

ENHANCED EFFECTIVE THICKNESS FOR REMAINING STRENGTH ESTIMATION OF CORRODED STEEL BRIDGE MEMBERS

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Abstract

Infrastructure plays a major role in the economy of a country. Bridges are a major component of any infrastructure and the failure of a bridge will affect the economy of any country. Over the past decades there have been many damage examples of older steel bridge structures due to corrosion around the world. Exposure of a steel structure to the natural environment and inadequate maintenance will cause corrosion and leads to impairment of its operation. Efficient maintenance, repair and rehabilitation of existing bridges require the development of a methodology that allows for an accurate evaluation of load carrying capacity and prediction of remaining life. Therefore, careful evaluation of remaining load-carrying capacities of corroded steel bridge structures is of high importance in transportation and maintenance engineering.

Even though there are some published methods to assess the strength reduction due to corrosion of bridges, all of them were developed by using specimens with about 30mm width. However during the preliminary investigation, it was found 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 neglected and hence their actual remaining strengths might be different than those were obtained from those experimental studies. Therefore, this paper investigates the effect of actual corroded conditions on their remaining strength capacities and proposes a simple, efficient and accurate residual strength estimation method by using an enhanced effective thickness parameter with the correlation of maximum corroded depth, which can be used for the maintenance management of aged steel bridge infrastructures.

Keywords: Corrosion, Effective thickness, Maximum corroded depth, Remaining strength

1.0 Introduction

Deterioration of steel bridge infrastructures constitutes a major worldwide problem in transportation engineering and maintenance management industry. Corrosion becomes one of the most important causes of deterioration of steel girder bridges which reduce their load carrying capacities and eventually leads to catastrophic collapses. Controlling corrosion on bridge structures can prevent premature failure and lengthen their useful service life, both of which save money and natural resources, and promote public safety. Efficient maintenance, repair and rehabilitation of existing bridges require the development of a methodology that allows for an accurate evaluation of load carrying capacity and prediction of remaining life. Therefore, understanding of the influence of damage due to corrosion on the remaining load-carrying capacities is currently of high concern among the bridge maintenance engineers.

In Japan, there are more than 50,000 steel railway bridges, where more than half of them have been used over 60 years and some bridges are aged over 100 years (Sugimoto, 2006). Many existing bridges in Japan are suffering from damage due to the deterioration of materials, fatigue cracks in RC slabs, steel decks and steel members due to the passage of many overweight vehicles, much heavier than those specified in bridge design specifications, and so on (Kitada, 2006). So the damage incurred due to above mentioned factors can give rise to significant issues in terms of safety, health, environment, and life cycle costs. As a result, many bridges require substantial strengthening and repair works. Instead of constructing large and long-span bridges, high-quality maintenance, repair and retrofitting of existing steel bridges will take an increasingly important part of the future steel bridge market in Japan. Furthermore, about one half of the approximately 600,000 highway bridges in the United States were built before 1940 and many have not been adequately maintained. It is reported that at the end of last century, almost 40% of the nation's bridges are classified as deficient and in need of rehabilitation or replacement (Klaiber, 2000 and Chen, 2009). Of those structurally deficient bridges, 56% have steel superstructures (Miller, 2001). As it would be an exigent task to retrofit or rebuild those aged bridges at the same time, it is important to evaluate the remaining strength capacities of those bridges, in order to keep them in-service until they require necessary retrofit or rebuild in appropriate time.

To assure adequate safety and determine the ongoing maintenance requirements, thorough regular inspections are required. These inspections should form the essential source of information for carrying out a comprehensive evaluation of its current capacity. The accurate estimation of remaining strength of steel members will give the necessary information on establishing the performance recovery methods and necessary retrofitting techniques or replacements of severe corroded members. Therefore, establishment of more accurate remaining strength estimation method will be the core part in all maintenance tasks.

During past few decades, several experimental studies and detailed investigations of corroded surfaces were done by some researchers in order to introduce methods of estimating the remaining strength capacities of corroded steel plates (Matsumoto, 1989; Muranaka, 1998; Kariya, 2003; Appuhamy, 2009). Namely, Matsumoto *et al.* (1989) investigated the tensile strength, using tensile coupons with corrosion and predict the remaining tensile strength of

corroded plates, using minimum value of average thickness ($t_{\text{avg_min}}$) of the cross section perpendicular to the loading axis as a representative thickness. Further, Muranaka *et al.* (1998) and Kariya *et al.* (2003) proposed different representative thickness parameters with a correlation of average thickness (t_{avg}) and standard deviation of thickness (σ_{st}), to estimate the tensile strength of corroded members based on many tensile tests. Thus, it is very clear that, many researchers usually use representative thickness based on several statistical parameters to estimate the remaining strength. Appuhamy *et al.* (2009) proposed a representative effective thickness with the correlation of initial thickness (t_0) and standard deviation of thickness (σ_{st}) with high accuracy than other available methods. And in 2011, it was simplified by introducing maximum corroded depth ($t_{\text{c,max}}$) instead of standard deviation of thickness to estimate the remaining strength capacities of corroded steel members (Appuhamy, 2011).

