallel.
2. The origin for measurements is set automatically.
3. The measurement range is set (start point and end point).
4. The based-surface is determined. In the case of the connection P25d, the specimen was measured from both sides because corrosion was so severe over the whole gusset. In the cases of the other connections (P73d, P72d, P72u), the based-surface was determined using the three-point method. Five points with no corrosion on the gusset plate were

\[
\begin{align*}
(a) & \text{Corrosion depth calculation method} \\
(b) & \text{Base surface identification} \\
(c) & \text{Remaining thickness calculation}
\end{align*}
\]

Fig. 2 Corrosion measurement and corrosion depth calculation method
selected, then three of these were used to identify the base plane, as shown in Figure 2(a) and 2(b).

Measurements are started.

At any specific point, the corrosion depth on the right, outer surface, \( d_{oi} \) (i = 1, 2, ..., n), is calculated by

\[
d_{oi} = H_r - h_{oi}
\]  

(1)

where \( h_{oi} \) is the distance from the laser meter to the corrosion surface at point i and \( H_r \) is the distance from the laser measurement equipment to the base-surface. The value of \( d_{oi} \) may be either negative (at a corroded point) or positive (in the area of a rivet head).

3.3 Inner surface measurement

Inner surfaces of the specimens and other tight spaces, such as the inner surface of the gusset plate, could not be measured directly using the equipment. In these cases, a method using molded plaster was adopted. Photo 2 illustrates the steps in taking a plaster mold of the specimen in the case of the P25d connection. The surface of a plaster specimen was then measured using the same laser measurement equipment, as shown in Photo 3. The base-surface in the case of inner surface measurements is set using three corrosion-free points on the plaster specimen surface. If a plaster specimen was not suitable for supporting with the clamp stand, it was held in a vise on the desk for measurement. The actual measuring procedure was the same as for outer surface measurements.

At any specific point, the corrosion depth on the left, inner surface, \( d_{il} \) (i = 1, 2, ..., n), is calculated by

\[
d_{il} = -(H_l - h_{il})
\]  

(2)

where \( h_{il} \) is the distance from the laser measurement equipment to corrosion point i and \( H_l \) is the distance from the laser measurement equipment to the base plane. The minus sign in the formula represents use of the indirect method to identify the corrosion using molded plaster. The value of \( d_{il} \) is either negative (at a corroded point) or positive (in the area of a rivet head).

Then the remaining thickness, \( t_{il} \), at the specific point i is calculated as follows:

\[
t_{il} = t_0 - d_{il} - d_{oi}
\]  

(3)

where \( d_{il}, d_{oi} \) are the corrosion depths on the left, inner surface and the right, outer surface, respectively, and \( t_0 \) is the initial thickness of the steel, as shown in Figure 2(a).

With readings taken from molded plaster for the inner surface measurements, there is uncertainty in setting the same start and end points for measurement. This means that the remaining thickness at the specific point could not be calculated with precision and the term “average remaining thickness”, the average remaining thickness is the average of every measuring points’ remaining thickness on a specific area, is used in the analysis from now on. Further, where the gusset plate and flange of the diagonal member overlap, corrosion on the inner surface of the gusset plate and the outer surface of the flange of the diagonal member could not be measured so the corrosion depth was considered zero here, as shown in Figure 2(c).

4. CORROSION STATE OF THE GUSSET PLATE CONNECTIONS

4.1. Connection P73d

Connection P73d was taken from the downstream side of the fifth span of the bridge, as shown in Figure 1. To measure the outer surfaces of the gusset plates, measurements were divided into four sections on both the upstream and downstream sides, as shown in Figure 3. The measurement grid was set to 1mm. Photo 3
Fig. 3 Measurement range of connection P73d

Photo 3 Outer surface measurement of connection P73d

Fig. 4 Corrosion depth distribution on the outer surface of connection P73d

Fig. 5 Corrosion depth distribution around rivet heads of connection P73d on the upstream side

Photo 4 Corrosion condition of the inner surface of connection P73d
The corrosion depth distribution on the inner surface of connection P73d is shown in Figure 6. As can be seen, there is severe corrosion at the edges of the gusset plate on both upstream and downstream sides, as well as on the flange of the tensile diagonal member on the upstream side and on the compressive diagonal member on the downstream side. The average corrosion depths are 0.9mm and 1.6mm on the upstream and downstream sides, respectively.

