FIELD LOADING TEST AND LOADING CAPACITY EVALUATION OF A SERIOUSLY CORRODED STEEL - TRUSS BRIDGE

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Abstract

With the stock aging of the majority of highway bridges in Japan constructed during the 1950s–1970s, some serious corrosion deterioration cases of fracture critical members in steel truss bridges have been reported recently. In particular the damage of main component of a truss and an arch bridge by corrosion may have a serious influence on the safety of the whole bridge system. Therefore, the development of the appropriate investigation and diagnosis technique for corroded bridges is required.

In this study, field loading test was conducted on a seriously corroded steel-truss bridge in order to collect basic data to develop such maintenance technique. The measured data from the loading test were compared with the numerical results obtained from FE analysis. Also, the influence of uncertain factors in the modeling of the bridge on the estimated loading capacity and loading capacity evaluation technique were discussed.

Introduction

The majority of highway bridges in Japan were constructed during the 1950s–1970s which coincides with Japan's high economic growth period, and the number of bridges over 50 years is increasing drastically. With increase of aged bridges, since these bridges are exposed to heavy traffic and severe natural environment, it is highly probable that the deterioration will increase rapidly. Improvement of technologies related to inspection, diagnosis, repair, and rehabilitation is required. Concerning steel bridges, some serious deterioration cases of FCMs on steel truss bridges have been reported recently. Tension diagonal members of steel truss embedded inside the deck concrete fractured in the Kiso River Bridge and Honjo Bridge on the National Route in 2007 because of section loss due to corrosion.

Fracture of diagonal members or gusset plate connections of truss bridge is likely to lead to fatal damage of whole bridge system. However, there was no effective technique to evaluate loading capacity and remaining strength of such the whole bridge system and deteriorated components with the section loss by corrosion. Therefore authors conduct research project in order to identify the structural behavior and to evaluate remaining strength of whole bridge system and steel members subjected to severe corrosion. Figure 1 shows the outline of research project.

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In this study, field loading test of a seriously corroded steel-truss bridge and FE analysis were carried out, and measured data were compared with numerical results to verify the modeling of the bridge. Also, the influence of uncertain factors in the modeling of the bridge on the estimated loading capacity and loading capacity evaluation technique were discussed.

Bridge Description

Figure 2 shows a bridge utilized in this project, which is called Choshi Bridge. It was built in 1962 across Tone River. It was 5-span steel through truss bridge with total length of 407.4m. Figure 3 shows general view of the bridge. The average daily traffic is about 20,000 with 10% of heavy vehicles. It was located in river mouth and had suffered from salt damage by airborne salt and heavily corroded. Although repainting, strengthening and partial replacement of severely corroded members were conducted several times through its service life, it was finally replaced in 2009 at 47 years old, because the corrosion was unlikely to stop and it is considered to be impossible to assess remaining strength and remaining service life.

Figure 4 shows corrosion damage focusing on main members and gusset plate connection that influence safety of the whole bridge. Steel members of this bridge have been repainted by the thick fluorine coating material, so section loss was not able to be observed exactly by visual inspection. Corrosion of gusset plate connections are shown in Figure 4(a) (b). Several connections and diagonals were strengthened with steel plate bonding (see Figure 4(c)). Intense corrosion of diagonal joint is shown in Figure 4(d). Pitting of diagonal was observed in Figure 4(e). Concerning floor beams, Figure 4 (f) shows typical area of deterioration of floor beam with debris accumulation.

Field Loading Test and Examination of the modeling technique of the FE analysis

Field Loading Test method

Field loading test was carried out by dump truck in P16 - P17 span (cantilever span) mainly. Figure 5 shows measured points in the main truss. Figure 6 shows location of strain gauge in the main truss section.

Strain of maim truss and floor system and displacement were measured in order to catch the behavior of whole bridge, and strain of gusset plate and diagonal member were measured in order to catch the behavior of around gusset plate on field loading test. Table 1 shows contents of measurement. At first measurement under service for traffic carried out in order to investigate the actual state of the live load. After that, field loading test by dump truck which adjusted to gross weight 20 tonf in order to investigate the detailed behavior of main truss and floor system. In fixed point loading, two dump trucks were located at the position of gusset plate by two lines of series or parallel placement (Figure 7(a), (b)). In dynamic loading, a dump truck was located while moving every 1meter (Figure 7(c)).

FE analysis method

Elastic three-dimensional FE analysis that simulated field loading test was conducted, and then comparison between analysis and measurement results was carried out. Table 2 shows outline of the analysis model. Figure 8 shows the analysis model. The analysis was elastic infinitesimal deformation analysis. In modeling, beam elements were used for main truss, floor system and lateral bracing (reflected reinforcement) and 4 nodes shell elements were used for slab. Table 3 show material properties used in the analysis. The boundary condition of the main truss namely rotation condition of the in-plane and out-plane direction assumed rigid. The joining condition of slab and stringer assumed same as non- composite girder and spring element were used for joint of slab and stringer. The analysis software was NX Nastran[1)].

