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# ESTIMATION OF EFFECTIVE THICKNESS OF CORRODED STEEL PLATES FOR REMAINING STRENGTH PREDICTION

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Many steel bridge infrastructures of the world are getting old and hence subjected to age-related deterioration such as corrosion wastage, fatigue cracking, or mechanical damage during their service life. These forms of damage can give rise to significant issues in terms of safety, health, environment, and life cycle costs. Since it is not possible to retrofit or rebuild those aged bridges at the same time, it is necessary to develop advanced technologies which can be used to assist proper maintenance of highway and railway infrastructures and evaluate the remaining strength capacities of those bridges, in order to keep them in-service until they required necessary retrofit or rebuild in appropriate time. This paper describes a simple method to estimate the remaining yield and tensile strength of corroded steel members by using a concept of representative effective thickness ($t_{eff}$) with the correlation of initial thickness ($t_0$) and the maximum corroded depth ($t_{c,max}$), based on the results of many tensile coupon tests of corroded plates obtained from a steel plate girder used for about 100 years with severe corrosion.

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*Keywords:* Corrosion, Remaining Strength, Effective thickness, Maximum corroded depth

## 1. Introduction

Corrosion is a time-based process of deterioration of a material as a result of a reaction with its environment. In this electrochemical process, initial attack occurs at anodic areas on the surface, where ferrous ions go into solution. Electrons are released from the anode and move through the metallic structure to the adjacent cathodic sites on the surface, where they combine with oxygen and water to form hydroxyl ions. These react with the ferrous ions from the anode to produce ferrous hydroxide, which itself is further oxidized in air to produce hydrated ferric oxide (i.e. red rust). The sum of these reactions can be represented by the following equation:

$$4Fe + 30_2 + 2H_20 = 2Fe_20_3.H_20 \qquad (1)$$

(Steel) + (Oxygen) + (Water) = Hydrated ferric oxide (Rust)

This process requires the simultaneous presence of water and oxygen. In the absence of either, corrosion does not occur. The consequences of corrosion are many and varied and the effects of these on the safe, reliable and efficient operation of structures are often considered than simply losing a volume of metal. One of the major harmful effects of corrosion is the reduction of

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metal thickness leading to loss of mechanical strength and structural failure, causing severe disastrous and hazardous injuries to people. There are more than 50,000 steel railway bridges in Japan, where more than half of them have been used over 60 years and some bridges are aged over 100 years (Sugimoto, 2006). With aging, Corrosion becomes one of the major causes of deterioration of steel bridges, and its' damages seriously affect on the durability of steel bridges (Fujii 2003 and Rahgozar, 2009).

Recently, there are many damage examples reported due to corrosion and fatigue around the world. Though it's a maintenance issue, it can be addressed appropriately by specification of a proper corrosion system in the design phase. It has been proved that the corrosion played a significant role in the catastrophic collapse of both the Silver Bridge (Point Pleasant, WV) in 1967 and the Mianus River Bridge (Connecticut) in 1983, USA (Steel Bridge Design Handbook). Those collapses indicated the paramount importance of attention to the condition of older bridges, leading to intensified inspection protocols and numerous eventual retrofits or replacements. Therefore corrosion is not an issue to be taken lightly either in design phase or in maintenance stage. Further, as some recent earthquakes demonstrated the potential seismic vulnerability of some types of steel bridges (Bruneau, 1997 and Zahrai, 2003), it would be very important to understand the behaviour of existing steel bridges which are corroding for decades, in future severe seismic events as well.

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.

It is known that the corrosion wastage and the stress concentration caused by the surface irregularity of the corroded steel plates influence the remaining strength of the corroded steel plates (Kariya, 2005). Therefore, the effect of different forms of corrosion to the remaining strength capacities of the existing structure is a vital task for the maintenance management of steel highway and railway infrastructures.