The state of corrosion in several regions of severe corrosion on the gusset plates and the diagonal member flanges on both the upstream and downstream sides is enumerated in Table 6. On the gusset plates, the average corrosion depth, average remaining thickness and thickness loss ratio fluctuated around 2.5mm, 9.5mm and 20%, respectively. However, on the corroded region of the diagonal member flanges the corrosion is more intense. Here, the average corrosion depth ranged from 1.9mm to 5.6mm, while the thickness loss ratio ranged from 21.2% to 62.2% in the most severely corroded region (G-5) on the flange of the compressive diagonal on the downstream side.

The corrosion depth distribution of the outer surface of the upper chord member of P73d on both the upstream and downstream sides is shown in Figure 7. On the downstream side, corrosion has occurred over the center of the rivet head is 4.3mm.

The corrosion depth distributions on the outer surfaces of P73d are shown in Figure 4. This clearly indicates that corrosion occurred locally around the rivet heads on both upstream and downstream sides, at the edge of the gusset plate on the upstream side and more severely on the tensile diagonal member on the upstream than on the downstream side. The average gusset plate corrosion depth is 1.2mm and 0.6mm, respectively, on the upstream and downstream sides.

Several areas of severe corrosion were selected for remaining thickness calculations, as also shown in Figure 4. These areas (D-1, D-1~D-5) correspond to the areas of most severe corrosion on the inner surfaces, as shown in Figure 6.

Figure 5 shows details of the corrosion around one rivet head on the diagonal tensile member side of the gusset on the downstream side of P73d. The initial rivet head is described by the dashed red line on the graph. The figure clearly shows that doughnut-shaped corrosion has occurred at a radius of about 20mm from the center of the rivet head, while the corrosion depth at the center of the rivet head is 4.3mm.

The inner surfaces of P73d are shown in Photo 4. Eight plaster specimens were created to make the inner surface measurements and corrosion depth was measured using the procedure described in section 2. The corrosion depth distribution of the inner surfaces of P73d is shown in Figure 6. As can be seen, there is severe corrosion at the edges of the gusset plate on both upstream and downstream sides, as well as on the flange of the tensile diagonal member on the upstream side and 2% of the diagonal member on the downstream side. The average corrosion depths are 0.9mm and 1.6mm on the upstream and downstream sides, respectively.

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the entire surface with the most severe corrosion at the lower edge. The average corrosion depth of these outer surfaces is 1.13mm on the upstream side and 0.89mm on the downstream side.

4.2 Connection P25d
Connection P25d was taken from the second span of the five-span cantilever truss bridge. Its inner surfaces have suffered severe corrosion damage due to the influence of salt[3]. Corrosion of the gusset plate outer surfaces is not found, except in the area of the rivet groups, as shown in Figure 8. The average depth of surface corrosion of the rivets is 1mm on the upstream side and 2mm on the downstream side, respectively.

In the transition area between the flanges of the compression and the tensile diagonal members, the average corrosion depth is about 4mm on the upstream side, while the maximum corrosion depth on the downstream side reached 7mm. Corrosion around the rivet heads was in the shape of a doughnut at a radius of about 20-30mm from the center of the rivet head, and the maximum corrosion depth in this area is 4.9mm.

In order to measure corrosion of the inner surfaces of the gusset plate of connection P25d, eight plaster specimens were created, four each on the upstream and downstream sides. Figure 9 shows the corrosion depth distribution with respect to the inner surface of the gusset plates and the diagonal member flanges. Severe overall corrosion was observed on the surface of the gusset plates. The flange surface where diagonal members were joined to the gusset plates with rivets was corroded as a whole. The areas of severe corrosion shown in Figure 9 are enumerated in Table 7.

4.3 Connection P72d
The location of connection P72d is shown in Figure 1. In measuring the outer surface of P72d, the measurement grid was set to 1mm with the aim of investigating mechanical performance. The based-surface was set manually. In this case, the measurement range was divided into five sections in the vertical direction for both the upstream and downstream sides.