However, it was noticed that the widths of above mentioned test specimens are very small (less than 30mm). But, during the preliminary investigation it was found 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. Then, a simple and more accurate method of predicting remaining yield and tensile strength capacities by using a concept of representative effective thickness (t_{eff}) with the correlation of initial thickness (t_0) and the maximum corroded depth ($t_{\text{c,max}}$), is proposed and compared with the other available remaining strength estimation methods.

2.0 Investigation of Corroded Surfaces

2.1 Test Specimen Configuration

The tensile test specimens used for this study were cut out from a steel girder of Ananai River Bridge in Kochi Prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years. This bridge had simply supported steel plate girders with six spans, with each of 13.5m and it 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 and web plate respectively.

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 ($t=16\text{mm}$) 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. In addition, 4 corrosion-free specimens (JIS5 type) were made of each two from flange and web, and the tensile tests were carried out in order to clarify the material properties of test specimens. The material properties obtained from these tests are shown in Table 1.

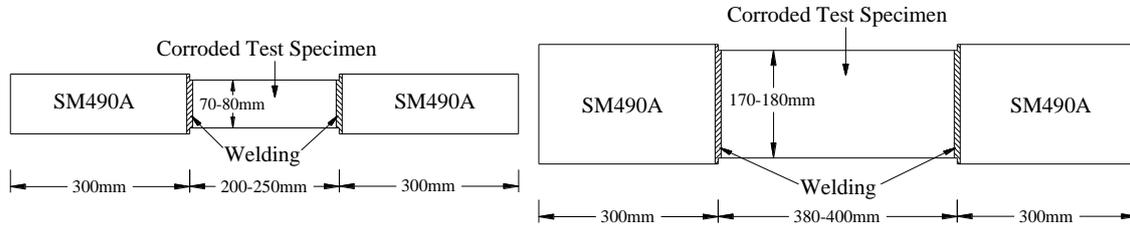


Figure 1: Dimensions of test specimens

Table 1: Material properties

Specimen	Elastic modulus /(GPa)	Poisson's ratio	Yield stress /(MPa)	Tensile strength /(MPa)	Elongation at breaking /(%)
Corrosion-free plate (flange)	187.8	0.271	281.6	431.3	40.19
Corrosion-free plate (web)	195.4	0.281	307.8	463.5	32.87
SS400 JIS	200.0	0.300	245~	400~510	–

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-dimensional scanning system, which can measure the 3-dimensional 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 (Kaita 2005).

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). The condition of thickness measurement is shown in Figure 2. Since this probe scans the steel surface with a laser beam, which has about 100mm width, the large number of 3-dimensional coordinate data can be obtained quickly. In this measurement, the 3-dimensional coordinate data is obtained as many in-line dot data and the accuracy of the measurement device is about 0.1mm. 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. The remaining thicknesses of all grid points were calculated by using the

difference of the coordinate values of both sides of those corroded specimens and the statistical thickness parameters such as average thickness (t_{avg}), minimum thickness (t_{min}), standard deviation of thickness (σ_{st}) and coefficient of variability (CV) were calculated from those thickness measurement results.



Figure 2: Condition of thickness measurement

2.3 Corrosion Level Classification

Various types of corrosion conditions in actual steel structures can be seen as the corrosion damage can take place in many shapes and forms. But, it would be important to categorize those different corrosion conditions to few general types for better understanding of their remaining strength capacities considering their visual distinctiveness, amount of corrosion and their expected mechanical and ultimate behaviors. Here, it is important that these corrosion levels could easily identified through few thickness measurements at the site and they represent not only the amount of corrosion, but also the remaining strength capacities for a brisk assessment of the structures' present condition. Figure 3 shows the relationship between the nominal ultimate stress ratio (σ_{bn}/σ_b) and the minimum thickness ratio (μ), where σ_{bn} is the nominal ultimate stress and σ_b is the ultimate stress of corrosion-free plate. Here, the minimum thickness ratio (μ) is defined as:

$$\mu = \frac{t_{min}}{t_0} \quad (1)$$

There, the initial thickness (t_0) of the flange specimens and web specimens are 10.5mm and 10.0mm respectively. Therefore, three different types of corrosion levels were identified according to their severity of corrosion and they are classified accordingly as follows:

- | | |
|--------------------------|----------------------|
| $\mu > 0.75$ | ; Minor Corrosion |
| $0.75 \geq \mu \geq 0.5$ | ; Moderate Corrosion |
| $\mu < 0.5$ | ; Severe Corrosion |

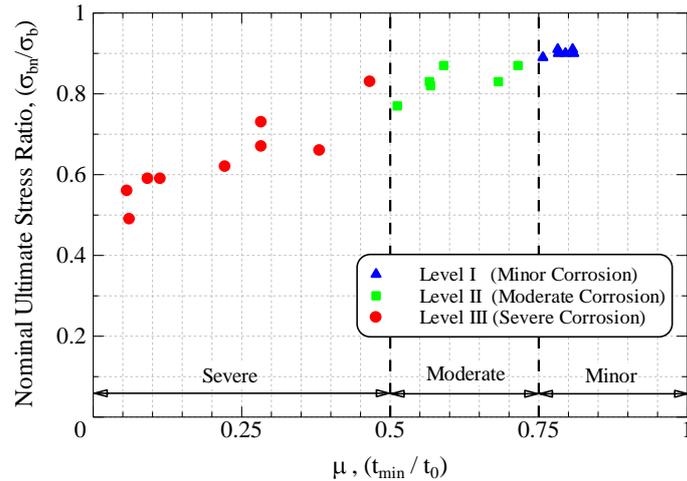


Figure 3: Relationship of ultimate stress ratio & minimum thickness ratio (μ)

3.0 Experimental Analysis

3.1 Experimental Setup



Figure 4: Specimen prepared for the tensile test

All the flange and web specimens were prepared for the tensile loading tests. There, different numbers of strain gauges were attached to each specimen considering their corrosion conditions. One example of prepared corroded specimen with strain gauges is shown in Figure 4. There, more attention was paid on both the minimum section and local portions with serious corrosion damage for attaching the strain gauges. And the intervals of strain gauges were decided by considering the surface condition.

Tensile loading tests were carried out at constant velocity under loading control by using a hydraulic loading test machine (maximum load: 2940KN) for all 26 specimens with different corrosion conditions. The loading velocity was set to 200N/sec for minor corroded specimens and 150N/sec for moderate and severe corroded specimens.

3.2 Experimental Results and Discussion

Figure 5 shows the load-elongation curves for three different corroded specimens with 3 corrosion types. The specimens F-14 and F-13 have comparatively larger minimum thickness ratio ($\mu = 0.783$ and 0.512 respectively) and the specimen F-19 in which the corrosion progression was more severe, the minimum thickness ratio is also diminutive ($\mu = 0.061$). Herein, the specimen (F-14) with minor 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 moderate corroded specimen (F-13) and the severely corroded specimen (F-19) show obscure yield strength and the elongation of the specimen F-19 decreases notably. 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 moderate and severe corroded members elongate locally and reach to the breaking point.

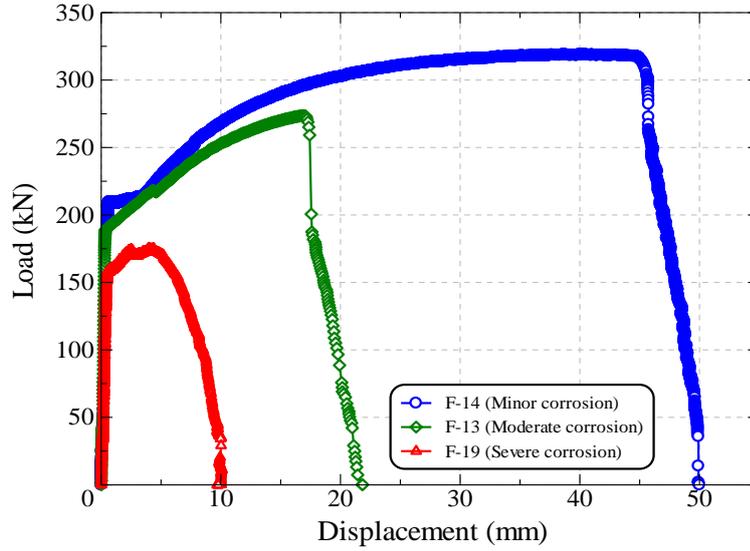


Figure 5: Load-displacement curves

4.0 Remaining Strength Estimation

Two basic definitions for the experimental effective thickness (t_{eff}^*) for the yield and tensile strength estimations can be expressed as follows:

$$t_{eff}^* = \begin{cases} \left(\frac{P_y}{B \cdot \sigma_y} \right) & ; \text{Yield strength} \\ \left(\frac{P_b}{B \cdot \sigma_b} \right) & ; \text{Tensile strength} \end{cases} \quad (2)$$

Where, P_y : yield load, P_b : tensile load, B : width of the specimen for the corroded state and σ_y and σ_b are yield and tensile stress of corrosion-free plate respectively. But it is not easy to obtain the above defined effective thickness for the in-service structures because of the difficulty to get the P_y and P_b . So, a measurable statistical parameter (such as: t_{min} , t_{avg} , t_{avg_min} and σ_{st} etc.) with a high correlation with the experimental effective thickness will be essential for remaining strength estimation of those structures. Therefore, in this study, the correlations between effective thickness and measurable statistical parameters were examined and two relationships were defined for remaining yield and ultimate strength estimations of corroded steel plates.

4.1 Estimation of Remaining Yield and Tensile Strengths

The tensile test results of wide corroded specimens were analyzed in order to find out a statistical thickness parameter which can be used to estimate the remaining yield and tensile strengths. Here, the correlations between effective thickness and measureable statistical parameters were examined and a better relationship was found with the minimum thickness ratio (μ). Hence, in this study, a representative effective thickness (t_{eff}) based on the initial thickness (t_0) and the minimum thickness (t_{min}) was introduced as a new trial. So the aim is to use minimum thickness as the only variable parameter to represent the corrosion condition in the process of estimating remaining strength capacities. The relationships obtained for yield and tensile stress conditions for wide corroded specimens are shown in Figure 6(a) and 6(b). From these relationships, two formulas for representative effective thickness (t_{eff}), which can be used to estimate the remaining yield and tensile strength capacities can be obtained as described below.

From Figure 6(a),

$$\left(\frac{\sigma_{\text{yn}}}{\sigma_{\text{y}}} \right) = 0.631 + 0.372 \left(\frac{t_{\text{min}}}{t_0} \right)$$

$$t_{\text{eff}} = 0.631 t_0 + 0.372 t_{\text{min}} \quad (3)$$

In same way from Fig. 6(b),

$$\left(\frac{\sigma_{\text{bn}}}{\sigma_{\text{b}}} \right) = 0.531 + 0.483 \left(\frac{t_{\text{min}}}{t_0} \right)$$

$$t_{\text{eff}} = 0.531 t_0 + 0.483 t_{\text{min}} \quad (4)$$

So, a generalized equation for the representative effective thickness parameter, which satisfies the non corrosion condition, where, t_{min} is equal to t_0 and the value of t_{eff} should be equal to t_0 as well, can be expressed as:

$$t_{\text{eff}} = \lambda t_0 + (1 - \lambda) t_{\text{min}} \quad (5)$$

Figure 6(c) shows that $\lambda=0.6$ and $\lambda=0.5$ give the best agreement in both yield and tensile strength estimations respectively. Therefore the representative effective thickness parameter for yield and tensile strength estimations can be defined as:

$$t_{\text{eff}} = \begin{cases} 0.6 t_0 + 0.4 t_{\text{min}} & ; \text{Yield strength} \\ 0.5 t_0 + 0.5 t_{\text{min}} & ; \text{Tensile strength} \end{cases} \quad (6)$$

Now, the maximum corroded depth ($t_{\text{c,max}}$) can be expressed as:

$$t_{\text{c,max}} = t_0 - t_{\text{min}} \quad (7)$$

Therefore, considering Eq. 6 and Eq. 7, the following relationship can be obtained for representative effective thickness, which can be used to estimate the remaining yield and tensile strengths of a corroded steel plate.

$$t_{\text{eff}} = \begin{cases} t_0 - 0.4 t_{c,\text{max}} & ; \text{Yield strength} \\ t_0 - 0.5 t_{c,\text{max}} & ; \text{Tensile strength} \end{cases} \quad (8)$$

Since the proposed effective thickness equations have only a single variable, maximum corroded depth ($t_{c,\text{max}}$), which is an easily measurable parameter and the value of initial thickness (t_0) is a well known parameter, it will reduce the contribution of errors occurred during the practical investigation of a corroded member. Further this method is simple and can be used after conducting a rapid visual investigation of the corroded surface and obtaining the required easily measurable thickness measurements.

