INFLUENCE OF CORROSION OF TRANSVERSE STIFFENER AT SUPPORT ON LOAD-CARRYING CAPACITY OF STEEL GIRDER

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Abstract

The transverse stiffener at a support is often found corroded. For efficient maintenance, it could be essential to know its residual strength. The present study investigates the influence of the corrosion of the transverse stiffener at a support. To be specific, the degradation of the load-carrying capacity of a steel girder is evaluated numerically. The study reveals that the reduction in strength could grow rapidly as the plate of the corrosion part is getting thinner and that a careful consideration is needed if a heavy wheel load is expected above the corroded stiffener.

Introduction

The maintenance of bridges is now a very important issue in Japan to keep a highway network in good shape, as many bridges were constructed in 1970s/1980s and they are getting aged. As for the steel bridge, corrosion is one of the most influential phenomena on its service life: the corrosion could reduce the load-carrying capacity of the steel bridge, threatens its safety and eventually force to terminate its service. Some 15% of highway steel bridges renewed and some 50% of railway bridges renewed were said to be due to corrosion (Hung et al. 2002).

Replacement of a bridge requires substantial cost. If repair can be done with reasonable cost, it would be a better choice for efficient maintenance. To that end, it is essential to evaluate residual strength in case of a corroded bridge. Quite a few research works indeed have been carried out, but much remains to be done. The research is continued: for example, the shear capacities of locally corroded steel I-girders have been investigated and reported in 2011 (Liu et al. 2011).

The expansion joint is one of the most susceptible elements of the bridge to damage due to impact loads of vehicles. Therefore, water leakage from the expansion joint is often found, leading to the deterioration of corrosion environment near the girder end. As a result, more corrosion problems occur near girder ends than in the other parts. Photo 1 shows an example. Clearly observed is the thinning of the transverse stiffener at the support.

The transverse stiffener at a support is subjected to a concentrated load at its bottom

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Photo 1 Corroded girder

end, a reaction force from the support, and thus an important member for bridge safety. However, the strength of the corroded transverse stiffener at a support is yet to be studied much although a detailed case study using an actual corroded girder has been conducted by Huang et al. (2002).

In the present study, the residual strength of the steel corroded girder is investigated numerically. Various levels of corrosion in transverse stiffeners are taken into account and two loading conditions are considered. The results are compared with the design strength and discussed. Herein ABAQUS (2006) is used for all the analyses in which the effects of both material and geometrical nonlinearities are included.

Girder Model

Referring to the steel bridge model in the research work of Nagai et al. (1997), a steel I-girder shown in Figure 1 is employed as the analysis model in this study. It is 40.6-m long with the span of 40 m and the transverse stiffeners are spaced at 5 m. Young's modulus is 2.06×10^5 N/mm^2, Poisson's ratio 0.3 and the yield strength 355 N/mm^2. The uniaxial stress-strain relationship is assumed bilinear with the second slope 1% of Young's modulus.

Loading Conditions

In the design of the transverse stiffener at a support, the axial force acting in it is assumed to increase linearly toward the support. To reproduce this internal force condition closely, a distributed load rather than a concentrated load needs be applied on the upper flange. The length of the loading zone in the longitudinal direction has to be determined.