## 2. Problem statement

Some researchers have done some experimental studies and detailed investigations of the corroded surfaces to introduce methods for estimating the remaining strength capacities of corroded tensile steel plates. Namely, Matsumoto *et al.* (1989) investigated the tensile strength, using tensile coupons with corrosion and 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. 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 ($\sigma_{st}$), 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. The all above described representative thickness concepts were derived with relation to the average thickness of the corroded plate ($t_{avg}$) which eventually depends on the accuracy of the thickness measurements. But, it is not easy to conduct bridge inspections with detailed investigations for each and every structure in regular basis as the number of steel bridge infrastructures in the world is steadily increasing as a result of building new steel structures and extending the life of older structures. Therefore, it is important to establish a simple and accurate procedure to predict the remaining strength capacities of a corroded steel member by measuring lesser number of points with an acceptable accuracy level. So, the objective of this paper is to present a remaining strength estimation method by using of a representative effective thickness which is related with an easily measurable dimension like initial thickness ($t_0$), minimum thickness ($t_{min}$) or etc.

## 3. Experimental investigation

### 3.1 Measurement of Corroded Surface

In this study, 42 specimens (21 each from web and flange) cut out from a girder of Ananai River in Kochi Prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years. 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. Further, four corrosion-free specimens were cut down smoothly from both sides of corroded steel plate also fabricated in order to clarify the material properties. The JIS No.5 test specimen is shown in Figure 1.

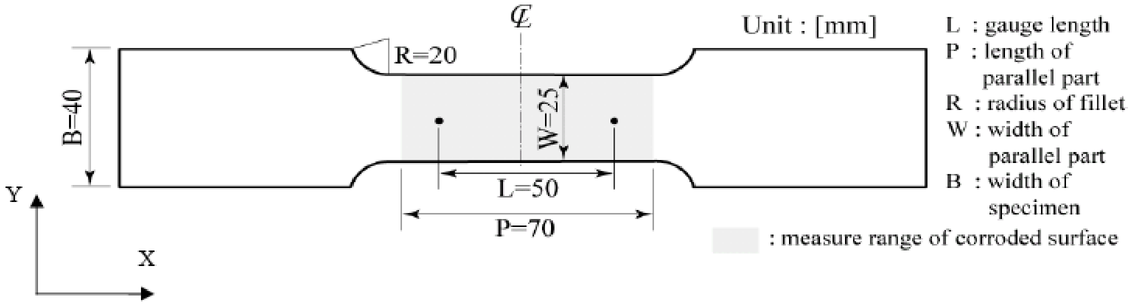


*Fig. 1. JIS No.5 Specimen for tensile test*

Before conducting the thickness measurements, the rust and paint on the surface were removed by using a steel wire brush and then applying high pressure water carefully in order to not change the condition of the corrosion irregularity. Then the thicknesses of all scratched specimens were measured by using a laser displacement gauge and the intervals of measurement data are 1mm and 0.3 mm in X and Y directions respectively. The measurement performed shaded area (70mm x 25mm) is shown in Figure 1 and the condition of thickness measurement is shown in Fig. 2. Then, the statistical parameters such as average thickness ($t_{avg}$), minimum thickness ($t_{min}$), standard deviation ($\sigma_{st}$) and coefficient of variability (CV) were calculated from the measurement results.

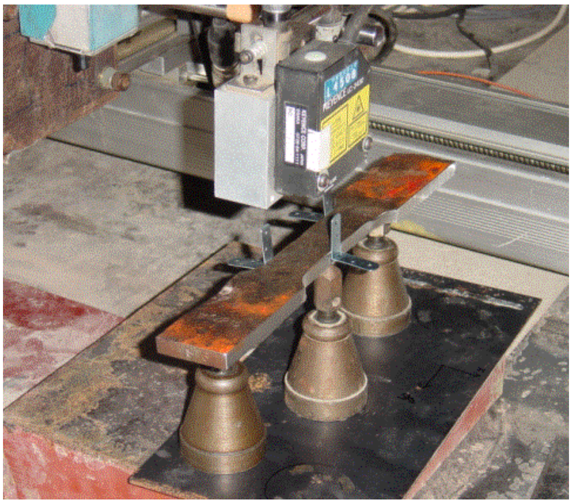


*Fig. 2. Condition of thickness measurement.*

### 3.2 Outline of Tensile Test

The extensometer which can be used to measure elongation until maximum load was set between two marked points as shown in Figure 3 for all 42 corroded specimens and the yield strength, tensile strength and elongation were obtained from the load-elongation curves. The tensile test was performed very carefully at the loading velocities of 0.2 mm/min at elastic region and 0.5 mm/min at plastic region.