The measurement results for the outer surface of the upstream and downstream sides are shown in Figure 10. There was no identifiable corrosion of the outer surface on the downstream side of the P72d gusset plates. Meanwhile, due to the floor beam attached to the surface of the gusset plate on the upstream side, which
**Table 8** Severely corroded regions on the outer surface of connection P72d

<table>
<thead>
<tr>
<th></th>
<th>①</th>
<th>②</th>
<th>③</th>
<th>④</th>
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<th>⑪</th>
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<td>10</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<td>Outer average corrosion depth, $t_{ave}$</td>
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<td>1.87</td>
<td>0</td>
<td>2.3</td>
<td>2.22</td>
<td>1.09</td>
<td>1.4</td>
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<td>0.81</td>
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<td>0.84</td>
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<tr>
<td>Inner average corrosion depth, $t_{ave}$</td>
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<td>0</td>
<td>0.81</td>
<td>1.29</td>
<td>0</td>
<td>0.11</td>
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<td>2.95</td>
<td>1.79</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Average remaining thickness, $t_{ave}$</td>
<td>8.26</td>
<td>8.13</td>
<td>9.19</td>
<td>6.41</td>
<td>6.78</td>
<td>8.8</td>
<td>7.12</td>
<td>6.89</td>
<td>7.21</td>
<td>9.19</td>
<td>8.68</td>
<td>8.88</td>
<td>9.16</td>
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<tr>
<td>Thickness loss rate (%)</td>
<td>17.4</td>
<td>18.7</td>
<td>8.1</td>
<td>35.9</td>
<td>25</td>
<td>12</td>
<td>28.8</td>
<td>31.1</td>
<td>19.9</td>
<td>8.1</td>
<td>13.2</td>
<td>11.2</td>
<td>8.4</td>
</tr>
</tbody>
</table>

**Fig. 10** Corrosion depth distribution on the outer surface of connection P72d

**Fig. 11** Corrosion depth distribution on the inner surface of connection P72d

**Fig. 12** Corrosion depth distribution of the outer surface of lower chord member of connection P72d

**Photo 5** Corrosion condition of the inner surface of connection P72d

**Photo 6** The floor beam on upstream side of P72d connection
is visible in Photo 6, non-uniform corrosion occurred over the whole left side, when viewed from left to right of Photo 6, of the gusset plate, while on the right no corrosion occurred. According to the measurements, the corrosion on the left part of the floor beam was more severe than that of the right one. Some of the severe regions of corrosion on the outer surface of P72d are enumerated in Table 8. The average corrosion depth of the two most severe corrosion areas on the left side, 1 and 2, as shown in Figure 11, are 1.74mm and 1.87mm, respectively, while the maximum corrosion depth on this left side is 7.97mm. Further, the average thickness loss ratio of this left side of the upstream gusset plate reaches 18.7%. The corrosion depth distribution of the outer surface of the lower chord member of connection P72d is shown in Figure 12 while Table 8 enumerates several severely corroded regions.

Photo 5 shows the corrosion situation on the inner surfaces of the gusset plates of connection P72d. The plaster method was again used. A total of eight plaster specimens were taken. As shown in Figure 11, there was localized corrosion of the inner surfaces of P72d, concentrated mostly on certain regions at the edges of the gusset plates, on the flanges of the diagonal members and on the transition areas between gusset plate and diagonal member flange. The characteristics of these corroded regions are enumerated in Table 8. The average corrosion depth of these corroded regions ranged from 0.81mm to 3.59mm and the maximum corrosion depth on the gusset plates was approximately 8mm. The maximum thickness loss ratio was 35.9%, with a minimum of 8.1%.