Experimental and Analysis Results

(1) Behavior of floor system

Figure 9 shows stress hysteresis of upper flange and lower flange of the stringer which was measured on dynamic loading test. Figure 10 shows stress distribution of stringer around center of span which was measured on the fixed point loading test. Generally existing bridges show composite behavior because of effect of slab anchor, but in this bridge showed middle behavior of composite and non-composite. According to the appearance investigation after the bridge removed corrosion deterioration was seen in the upper flange entire surface in most stringers (Figure 11), and it is supposed that adhesion with the concrete slab was lost.

Figure 12 shows 24 hours stress range histogram of lower flange at center span of stringer. Measured stress by 20tonf dump truck was about 12 N/mm^2. On the other hand in this measurement maximum stress was about 43 N/mm^2 including impact. Gross weight traffic vehicle was limited in 20tonf or less at this bridge, but it is supposed that traffic vehicles more than 20tonf had gone routinely although the ratio was around 3%. In addition, Figure 13 shows traffic vehicle in the down line stringer when stress maximum was measured.

(2) Behavior of main truss member

Figure 14 shows comparison of measurement and analysis results for axial stress of main truss on dynamic loading test. In both members analysis results agree with measurement results relatively well. It was found that the axial section force of main truss in the live load loading can be estimated by the above-mentioned analysis model appropriately. Also, the validity of the analysis model was confirmed.

Figure 15 shows analysis result of main truss stress by the model supposed joining condition of slab and stringer as composition and non-composition. There are few differences of both, and the influence that the difference in supposition of composition or the non-composition gives for whole bridge behavior is small.

Influence on whole bridge of corrosion deterioration and the boundary condition

(1)FE analysis condition

The examination of the influence that various uncertain factors in the analysis model gave in main truss responses was conducted by sensitivity analysis using the above-mentioned analysis model.

Table 4 show boundary conditions in the analysis model and Table 5 show analysis cases. The influence of adhesion deterioration of a slab and the stringer and section loss by corrosion gave in main truss responses were investigated. It is generally designed as non-composite between a slab and stringers, but the actual behavior may show near to composite. Here, three cases of analysis of completely composite and composite with partial interaction and non-composite were carried out. In the case of composite with partial interaction, spring value between slab and stringers based on laboratory finding results [2)] in the past. Figure 16 show the modeling of the slab anchor.

Generally, the boundary conditions of the main truss in the design are assumed to be pin connection, but out-plane bending stress that is relatively large on field loading test for this bridge. And it is thought that the behavior of the gusset plate connection shows near to relatively rigid in the case of a truss bridge joined through a gusset plate. Here, three cases of analysis of pin condition same as design and rigid condition only for chord members and rigid condition chord and diagonal members were conducted (Figure 17).

About the section loss by corrosion, Figure 18 shows the cases of analysis that were carried out in a supposition that corrosion condition considered as equality loss of the main truss.

(2)FE analysis results

Figure 19 show analysis results. The stress shows the total value of an axial stress and the bending stress.

1) Influence of the modeling of the boundary condition

ⅰ)Boundary condition of main truss

Some differences were seen in diagonal members and lower chord members, but the difference is small in the analysis condition that assumed the boundary condition of the main truss as pin. Little moment of bending occurs by having assumed boundary condition of main truss with rigid, but the axial force change is not large for axis stress.

ⅱ) Adhesion deterioration of slab and stringer

The influence that difference of joint condition between slab and stringer of the stringers gives in responses of the main truss is small. In other words, the influence that the adhesion deterioration of slab and stringers gives to a main truss is small.

2) Influence of the section loss by corrosion

Figure 20 shows rate of axial force and stress change of the main truss in each case which assumed corrosion for design condition. The influence occurs only to the members which a section loss caused by corrosion greatly. This is reason that the difference of axial force is small in any corrosion pattern. Of course, when we calculate the response of main truss, consideration of corrosion influence is needed because there is increase of stress depending on the section loss.

<u>Loading capacity evaluation</u>

Examination about the stress state of main truss when other main truss member was broken was carried out in the case of this bridge.

The evaluation technique by putting loading capacity evaluation for the current design code standard and loading capacity evaluation based on the influence on stress state of main truss when other main truss was broken together was considered.

At first elastic analysis by the above-mentioned model that simulated the fracture member was conducted. Because elastic analysis is applied, the behavior such as the section force redistribution by the stiffness change after the plasticity or the chain destruction of other members is not evaluated, but it was thought that it could express the relative state. And then, the strength check of the members were done by Japanese design code specification[3)], namely checked by strength equation (1)～ (5) as the members which caught the axial force and moment of bending.

