Abstract

Corrosion is one of the most important causes of deterioration of steel girder bridges which affects their long term mechanical performance, usability and durability. Lack of information on yield and ultimate behavior of corroded tensile members make it a difficult task for the civil engineers to evaluate their remaining strength which eventually accounts for the estimation of useful service life, decisions on necessary retrofit or replacements to promote public safety. In the past, many experimental studies were done on corroded coupon specimens such as JIS No.5 with about 30mm width, in clarifying the influence of corrosion on the remaining strength. However in actual corrosion conditions, severe corrosion damages with large corrosion pits exceeding 30mm in diameter are observed in aged steel bridges. Therefore the existing coupon specimens would not reflect the actual effects of corrosion in their corresponding tensile tests.

A more accurate method of remaining strength estimation for the corroded tensile plates based on the experimental results of tensile tests conducted on 26 specimens having different corrosion conditions and wide widths of 70-180 mm is presented in this paper. These results divulged the importance and possibility of using of a representative effective thickness parameter on estimating the residual yield and tensile strengths of corroded steel plates with more accuracy. Therefore, two approaches to estimate the remaining yield and tensile strength of corroded steel plates are proposed by considering the statistical parameters such as initial thickness, standard deviation of thickness etc., which represents the condition of corrosion surface. The proposed methods revealed more accurate and reliable estimation for the maintenance management of existing corroded steel structures.

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Keywords: Corrosion; Effective thickness; Maintenance; Remaining strength; Standard deviation of thickness.

1. INTRODUCTION

Since the initiation of construction of first steel bridges around 200 years ago, steel has instituted itself worldwide in the 19th and 20th centuries and in a multiplicity of bridge constructions as best building material. This is due to the fact that opposing to concrete it has a better strength to weight relationship. With steel, the construction of bridges becomes easier with shorter construction time and reduced construction costs. However, the disadvantage is the unprotected structural steel in the atmosphere subjects to corrosion which leads to the reduction of their carrying capacities. Therefore, a reliable maintenance of steel bridges is crucial as these bridges have to ensure smooth traffic for cars, trucks as well as rails which represent the most important mediums for the transportation of goods and services in our modern society. Therefore, it is very important to understand the behavior of existing bridges which are corroding for decades and establish an accurate methodology to estimate the remaining load carrying capacities for proper maintenance of steel highway and railway infrastructures, ensuring their safety.

Literature review reveals that quite a few numbers of experimental loading tests of corroded steel plates under tensile force were carried out in past few years. Namely, Matsumoto et al. (1989) investigated the tensile strength, using tensile coupons with corrosion. They predict the remaining tensile strength of the corroded plates, using the minimum value of average thickness \(t_{sa}\) of the cross section perpendicular to the loading axis as a representative thickness. Muranaka et al. (1998), proposed a representative thickness \(t_R = t_{avg} - 0.7\sigma_{st} \) (\(t_{avg}\): average thickness, \(\sigma_{st}\): standard deviation of thickness) for estimating the tensile and fatigue strength, based on the tensile test. Also, Kariya et al. (2003) conducted some tensile tests of corroded plates and proposed a representative thickness \(t_R = t_{avg} - 1.3\sigma_{st}\) to estimate the tensile strength. However, it was noticed that the widths of those test specimens are very small (less than 30mm). But, it is noticed that many corrosion pits with more than 30mm diameters exist in actual severe corroded members. So, the influence of such corroded conditions could have been derelict and hence their actual remaining strengths might be different than those were obtained from those experimental studies. Therefore, in order to clarify the effect of corrosion conditions on remaining strength, it is an essential task to conduct some experimental studies with steel members close to the actual size of the steel members. For this purpose, tensile tests were conducted on 26 specimens with 70-180 mm width and different corrosion conditions in this research study. Further, the relationship between the remaining yield and tensile strength capacities and statistical thickness parameters are discussed in this paper.