4.4 Connection P72u

The location of connection P72u is shown in Figure 1. There were no obvious signs of corrosion on the outer surface of P72, so the measurement grid was set to 3mm and the based-surface was at zero. Measurements were divided into several sections (seven on the upstream side and six on the downstream side). Results for the upstream and downstream sides

![Fig. 13 Corrosion depth distribution on the outer surface of the gusset plates of connection P72u](image1)

![Photo 7 The inner surfaces of connection P72u](image2)

<table>
<thead>
<tr>
<th>Table 9 Severely corroded regions on the outer surfaces of gusset plate and lower chord member of connection P72u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial thickness, $t_0$</td>
</tr>
<tr>
<td>Outer average corrosion depth, $t_{ave}$</td>
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<tr>
<td>Maximum corrosion depth, $t_{max}$</td>
</tr>
<tr>
<td>Average remaining thickness, $t_{ave}$</td>
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<tr>
<td>Thickness loss rate (%)</td>
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</tbody>
</table>

Due to the bolt connection, the inner surface could not measure so the corrosion depth is considered equal to zero.
are shown in Figure 13. Most corrosion was on the flanges of the reinforced diagonal members. The average corrosion depths on the flanges are 0.5mm and 1.8mm on the upstream and downstream sides, respectively. Regarding the non-reinforced diagonal members, the average corrosion depths on the flanges are 0.21mm on the upstream side and 0.43mm on the downstream side. The maximum corrosion depth on the outer surface of P72u reached 7.09mm.

Figure 14 shows the corrosion depth distribution on the outer surface of the lower chord member of connection P72u. The average corrosion depth and maximum corrosion depth on the upstream side are 1.8mm and 7.09mm, respectively, while those on the downstream side are 0.41mm and 3.91mm, respectively. Several regions of corrosion were also analysed and their characteristics are enumerated in Table 9. In these regions, the average corrosion depth ranged from 0.43mm to 1.8mm, the maximum corrosion depth was 7.09mm and the thickness loss ratio was 20% with a minimum of 4.7%.

In the case of this connection, past loading capacity requirements had been met by strengthening the gusset plates using high strength bolt joints. Since the ends of these connecting bolts are very long, as can be seen in Photo 7, plaster specimens could not be taken. As a result, the inner surfaces of P72u could not be measured.

5 DISCUSSION
5.1 The upper connections
In general, the upper connections (P25d and P73d) had suffered more severe corrosion than the lower connections. In the case of P25d, corrosion occurred on the gusset surfaces on both upstream and downstream sides, on the diagonal members and on most of the riveted joints. The inner surfaces of the gusset plates had severe corrosion along the edges toward the top of the diagonal members on both the upstream and downstream sides, while outer surface corrosion was mostly around the rivet heads and on the edges of the flanges of the diagonal members. In the case of P73d, corrosion occurred locally on the edges of the gusset plates and the flanges of diagonal members on the inner surfaces on both upstream and downstream sides while, on the outer surfaces, most corrosion was on the tensile diagonal members on the upstream side.

With regard to the remaining thickness of the gusset plates of these upper connections, in the case of P25d, the average remaining thickness was 9.0mm on the upstream side and 9.4mm on the downstream side, equivalent to thickness loss ratios of 25% and 21.6% for the upstream and downstream sides, respectively. With P73d, the average remaining thickness of the gusset plates were 10mm and 10.4mm, which are equivalent to 16.6% and 13.3% thickness loss ratios on the upstream and downstream sides. Because the corrosion depth distribution is not consistent over the whole of each gusset plate and on the diagonal members, the gusset plates were divided into several parts (① ~ ⑩), as shown in Figure 15, to understand more about the average remaining thickness distribution on the gusset plates and on the flanges of the diagonal members. The remaining thickness of these parts of the upper connections is shown in Table 10. In the case of P25d, the remaining thickness varied from 7.6mm to 11.73mm on the gusset plates while on the flanges of the diagonal member it ranged from 7.1mm to 12mm. On P73d, the average remaining thickness of these parts of the diagonal member ranged from 9.3mm to 11.58mm, corresponding to thickness loss ratios from 3.5% to 22.5%. On the flanges of the diagonal members, the inner surfaces were heavily corroded. The remaining flange thickness of the diagonal members is also given in Table 10; it ranged from 6.4mm to 8.6mm, equivalent to a thickness loss ratio ranging from 4.4% to 28.9%.

At the rivet region of the upper connections, corrosion was concentrated around the rivet heads in the shape of a doughnut at a radius of about 20-30mm from the centre of the rivet head.