(a) Tension axial force

$$\sigma_t + \sigma_{bty} + \sigma_{btz} \le \sigma_{ta} \qquad \text{(Check for tension stress)} \qquad (1)$$

$$-\frac{\sigma_t}{\sigma_{ta}} + \frac{\sigma_{bcy}}{\sigma_{bagy}} + \frac{\sigma_{bcz}}{\sigma_{bao}} \le 1 \qquad \text{(Check for overall buckling)} \qquad (2)$$

$$-\sigma_t + \sigma_{bcy} + \sigma_{bcz} \le \sigma_{cal} \qquad \text{(Check for local buckling)} \qquad (3)$$

(b) Compression axial force

$$\frac{\sigma_c}{\sigma_{caz}} + \frac{\sigma_{bcy}}{\sigma_{bagy}\left(1-\dfrac{\sigma_c}{\sigma_{eay}}\right)} + \frac{\sigma_{bcz}}{\sigma_{bao}\left(1-\dfrac{\sigma_c}{\sigma_{eaz}}\right)} \le 1 \qquad \text{(Check for member's buckling)} \qquad (4)$$

$$\sigma_c + \frac{\sigma_{bcy}}{1-\dfrac{\sigma_c}{\sigma_{eay}}} + \frac{\sigma_{bcz}}{1-\dfrac{\sigma_c}{\sigma_{eaz}}} \le 1 \qquad \text{(Check for local buckling)} \qquad (5)$$

Where,

σ_t, σ_c : Tensile stress and compressive stress due to the axial force acting on the section to be checked, respectively (N/mm^2)

σ_{bty}, σ_{btz} : Bending tensile stresses due to the bending moment acting about the strong and weak axes, respectively(N/mm^2)

σ_{bcy}, σ_{bcz} : Bending compressive stresses due to the bending moment acting about the strong and weak axes, respectively(N/mm^2)

σ_{ta} : Allowable axial tensile stress shown in Table 3.2.1 (N/mm^2)

σ_{caz} : Allowable axial compressive stress (N/mm2) about the weak axis calculated by Equation 3.2.1 (N/mm^2)

σ_{bagy} : Allowable bending compressive stress (N/mm2) about the strong axis that does not consider local buckling, shown in Table 3.2.3(N/mm^2)

σ_{bao} : Upper limit of allowable bending compressive stress that does not consider local buckling, shown in Table 3.2.3 (N/mm^2)

σ_{cal} : Allowable stresses of edge-supported, projecting and stiffened plates and steel pipe with respect to local buckling, prescribed in Sections 4.2.2 to 4.2.4, and 14.3 respectively

σ_{eay}, σ_{eaz} : Allowable Euler buckling stresses about the strong and weak axes, respectively (N/mm^2)

$$\sigma_{eay} = 1{,}200{,}000/(l/r_y)^2 \qquad (6)$$

$$\sigma_{eaz} = 1{,}200{,}000 / (l / r_y)^2 \qquad (7)$$

l : Effective buckling length (mm)

r_y, r_z : Radii of gyration of area about the strong and weak axes, respectively (mm)

Figure 21 shows assessment result. The horizontal axis shows the ratio of allowable stress and design load stress. The vertical axis shows the ratio of the dead load stress and limit of allowable stress when main truss was broken.

For example, in the case of this bridge, it was confirmed that section force of the diagonal member near center of span was small and especially lower chord members even if other member was broken do not reach unstable state. On the other hand, when diagonal member of upper chord members or near bearing is broken, whole structure is not stable because of much increase of other members section force.

Conclusions

Field loading test was conducted on a seriously corroded steel-truss bridge. The acquired data from the loading test were compared with the numerical results obtained from FE analysis. Also, the influences of uncertain factors in the modeling of the bridge on the estimated loading capacity and evaluation technique were discussed.

1) Measured axial stress of the main truss almost agreed with the analysis results using FE analysis model applied in this study.
2) The influence that composite action between slab and stringer and boundary condition of gusset plate connection gives in response value of main truss is small in the situation before the main truss broken. Also, the influence that section loss by corrosion gives in response value of main truss is small.
3) In the case of this bridge, loading capacity evaluation in the state that a main truss fracture occurred was conducted.

References

[1] JSOL Corporation, LS-DYNA USER’S MANUAL, 2007.6.

[2] Tomoko Masuda, Hirokazu Hiragi, Hiroshi Watanabe, Yoshihide Takada, Shinichi Miyachi, Yoshitaka Ushijima. “En Experimental Study on Static Shear Strength Characteristics of Slab Anchors under various Bond Condition”, Journal of Structural Engineering Vol.47A, pp.1373-1380, 2001.3.