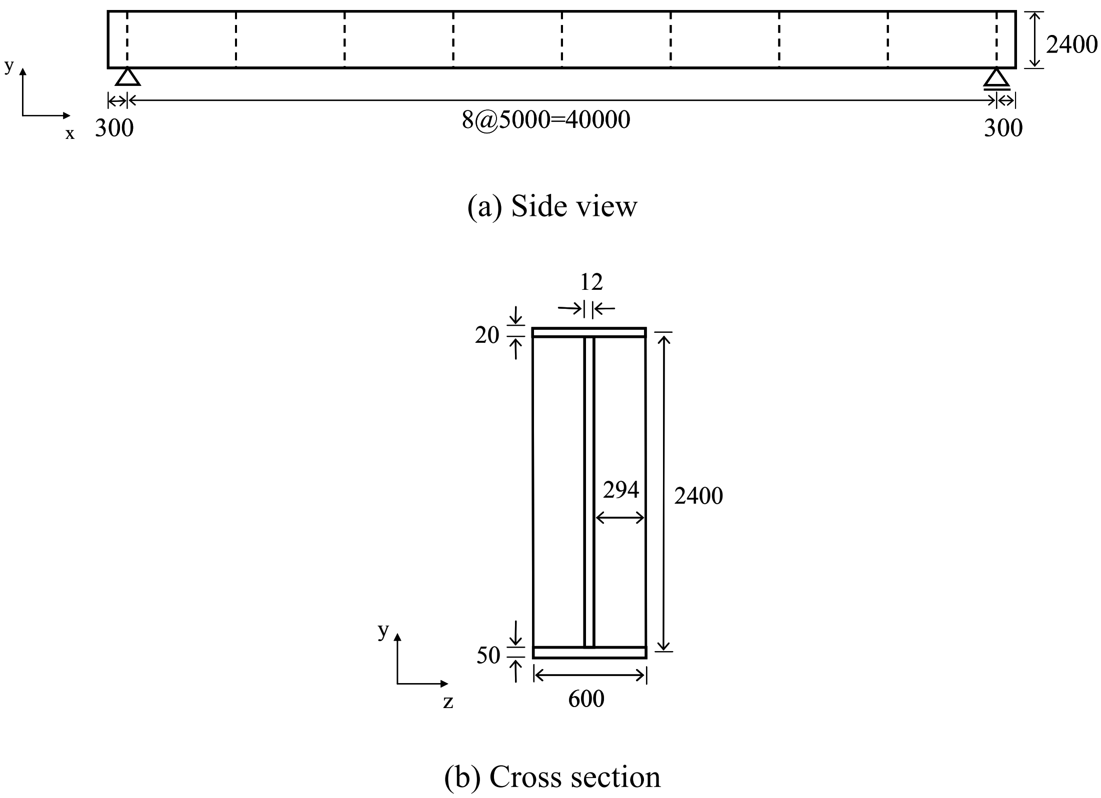
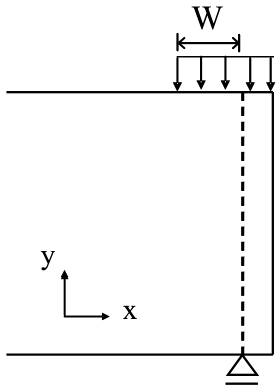


Figure 1 Girder model (Unit: mm)

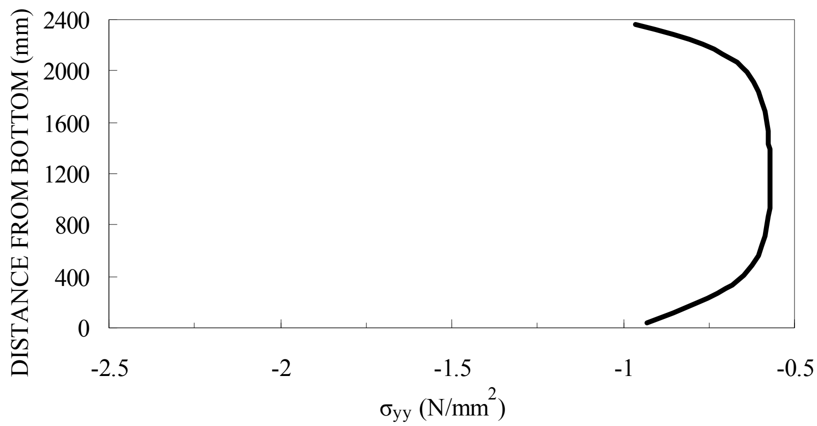
To this end, five lengths of the uniform loads are considered: 150 mm, 400 mm, 600 mm,800 mm and 1000 mm where each number indicates the distance from the location of the transverse stiffener at the support, W in Figure 2 (a). Under these loading conditions, the linear analysis is conducted by FEM. For this analysis, the girder is modeled by 26,208 four-node shell elements. The same element mesh is used for all the analyses in the present study.