2. CORRODED TEST SPECIMENS

2.1. Test Specimen Configuration

The test specimens for this research study were cut out from a steel girder of Ananai River in Kochi Prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years. This bridge was constructed as a railway bridge in 1900, and in 1975 changed to a pedestrian bridge, when the reinforced concrete slab was cast on main girders. The bridge was dismantled due to serious corrosion damage in year 2001. Many severe corrosion damages distributed all over the girder, especially, large corrosion pits or locally-corroded portions were observed on upper flanges and its cover plates. Then, 21 (F1~F21) and 5(W1~W5) test specimens were cut out from the cover plate on upper flange (initial thickness=10.5mm) and web plate (initial thickness=10.0mm).

Before conducting the thickness measurements, all rusts over both surfaces were removed carefully by
using the electric wire brushes and punches. Then, two new SM490A plates (t=16mm) were jointed to both sides of specimen by the butt full penetration welding for grip parts to loading machine, as shown in Figure 1. Here, the flange and web specimens have the widths ranged from 70-80mm and 170-180mm respectively. The test specimen configuration is shown in Figure 1.

2.2. Corrosion Surface Measurement

Accuracy and convenience are highly demanded in the measurement of corrosion surface irregularities. Furthermore, portability, good operability and lightness would be also imperative for choosing of a measurement device for on-site measurements. Therefore, the portable 3-dimentional scanning system, which can measure the 3-dimentional coordinate values at any arbitrary point on the corrosion surface directly and continuously, was used for the measurement of surface irregularities of the test specimens. Here, the thickness of the corroded surface can be calculated easily from those measured coordinates. The measuring device has three arms and six rotational joints, and can measure the coordinates of a point on steel surface by using the non-contact scanning probe (laser line probe). So, the thicknesses of all scratched specimens were measured by using this 3D laser scanning device and the coordinate data was obtained in a grid of 0.5mm intervals in both X and Y directions. Then, the remaining thicknesses of all grid points were calculated by using the difference of the coordinate values of both sides of those corroded specimens.

2.3. Classification of Corrosion Conditions

Even though, various types of corrosion conditions in actual steel structures can be seen as the corrosion damage can take place in many shapes and forms, it would be important to categorize those different corrosion conditions to few general types for better understanding of their remaining strength capacities. Therefore, in this study, all specimens were categorized into typical 3 corrosion types concerning their corrosion conditions and minimum thickness ratio, \( \mu \) (minimum thickness/initial thickness) and three thickness contour maps of those 3 corrosion types are shown in Figure 2.
The overall corrosion type is defined, where the percentage minimum thickness ratio is greater than 50%. Spreading of small corrosion pits on all over the plate surface can be seen in this corrosion type and an example of this corrosion type (F-14) is shown in Figure 2(a). When the corrosion is more progressed than the overall corrosion type, the corrosion surfaces with pitting corrosion type can be seen where few considerable corroded pits exist in some places and the percentage minimum thickness ratio is 10% - 50% in this corrosion type. An example of the thickness contour maps for pitting corrosion type (F-12) is shown in Figure 2(b). The local corrosion type is defined for those members having their percentage minimum thickness ratio less than 10%. Several extensive corroded regions with severe corroded pits can be seen on the member in this corrosion type and one example of local corrosion type (F-19) is shown in Figure 2(c).

3. EXPERIMENTAL INVESTIGATION

The Load-elongation curves for three different corroded specimens (F-14, F-12 and F-19) with 3 corrosion types are shown in Figure 3. Herein, the specimen (F-14) with overall corrosion has almost same mechanical properties (such as apparent yield strength and load-elongation behavior etc.) as the corrosion-free specimen. On the other hand, the pitting corroded specimen (F-12) and the locally corroded specimen (F-19) show obscure yield strength and the elongation of the specimen F-19 decreases significantly. The reason for this is believed to be that the local section with a small cross-sectional area yields at an early load stage because of the stress concentration due to irregularity of corroded steel plate. And this will lead the pitting and locally corroded members to elongate locally and reach to the breaking point.