[3] Japan Road Association (JRA), “Specification for Highway Bridges, Part II Steel Bridge”, 2002.(in Japanese)

Approach for the whole bridge system

◆Study on modeling technique for loading-capacity evaluations of the whole bridge system

・Field loading test
・Comparison results with analytical results
・Parametric FE analysis
・Development of analytical model

Approach for the members

◆Study on evaluation technique for remaining strength of the corroded steel member

・Corrosion investigation
・Static loading test of the corrosion member
・Analysis of relations of the corrosion condition and the remaining strength

Survey of damaged bridges

◆Guideline for maintenance

・Inspection method of the corroded member
・Evaluation technique for loading capacity
・Notes for inspection and evaluation

Figure 1 Outline of research project

Figure 2 Measured bridge (Choshi bridge)

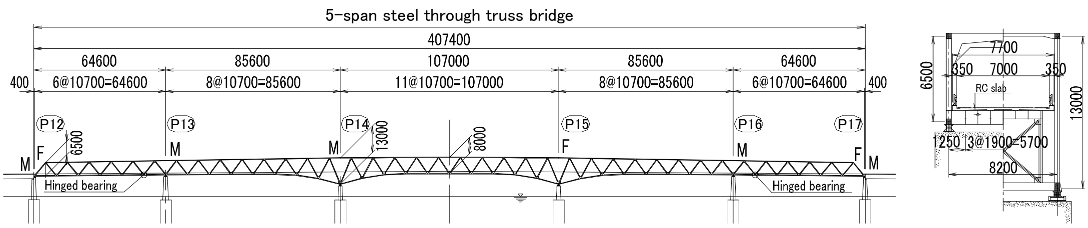


Figure 3 General view of Choshi bridge

(a) Lower chord connection

(b) Upper chord connection

(c) Plate bonding of lower chord connection

(d) Diagonal joint

(e) Pitting of diagonal

(f) Floor system

Figure 4 Corrosion damage of main members

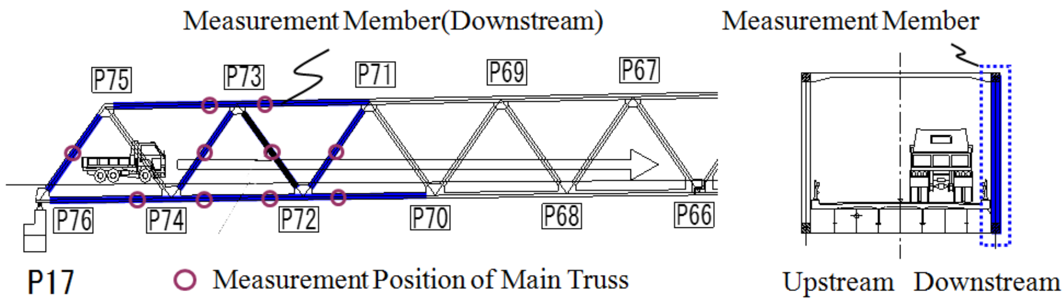


Figure 5 Measurement position in main truss

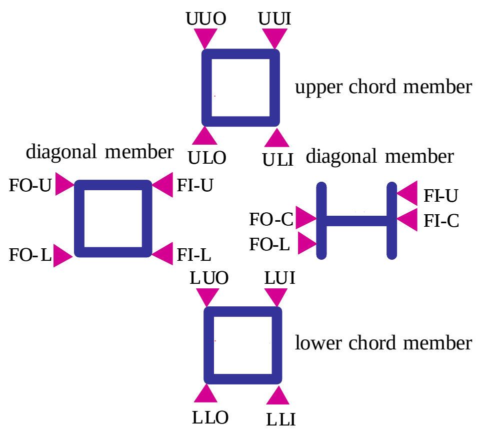


Figure 6 Location of strain gauge

Table 1 Contents of measurement

measurement item	purpose	contents
Measurement under service for traffic(1case)	Investigatione of the actual live load states	・Stress range measurement (24 hours) ・Video monitoring three hours)
Measurement under loading test by dump trucks(10cases)	Investigation of the whole bridge system	・Fixed point loading test ・Dynamic loading test

(a) Fixed point loading (Two series dump truck)　(b) Fixed point loading (Two parallel dump truck)　(c) Dynamic loading (One dump truck)

Figure 7 Situations of loading field tests

Table 2 Outline of analysis model

Item		Contents
Analytical method		Elastic three-dimensional FE analysis
Element model	Main truss, Lateral, Floor system	Beam Element
Element model	Slab	Shell Element
Element model	Slab anchor	Spring Element
Element model	Gusset plate conection	Rotation condition of the in-plane direction : Rigid Rotation condition of out-plane direction : Rigid