Out of five normal stress distributions along the connection between the transverse stiffeners and the web thus obtained, two results are plotted in Figure 2. When W is small, σ_{yy} is smaller in the middle part of the web and not comparable to the force distribution assumed in the design. If W is too big, the load-carrying capacity of the girder could be controlled by the phenomenon that doesn't have much to do with the load-carrying capacity of the transverse stiffener. Observing that σ_{yy} increases almost monotonically toward the support in Figure 2 (c), W=1000 mm is employed in the present study.

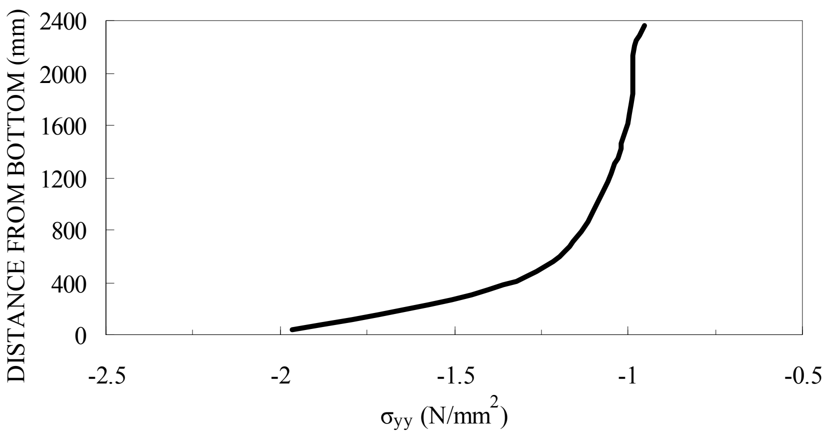
The wheel may pass right above the support. In such a case, the transverse stiffener is subject to a concentrated load at its top end. This loading situation is also taken into account in the present study. Namely, in addition to the uniformly distributed load, the concentrated load is applied to the upper flange right above the support. In this combined



(a) Length of loading zone



(b) W=150 mm



(c) W=1000 mm

Figure 2 Length of loading zone and normal stress distribution

loading condition, the distributed load is kept constant at the magnitude equivalent to dead load while the concentrated is increased to evaluate the load-carrying capacity.

The loading by the distributed load only is denoted by Load 1 while the combined loading of the distributed load and the concentrated load is Load 2.

Initial Imperfection

Initial imperfections of the steel girder influence the strength significantly. Therefore, initial deformation and residual stress need be modeled in the analysis.