5.2 The lower connections
In the case of the lower connections (P72d and P72u), corrosion was localized. In the case of P72d, localized corrosion occurred on the surface of the
Table 10: Remaining thickness of upper connections

<table>
<thead>
<tr>
<th></th>
<th>Initial thickness, ( t_0 )</th>
<th>Outer surface corrosion depth, ( d_{ose} )</th>
<th>Inner surface corrosion depth, ( d_{ise} )</th>
<th>Remaining thickness, ( t_{ave} )</th>
<th>Thickness loss rate (%)</th>
<th>Initial thickness, ( t_0 )</th>
<th>Outer surface corrosion depth, ( d_{ose} )</th>
<th>Inner surface corrosion depth, ( d_{ise} )</th>
<th>Remaining thickness, ( t_{ave} )</th>
<th>Thickness loss rate (%)</th>
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<tbody>
<tr>
<td>P25d</td>
<td>12</td>
<td>0.19</td>
<td>2.1</td>
<td>9.71</td>
<td>8.76</td>
<td>12</td>
<td>0.27</td>
<td>3.9</td>
<td>10.7</td>
<td>1.7</td>
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<tr>
<td>P72d</td>
<td>12</td>
<td>0.19</td>
<td>2.1</td>
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<td>12</td>
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<td>3.9</td>
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<tr>
<td>P73d</td>
<td>12</td>
<td>0.19</td>
<td>2.1</td>
<td>9.71</td>
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<td>12</td>
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</table>

Table 11: Remaining thickness of lower connections

|     | Initial thickness, \( t_0 \) | Outer surface corrosion depth, \( d_{ose} \) | Inner surface corrosion depth, \( d_{ise} \) | Remaining thickness, \( t_{ave} \) | Thickness loss rate (%) | Initial thickness, \( t_0 \) | Outer surface corrosion depth, \( d_{ose} \) | Inner surface corrosion depth, \( d_{ise} \) | Remaining thickness, \( t_{ave} \) | Thickness loss rate (%) | Initial thickness, \( t_0 \) | Outer surface corrosion depth, \( d_{ose} \) | Inner surface corrosion depth, \( d_{ise} \) | Remaining thickness, \( t_{ave} \) | Thickness loss rate (%) |
|-----|-------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------------|-------------------------------|---------------------------------|---------------------------------|------------------------|
| P25d | 12                            | 0.19                            | 2.1                             | 9.71                            | 8.76                   | 12                            | 0.27                            | 3.9                             | 10.7                            | 1.7                    |
|     |                               |                                 |                                 |                                 |                        |                                |                                 |                                 |                                 |                        |
| P72d | 12                            | 0.19                            | 2.1                             | 9.71                            | 8.76                   | 12                            | 0.27                            | 3.9                             | 10.7                            | 1.7                    |
|     |                               |                                 |                                 |                                 |                        |                                |                                 |                                 |                                 |                        |
| P73d | 12                            | 0.19                            | 2.1                             | 9.71                            | 8.76                   | 12                            | 0.27                            | 3.9                             | 10.7                            | 1.7                    |
|     |                               |                                 |                                 |                                 |                        |                                |                                 |                                 |                                 |                        |

Fig. 15 Corrosion depth distribution on outer surface of gusset plates of connection P72u
gussets on the upstream and downstream sides and on the flanges of the diagonal members on both inner and outer surfaces. On the outer surfaces, corrosion was concentrated mostly on the tensile diagonal member side of the gusset plate and on the flange of the compressive diagonal member on the upstream side.

On the inner surfaces of the gussets, there was severe localized corrosion at the edges of the gusset plates and in the transition region between the gusset plate and the diagonal member flanges on the both upstream and downstream sides. In the case of P72u, the corrosion state was unobservable over the whole of the gusset plate outer surfaces, on both upstream and downstream sides, because of previous strengthening of the original gusset plates. The strengthening consisted of additional gussets fixed in place with connecting bolts. The only visible corrosion was concentrated on the flanges of the reinforced diagonal members on both the upstream and downstream sides and on the flanges of the non-reinforced diagonal members on the upstream side. The bolts connecting the original gusset plates and the ones attached for strengthening prevented plaster specimens being taken, so the inner surfaces were not measured. The corrosion state and corrosion depth of the strengthening plates have been neglected.