Table 3 Mechanical properties

Material	Elastic modulus E(N/mm^2)	Poisson's ratio
Steel	2.0×10^5	0.3
Concrete	2.35×10^4	0.167

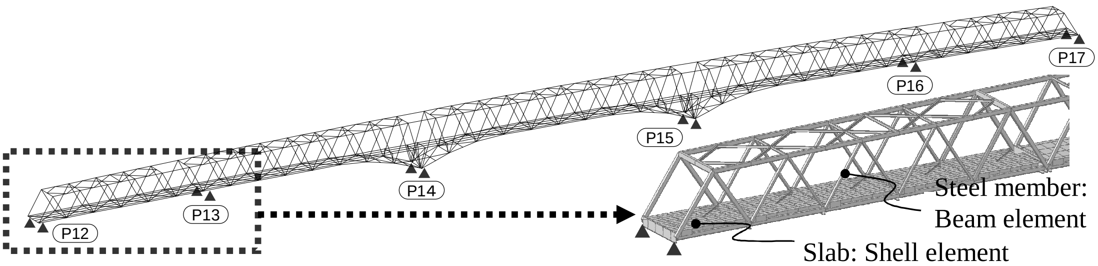


Figure 8 FE analysis model

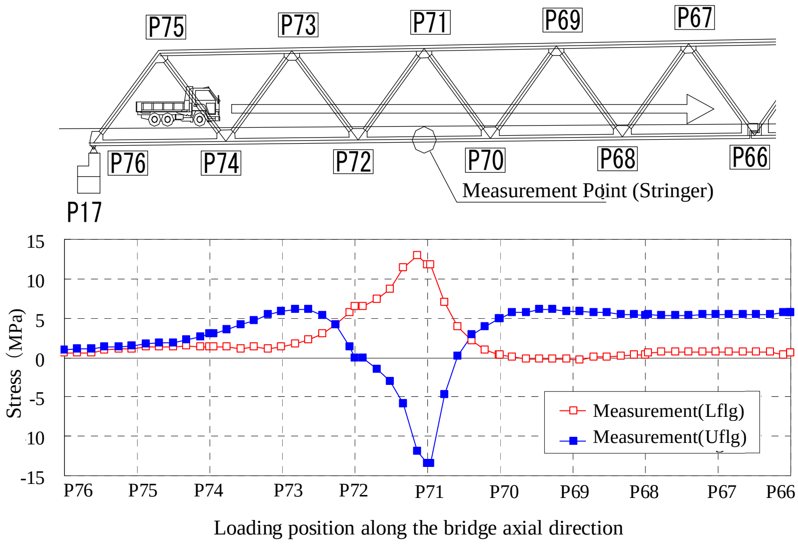
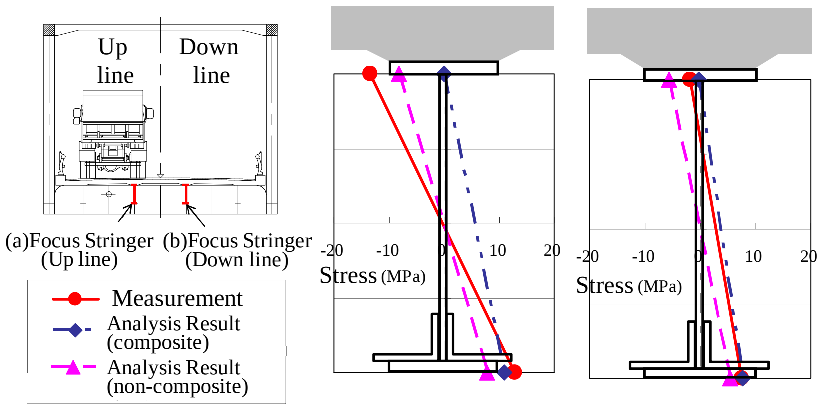