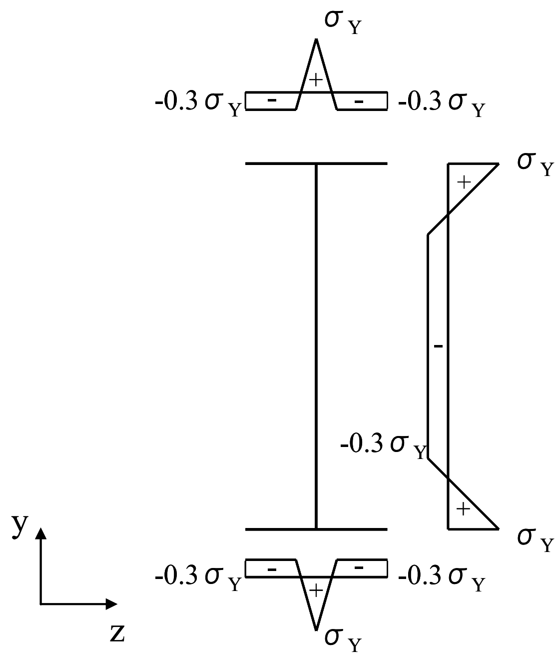


Figure 3 Residual stress distribution

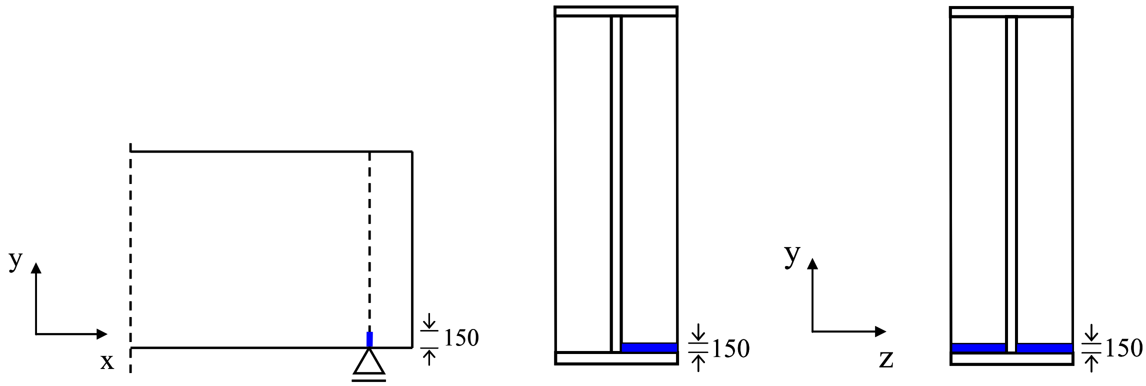
To find the relevant initial deformation, the eigenvalue analysis is conducted first to obtain buckling modes. The initial deformation mode is made identical to the mode of the smallest buckling strength. The initial deformation is then constructed so as to have the maximum displacement within the range of the fabrication tolerance specified in Japan (2012).

Several models of residual stress distribution are available in the literature (Usami 2005). In the present study, the residual stress distribution used by Tamada et al. (2009) is followed, which is shown in Figure 3. The residual stress is equal to the yield strength in tension at the joints between the flanges and the web. The residual stress away from the joints is 30% of the yield strength in compression. The variation of the residual stress is assumed linear.

The residual stress distribution is in a state of self equilibrium. To satisfy this condition, the residual stress is given to the analysis model by conducting thermal stress analysis. The analysis is done by assuming temperature distribution so as to insert the stress distribution desired. The relevant temperature distribution is found by a trial-and-error method.

Corrosion Model

The bridge in Photo 1 is located near the authors' school. One of the authors



(a) Side view
(b) Cross section (Corrosion 1)
(c) Cross section (Corrosion 2)

Figure 4 Corrosion model (Unit: mm)

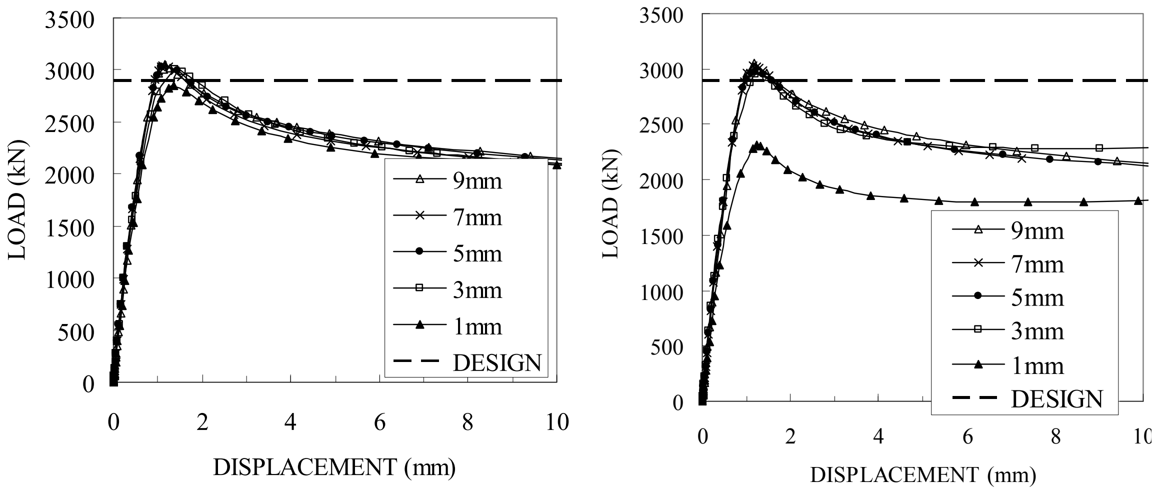
observed the bridge over 10 years. The badly corroded area appears almost unchanged, but the plate is thinning over the time period. The corrosion model is constructed based on this observation: the shaded area in Figure 4 is the corrosion part. As Figure 4 illustrates, the corrosion part is assumed constant, 150 mm high and 294 mm wide (full width of the stiffener). The plate thickness of this area is varied. There are two transverse stiffeners at the support. Correspondingly, two corrosion states are taken for the analysis: (1) only one stiffener is corroded and (2) two stiffeners are corroded. The former is denoted by Corrosion 1 while the latter is Corrosion 2. For Corrosion 2, the thickness losses in the two transverse stiffeners are assumed identical