First, the tensile test was performed for the four corrosion-free specimens (each two from flange and web) cut down smoothly from both sides of corroded steel plate. The fundamental mechanical properties of the material, such as elastic modulus, Poisson's ratio, yield stress, tensile strength and the elongation were obtained as shown in Table 1. The standard values by JIS are also indicated in the table as the reference. It can be seen that these specimens have the equality with the SS400 Japanese Industrial Standards. And also the web and flange have almost the same properties.

Then, the tensile tests were carried out for all flange and web specimens in order to clarify the relationship between the representative effective thickness which was used to estimate the remaining mechanical strength properties of the corroded plate and the degree of the corrosion state.

*Table 1. Material properties*

| **Specimen** | **Elastic modulus /(GPa)** | **Poisson's ratio** | **Yield stress /(MPa)** | **Tensile strength /(MPa)** | **Elongation at maximum load /(%)** | **Elongation after breaking /(%)** |
|---|---|---|---|---|---|---|
| Corrosion-free plate (flange) | 198.9 | 0.272 | 308.7 | 418.7 | 19.28 | 40.12 |
| Corrosion-free plate (web) | 192.7 | 0.284 | 291.1 | 415.4 | 20.82 | 39.65 |
| SS400 JIS | 200.0 | 0.300 | 245~ | 400~510 | 21.00 | – |

### 3.3 Classification of Corrosion Levels

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 and the featues of histograms, amount of corrosion and their expected mechanical and ultimate behaviors. Here, it is important that these corrosion levels could easily identified through few thickness mearesurements at the site and they represent not only the amount of corrosion, but also the remaining strength capacities for a brisk assessment of condition of the structure.