Figure 9 Stress hysteresis of stringer

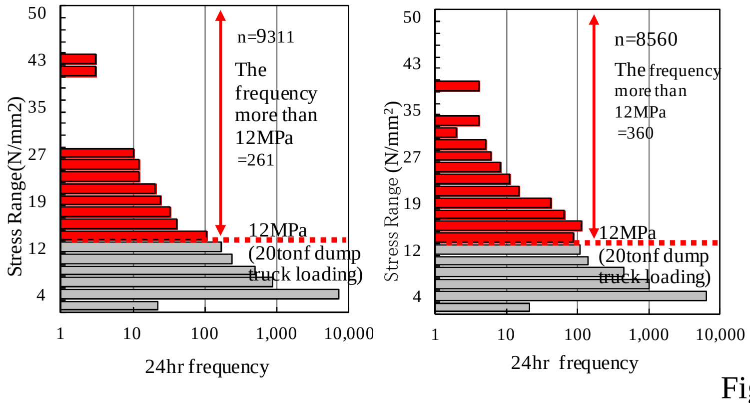


(a) Up line (b) Down line

Figure 10 Stress distribution of stringer

(a) Condition at stringer-slab connection (b) Corrosion of top flange surface

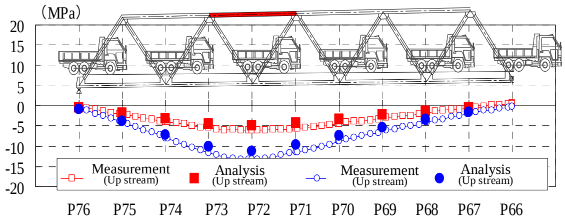
Figure 11 Corrosion condition of stringer



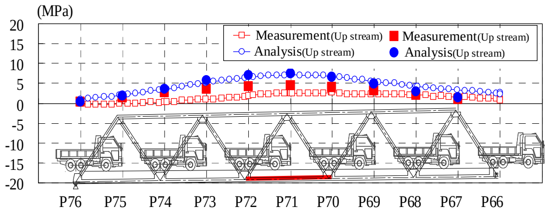
(a) Down line (b) Up line

Figure 12 Stress range histogram (RF low counting method) in the 24 hours measurement

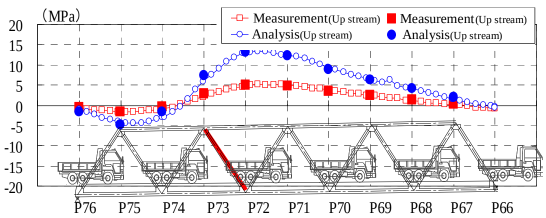
Figure 13 Traffic vehicle in the down line stringer stress maximum



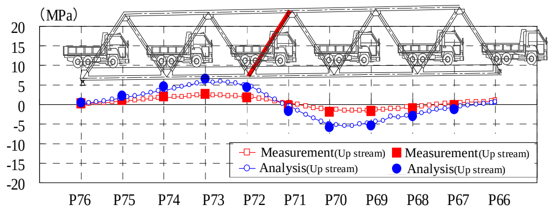
(a) Upper chord member U72d (box section)



(b) Lower chord member L71d (box section)



(c) Diagonal member D72d (H section)



(d) Diagonal member D71d (box section)

Figure 14 Axial stress measurement results of the main truss members

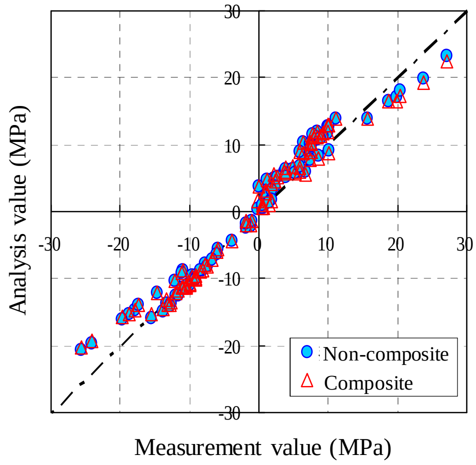


Figure 15 Stress of the main truss on fixed point loading

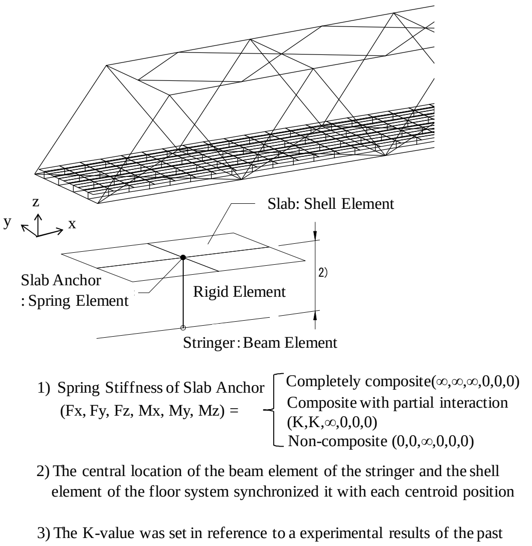


Figure 16 Modeling of slab anchor

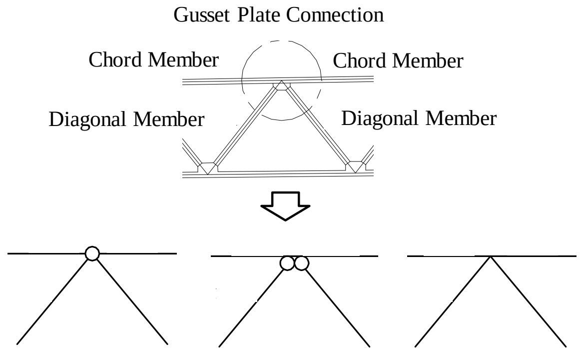


Figure 17 Modeling of main truss connection

Table4 Boundary conditions

Boundary condition	
Item	Boundary condition
Slab	Completely composite
	Composite with partial interaction
	Non-composite
Gusset Plate Connection	Rigid＋ Rigid
	Rigid ＋Pin
	Pin ＋ Pin