Design Strength

For the design of the transverse stiffener at a support, a cruciform-section column is constructed, consisting of the two transverse stiffeners and a part of the web (Japan, 2012). The latter is the 24t-long web where t is the web thickness. The effective buckling length of this column is a half of the girder height. The load-carrying capacity is then evaluated by the column-strength design equation. The design strength of the present model thus computed is 2,920 kN.

Numerical Result of Load 1

The load-displacement curves for Corrosion 1 are presented in Figure 5 (a) where the size such as 9 mm in the legend is the plate thickness of the corrosion part in the transverse stiffener. Since the original plate is 9 mm thick, the result of 9 mm is that of the original girder with no corrosion. The load is the reaction force at the support and the displacement is the vertical displacement at the mid-height of the connection between the stiffeners and the web.



(a) Corrosion 1

(b) Corrosion 2

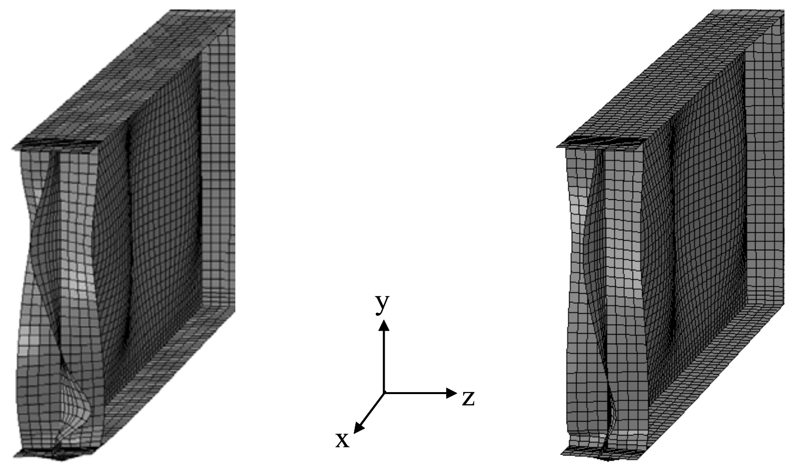
Figure 5 Load-displacement curve (Load 1)

The results show that the behavior of the girder changes very little as far as the plate thickness of the corrosion part is 5 mm or larger. Slight difference is recognized when the plate thickness reduces down to 3 mm, but the load-carrying capacity is still bigger than the design strength. A 6% reduction in load-carrying capacity is observed for the 1-mm plate thickness, and the capacity becomes smaller than the design strength.

Figure 5 (b) is the result for Corrosion 2. The changes in the behavior of the girder are insignificant for the 3-mm or larger plate thickness. The load-carrying capacities stay above the design strength for these cases. However, a large reduction in load-carrying capacity is observed for the1-mm plate thickness. The capacity becomes considerably smaller than the design strength.

Figure 6 presents the deformed configuration magnified by 10 times. It can be observed that local buckling occurs in the corrosion part and the deformation is localized there. The localization is clearer in the result of Corrosion 2. In Corrosion 1, the distortion at the girder end is recognized. This is caused by the asymmetric corrosion state.

A summary of the load-carrying capacity for both corrosion states is given in Figure 7. As the plate thickness of the corrosion part becomes smaller, the load-carrying capacity decreases. The rate of decrease in load-carrying capacity is small when the corrosion loss is small but tends to grow rather rapidly as the plate thickness reduces. In Corrosion 2, the reduction in load-carrying capacity is quite sudden after the plate thickness becomes smaller than 3 mm.