As can be seen clearly in Figure 15, the gusset plates of the lower connections were also divided into several parts for measurement (○1 ~ ○10 for P72d and ○1 ~ ○3 for P72u). The remaining thickness is shown in Table 11. Connection P72d exhibited less thickness loss to both gusset plates and diagonal member flanges than the upper connections, with the loss varying from 1.2% to 12.3%. In the case of P72u, there was severe corrosion on the flanges of the reinforced diagonal member, especially on the downstream side, with the average corrosion depth of 1.8mm representing a 20% thickness loss, while on the upstream side the thickness loss was 5.6% or equivalent to 0.5mm of average corrosion depth. On the flanges of the non-reinforced diagonal members, the thickness loss was 4.8% for the downstream side and 2.3% for the upstream side.

5.3 Comparison between the upper and the lower gusset plate connections

This steel truss bridge was constructed mostly with box and I-shaped elements so, in a severe environment with salt spray and airborne salt, it was readily affected by water and sediment pooling, especially on the inner surfaces of gusset plate connections. Further, in this design of steel truss bridge, the connections to the lower chord members are below the deck surface, making them susceptible to sedimentation and water, particularly on their outer surfaces.

The gusset plates on the upper connections are more severely affected by corrosion than those on the lower connections, as described in sections 5.1 and 5.2, respectively. The location of the bridge near the embouchure, where it is exposed to salinity, sediment accumulation and salty spray, suggests that strong winds intensified the salty airborne environment that plays an important role in corrosion. The accumulation of salt from spray on the inner surfaces of the gusset plates of the upper connections, where it could not be washed away by rain, led to generally high levels of corrosion, such as at connection P25d.

Further, outer surfaces on the upstream side of connection P72d were prone to salt accumulation, since the floor beam was perpendicular to the wind direction, leading to severe corrosion on the left side of the gusset plates.

In order to clarify the relationships between corrosion depths as measured in this work and the actual deposition of airborne salt, it will be necessary in future work to carry out an analysis of airborne salt, wind speed and wind direction.

6 CONCLUSION

Detailed corrosion measurements have been made of gusset plate connections taken from an aging steel truss bridge. The following is a summary of the conclusions drawn from this work:

1) P25d (upper connection; downstream side of bridge): Corrosion occurred on the upstream and downstream outer surfaces of the gussets, on the diagonal members and at most riveted joints. There was severe corrosion on the inner surfaces of the gussets, as well as on the edges of the upper ends of the diagonal members on both the upstream and downstream sides.

2) P73d (upper connection; downstream side): There was localized corrosion on the edges of the gusset plates and on the flanges of diagonal members on the inner surface on the both the upstream and downstream sides. On the outer surfaces, most corrosion was on the upstream side of the tensile diagonal member.

3) P72d (lower connection; downstream side): There was localized corrosion on the surface of the...
gussets on the upstream and downstream sides, as well as on the flanges of both inner and outer surfaces of the diagonal members. On the outer surfaces, corrosion was concentrated on the tensile diagonal member side of the gusset plate and on the flange of the compressive diagonal member on the upstream side. There was severe localized corrosion on the inner surface of the gusset plates near the edges and on the transition region between the gusset plate and the flange of the diagonal members on both upstream and downstream sides.

4) P72u (lower connection; upstream side): The outer surfaces of the gusset plates are almost free of corrosion. The only visible corrosion is on the flanges of the reinforced diagonal members on both the upstream and downstream sides. To meet loading capacity requirements, this connection had been strengthened in the past by bolting in place supplementary gussets. The length of the bolts used meant that the plaster specimens taken from other connections to investigate the inner surfaces could not be created; as a result, the inner surfaces were not measured.

5) The upper connections, especially their inner surfaces, are more severely corroded than the lower connections. This is attributed to the accumulation of salt that was not washed away by rain. Connection P25d is the prime example of this. The floor beam of the bridge is perpendicular to the prevailing wind direction, leading to accumulations of salt on the left side of the gusset plates on the upstream side. Connection P72d is an example of this phenomenon.

Due to the lack of information, the correlation between environmental conditions and corrosion could not analyze. The correlation and statistical analysis as well will be carried out in our further study in near future.

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