Table 5 Analysis cases

Analysis model	Boundary condition	
	Gusset plate connection (chord member＋ diagonal member)	Slab and stringer
Basic model	Rigid ＋Rigid	Completely composite
Modeling of gusset plate	Pin ＋Pin	Completely composite
	Rigid ＋Pin	Completely composite
Adhesion deterioration of slab and stringer	Rigid＋ Rigid	Composite with slab anchor
	Rigid ＋Rigid	Non-composite
Section loss by corrosion	Rigid ＋ Rigid	Completely composite

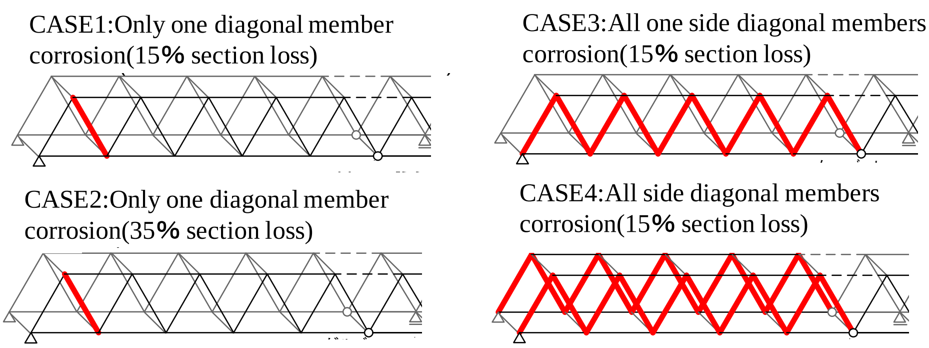
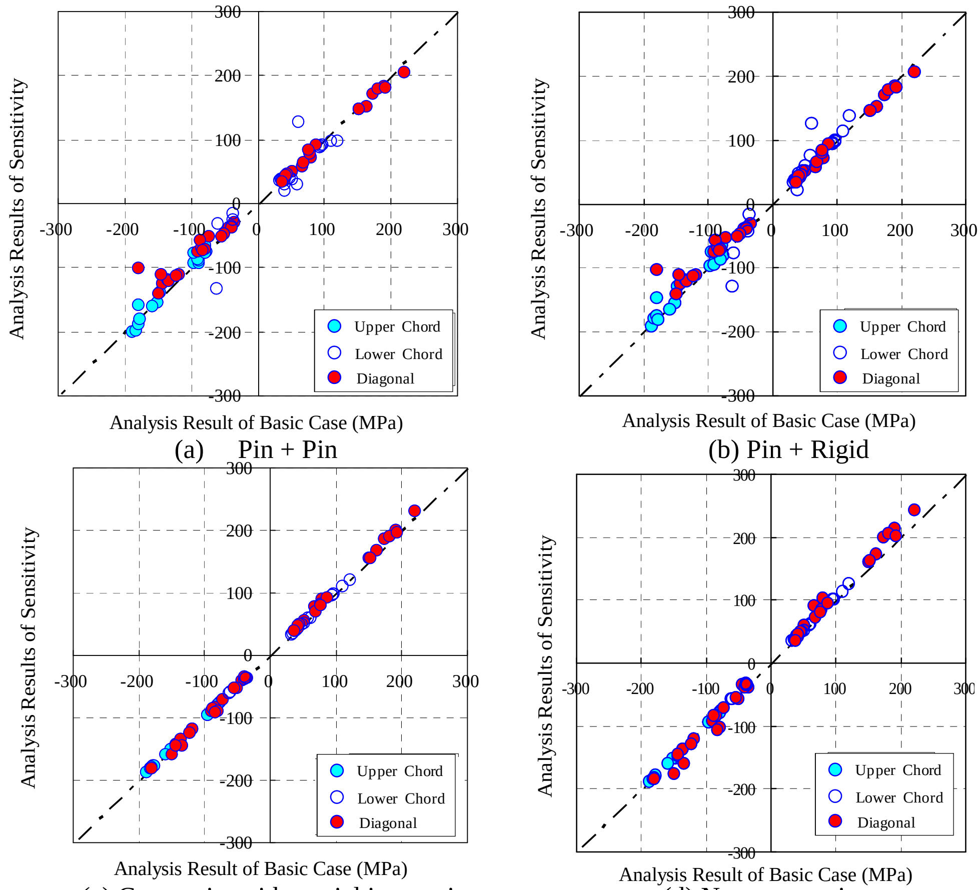