(a) Corrosion 1 (b) Corrosion 2

Figure 6 Deformed configuration at ultimate strength (Load 1, Plate thickness 1 mm)

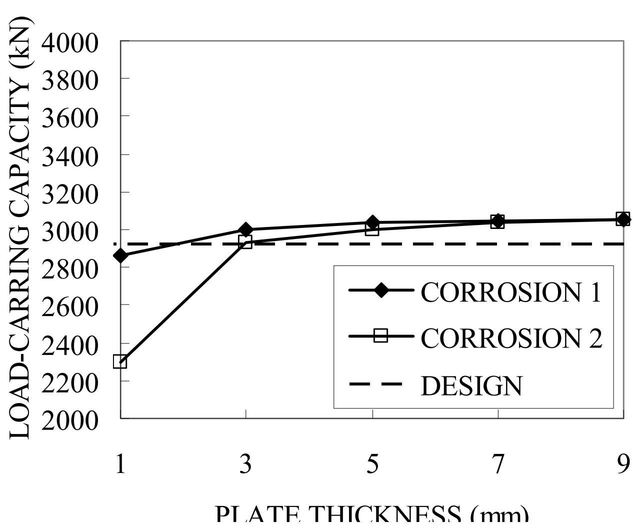
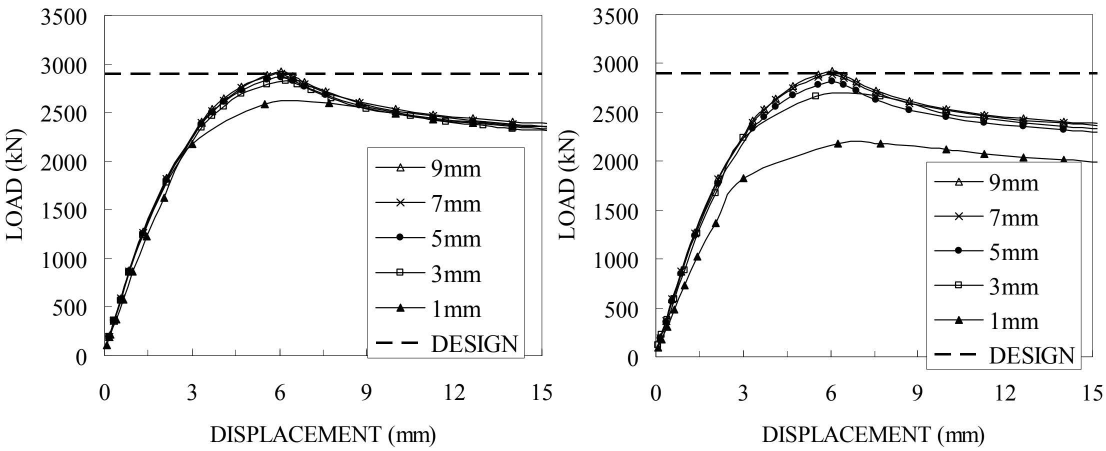


Figure 7 Variation of load-carrying capacity with plate thickness (Load 1)

<u>Numerical Result of Load 2</u>

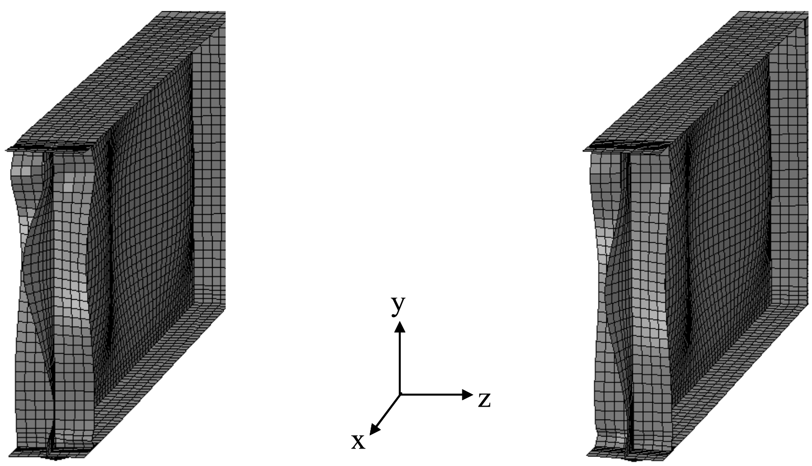
The load-displacement curves for Corrosion 1 are presented in Figure 8 (a). The curves are indistinguishable when the plate thickness is equal to or larger than 5 mm. The difference is recognized when the plate thickness becomes 3 mm, but it is still limited. When the thickness decreases to 1 mm, a 10% reduction in load-carrying capacity is observed.