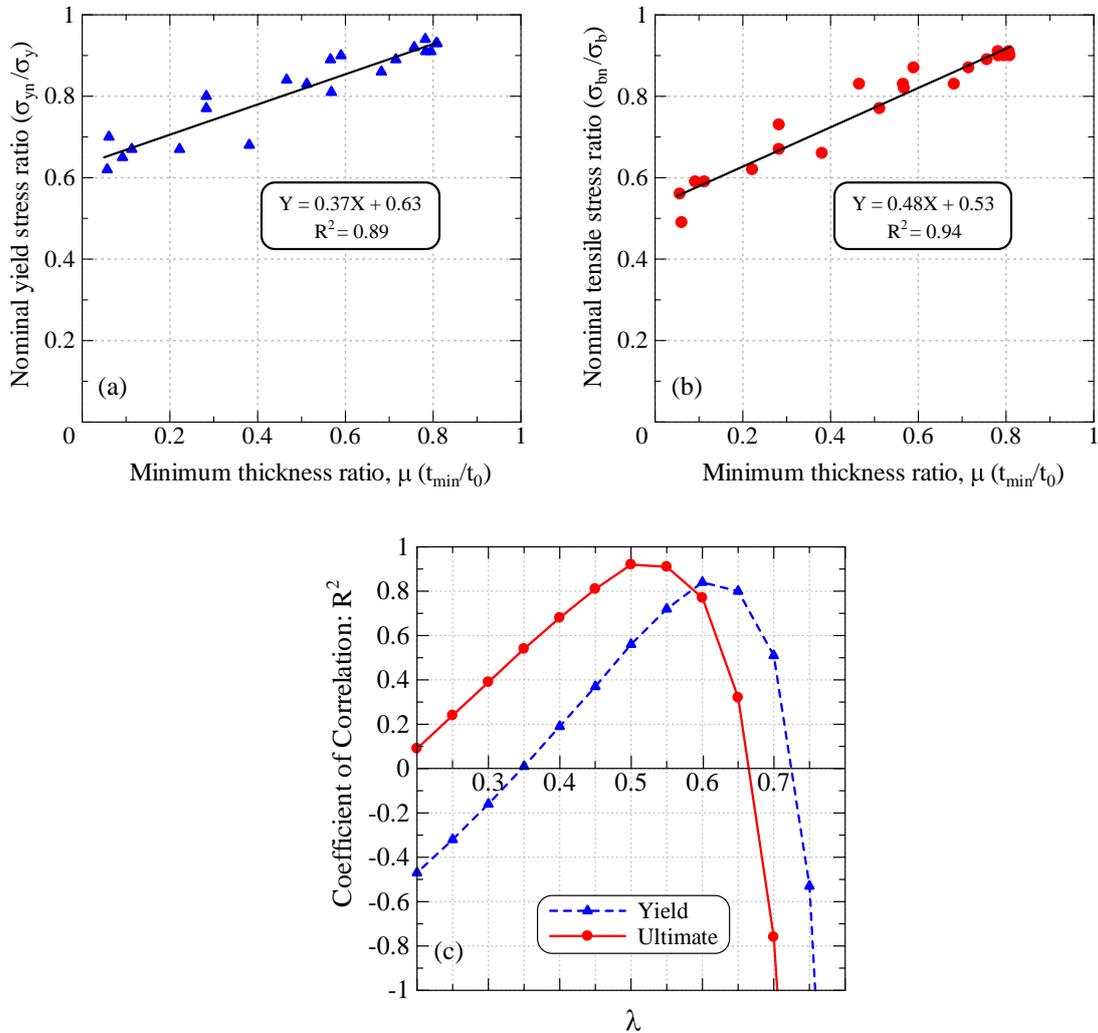


Figure 6: Relationship of (a) yield stress ratio, (b) tensile stress ratio and minimum thickness ratio (μ) and (c) estimation of coefficient, λ

4.2 Comparison of Proposed Effective Thickness

The proposed representative effective thickness (Eq. 8) and the other available representative effective thickness parameters were examined and compared with the experimental effective thickness (Eqn. 2) to understand the effectiveness of the proposed method of estimating the remaining strength capacities for corroded steel plates. Table 2 shows the coefficient of correlation values of available different methods and the proposed effective thickness estimation method and it clearly shows that the proposed effective thickness parameter gives more reliable and better prediction with the experimentally analyzed results than other available methods.