Figure 18 Analysis cases of main truss corrosion



(a) Pin + Pin (b) Pin + Rigid

(c) Composite with partial interaction (d) Non-composite

Figure 19 Results of sensitivity analysis (Axial stress + Bending stress)

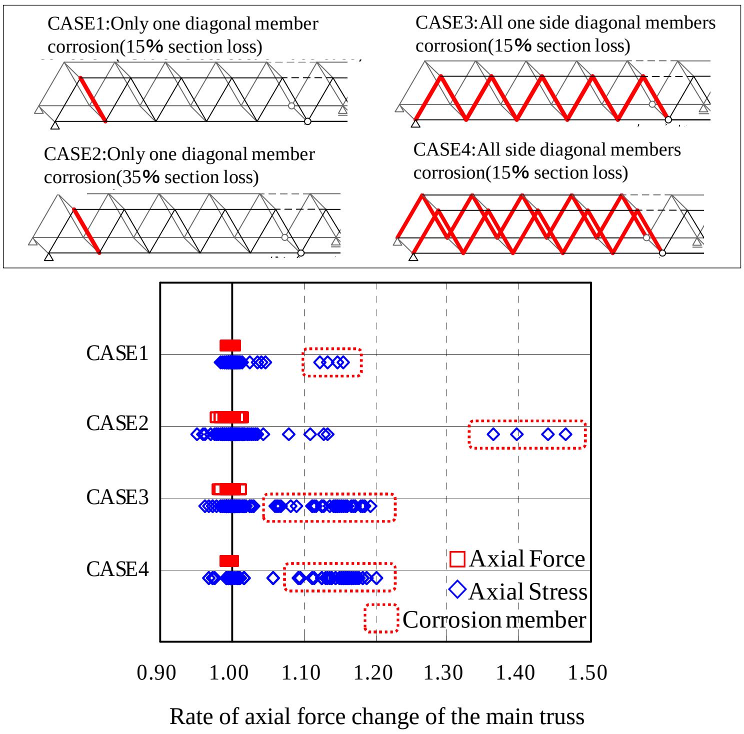
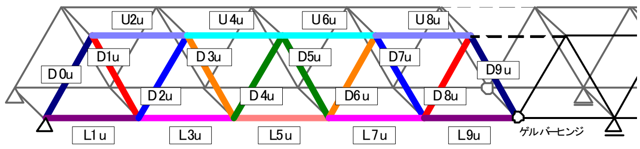
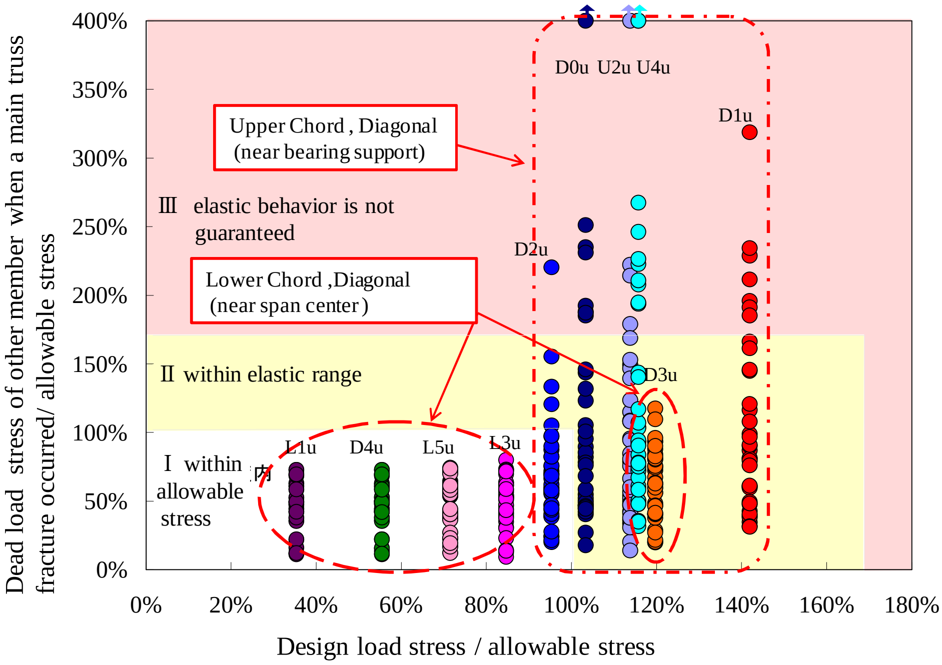


Figure 20 Influence of main truss corrosion



(a) Fracture member



(b) Stress state under the condition of main truss fracture

Figure 21 Example of loading capacity evaluation