The results for Corrosion 2 are given in Figure 8 (b). The influence of the corrosion



(a) Corrosion 1 (b) Corrosion 2

Figure 8 Load-displacement curve (Load 2)



(a) Corrosion 1 (b) Corrosion 2

Figure 9 Deformed configuration at ultimate strength (Load 2, Plate thickness 1 mm)

is much greater than in the case of Corrosion 1. As the corrosion progresses, the load-carrying capacity decreases noticeably, and a sharp drop is recognized when the thickness becomes 1 mm. In the case of the 1-mm plate, even the initial stiffness is significantly smaller and the reduction in load-carrying capacity reaches about 25%.

Figure 9 presents the deformed configuration magnified by 10 times. While deformation localized in the corrosion part is observed, the presence of the concentrated load causes larger deformation in the upper parts of the transverse stiffeners than under

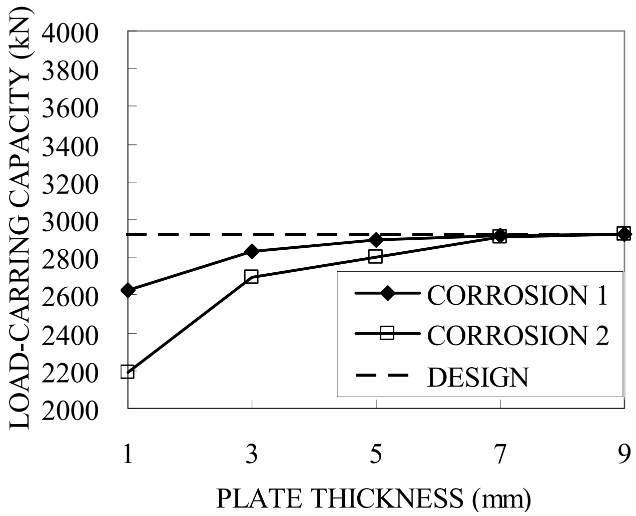


Figure 10 Variation of load-carrying capacity with plate thickness (Load 2)

Load 1. The localized deformation in the corrosion part is much clearer in Corrosion 2.

The load-carrying capacities are summarized in Figure 10. As for the capacity reduction rate with the progress of corrosion, a similar tendency to that of Load 1 is recognized. But obviously Load 2 is a more sever loading condition: unless the plate thickness of the corrosion part is equal to or larger than 7 mm, the load-carrying capacity becomes smaller that the design strength.

Concluding Remarks

Main findings in the present study are as follows:

(1) Under Load 1, the load-carrying capacity of the girder is found well above the design strength. Load 2 gives a quite different and more severe axial force distribution than that assumed in the design. Nevertheless, the load-carrying capacity of the girder is larger than the design strength unless corrosion develops to a considerable extent. The current design procedure is simple and practical, yet it seems to give a good safety margin.

(2) Load 2 is a severe loading condition. The reduction rate of load-carrying capacity due to corrosion is larger under Load 2. Hence, the safety of a bridge needs be checked very carefully if a large wheel load is expected above a corroded stiffener.

(3) With the decrease of plate thickness due to corrosion, the load-carrying capacity deteriorates. The decrease rate is not proportional to the thickness loss. At a certain point of the corrosion state, the load-carrying capacity may drop rather suddenly. Conversely, it may be stated that if the thickness loss is kept small, the reduction in load-carrying capacity can be insignificant.

(4) In Corrosion 2, the load-carrying capacity of the girder suffers more. The difference from the capacity of the girder in Corrosion 1 is not large when the corrosion loss is small, but the gap can grow rapidly as the corrosion loss increases.

Acknowledgments

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