Table 2: Comparison of correlation coefficients of different representative thickness prediction methods

Method	Matsumoto <i>et al.</i> 1989	Muranaka <i>et al.</i> 1998	Kariya <i>et al.</i> 2003	Proposed, t_{eff}
Equation of Thickness	$t_{\text{avg_min}}$	$t_{\text{avg}} - 0.7\sigma_{\text{st}}$	$t_{\text{avg}} - 1.3\sigma_{\text{st}}$	Yield: $t_0 - 0.4t_{\text{c,max}}$ Tensile: $t_0 - 0.5t_{\text{c,max}}$
Correlation Coefficient				
Yield	–	–	–	0.84
Tensile	0.57	0.38	0.64	0.93

4.3 Validation of Proposed Effective Thickness

The tensile test results of corroded steel plates obtained from a ferry bridge (Muranaka 1998) were also analyzed and their yield and ultimate behaviours are also studied. Figure 7(a) and 7(b) show the relationship of minimum thickness ratio with the yield stress ratio and tensile stress ratio respectively.

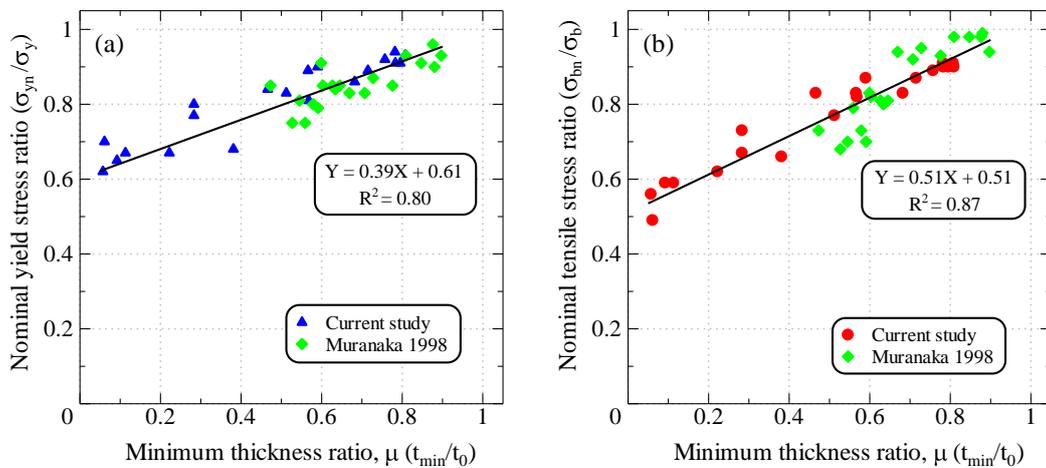


Figure 7: Combined relationship of current study and Muranaka 1998 for (a) yield stress ratio, (b) tensile stress ratio and minimum thickness ratio (μ)

The yield and tensile strengths obtained from the tensile tests conducted by Muranaka 1998 show a good agreement with the results of current study and it revealed that the effective thickness parameters obtained from this study are same as the equations shown in Eq. 8. Therefore, the proposed effective thickness (Eq. 8) can be used for the remaining strength estimation of corroded steel structures with a better confidence of safety.

5.0 Conclusions

The steel surface measurements and tensile tests were conducted on many wide specimens with different corrosion conditions, which are obtained from a plate girder which had been used for about 100 years with severe corrosion. Main conclusions obtained from this study can be summarized as follows.

1. Corrosion causes strength reduction of steel plates and minimum thickness ratio (μ) can be used as a measure of the level of corrosion and their strength degradation.
2. Remaining yield strength of corroded steel plates can be estimated by using the representative effective thickness defined as: $t_{\text{eff}} = t_0 - 0.4t_{\text{c,max}}$ with high accuracy.
3. Remaining tensile strength estimation can be done by using the representative effective thickness defined as: $t_{\text{eff}} = t_0 - 0.5t_{\text{c,max}}$ with high accuracy.

As the proposed effective thickness equations have only a single variable, maximum corroded thickness ($t_{\text{c,max}}$), which is an easily measurable parameter and the value of initial thickness (t_0) is a well known parameter, it will reduce the contribution of the errors occurred during the practical investigation of a corroded member. Further this method is simple and gives more reliable and closer results compared to the other available methods.

6.0 Acknowledgements

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