4. REMAINING STRENGTH ESTIMATION

The two basic definitions can be expressed for the experimentally predicted parameters for the yield effective thickness \( t_{e,y} \) and the tensile effective thickness \( t_{e,b} \) as follows:
\[
\begin{align*}
\text{t}_{e_y} &= \left( \frac{P_y}{B \cdot \sigma_y} \right) \\
\text{t}_{e_b} &= \left( \frac{P_b}{B \cdot \sigma_b} \right)
\end{align*}
\]

where, \( P_y \): yield load, \( P_b \): tensile load, \( B \): width of the specimen for the corroded state and \( \sigma_y \) and \( \sigma_b \) are yield and tensile stress of corrosion-free plate respectively. But the above defined effective thickness parameters cannot be obtained for the in-service structures. So, a measurable statistical parameter with a high correlation with the effective thickness parameter will be essential for remaining strength estimation of those structures. Therefore, the correlations between the effective thickness \( (t_{eff}) \) and many measurable statistical parameters were examined (such as average thickness \( t_{avg} \), minimum thickness \( t_{min} \), minimum average thickness \( t_{avg\_min} \) and standard deviation of thickness \( \sigma_t \) etc.) and two relationships were defined for remaining yield and ultimate strength estimations of corroded steel plates.

### 4.1. Estimation of Yield Strength

The correlation between the yield effective thickness and measurable statistical thickness parameters were examined and the best relationship was found with the minimum average thickness as shown in Figure 4(a). Further, it was found that the average thickness tends to become larger than effective thickness, as the influence of stress concentration due to corrosion will not be able to consider carefully. Therefore, the strength estimation using only \( t_{avg} \) will overestimate the remaining yield strength. On the other hand, it was found that the yield strength estimation using \( t_{min} \) will provide considerably underestimated results. So, it thought that \( t_{avg\_min} \) should be applied to effective thickness for the yield strength estimation with good accuracy. And it was noted that the influence of stress concentration due to corrosion will be able to consider by only using minimum section for yield strength estimation. Further, it was found that \( t_{avg\_min} \) has a very high coefficient of correlation \( (R^2=0.971) \) and hence it could be considered as a better parameter to predict the remaining yield strength of corroded steel plates with high accuracy.

### 4.2. Estimation of Tensile Strength

The relationships between measurable statistical parameters and tensile effective thickness \( (t_{e_b}) \) were investigated in this part of the research to find out a better parameter in estimating the remaining tensile strength of corroded steel plates. It was revealed, though the minimum average thickness \( (t_{avg\_min}) \) was better for predicting the remaining yield strength, it gives rather over estimated result for tensile strength estimation as shown in Figure 4(b).

Since the stress concentration due to surface irregularity of the corroded surface will also highly influence the tensile strength prediction, it was revealed that standard deviation of thickness will give the highest correlation in tensile strength estimation as shown in Figure 4(c). Further, the best relationship to predict the representative effective thickness for tensile strength estimation was found as: \( t_{eff} = t_0 - 3.3\sigma_t \), where \( t_0 \) is the initial thickness of the plate and \( \sigma_t \) is the standard deviation of thickness. As shown in Figure 4(d), the proposed relationship will give high coefficient of correlation \( (R^2=0.970) \) with the experimentally estimated tensile effective thickness \( (t_{e_b}) \) value and hence this can be used for more reliable remaining tensile strength estimation of corroded steel plates with better accuracy.
5. CONCLUSIONS

The steel surface measurements and tensile tests were conducted for many corroded steel plate specimens obtained from a plate girder which had been used for about 100 years with severe corrosion. The main conclusions obtained from this study can be summarized as:

1) 3 typical corrosion types were defined based on corroded surface thickness measurements.
2) Remaining yield strength of corroded steel plates can be estimated by using the minimum average thickness ($t_{avg\_min}$) with high accuracy.
3) The remaining tensile strength estimation can be done by using the representative effective thickness defined as: $t_{eff} = t_0 - 3.3\sigma_{st}$ with high accuracy.

6. ACKNOWLEDGMENTS

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