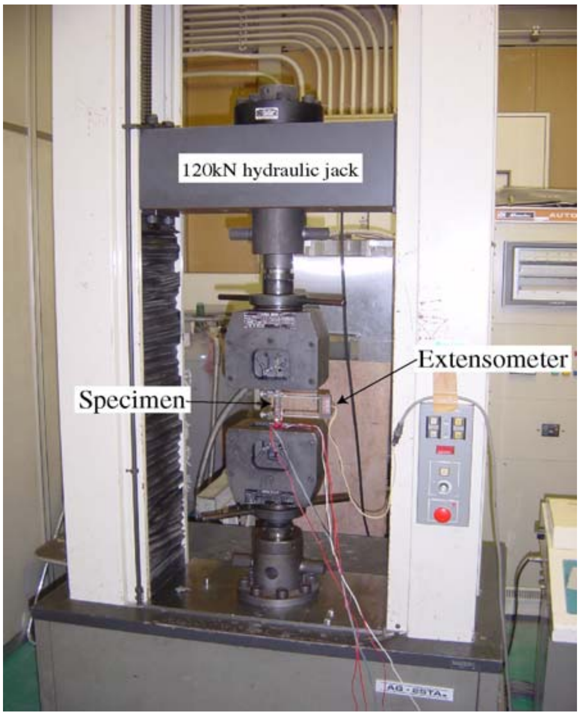


*Fig. 3. Experimental set up of the corroded specimen*

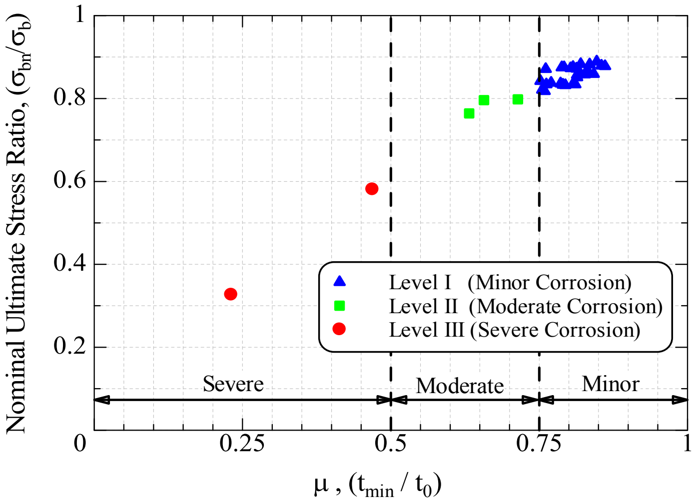


*Fig. 4. Relationship of ultimate stress ratio & minimum thickness ratio (μ).*

The Fig. 4 shows the relationship between the nominal ultimate stress ratio ($\sigma_{bn}/\sigma_b$) and the minimum thickness ratio ($\mu$), where $\sigma_{bn}$ is the nominal ultimate stress and $\sigma_b$ is the ultimate stress of corrosion-free plate. Here, the minimum thickness ratio ($\mu$) is defined as:

$$\mu = \frac{t_{min}}{t_0} \tag{2}$$

In this study, three different types of corrosion levels were introduced according to their severity of corrosion, and which can be used for reliable remaining strength estimation of actual corroded steel structures. They are;

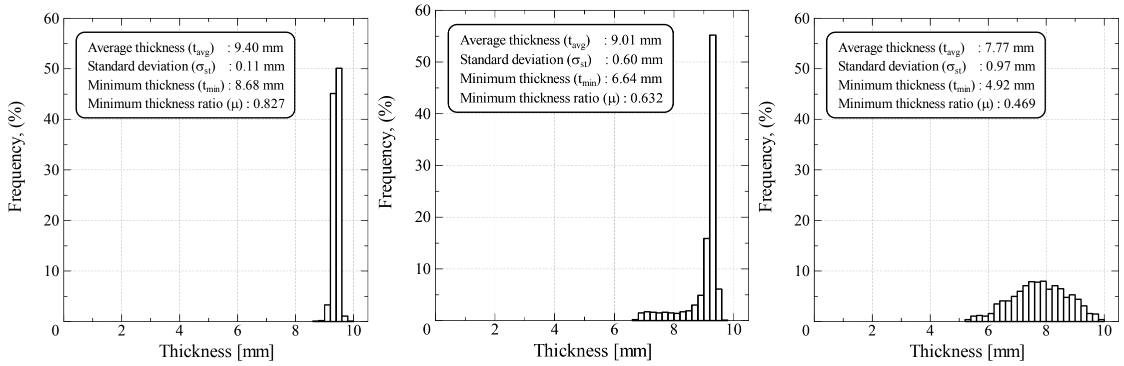
Minor Corrosion ; $\mu \geq 0.75$

Moderate Corrosion ; $0.75 > \mu > 0.5$
Severe Corrosion ; $\mu \leq 0.5$

Further, the follwing Fig. 5 shows the thickness histograms of three members which are classified in to the above mensined corrosion catergories. There, the significance of these three corrosion catergories can be recognized from the features of those thickness histograms as well.

Usually in minor corrosion members, many tiny corrosion pits (less than 3mm depth) can be seen thoughot the specimen. Figure 5(a) shaows that the peak of thickness histogram is almost the same as its average thickness for the minor corrosion type members. Further, it can be seen that the distribution width of the thickness histogram is very narrow.

In moderate corrosion type memebrs, though there are few considerable corroded pits (depth of 3-5 mm) exist in some places, many non-corroded portions also remain widely. Further, as it can be seen from Figure 5(b), the thickness distribution is larger than that of the minor corrosion members and the peak of thickness histogram is not same as the average thikness of the member.



a b c

*Fig. 5. Thickness histograms of (a) Minor corrosion type (FT-22), (b) Moderate corrosion type (FT-18) and (c) Severe corrosion type (FT-15).*

When the corrosion is more progressed, severe corrosion type can be seen with several extensive corroded regions (maximum corrosion depth over 5mm and the diameter of the corroded pits are exceeding 25mm) on the member. Usually in severe corroded members, few peaks of the thickness hustogram can be seen as shown in Figure 5(c), and the highest peak is widely different from the average thickness as well.

So, it is clear that the average thickness could not be able to use for the strength estimations of members with moderate or severe corrosion conditions.

### 3.4 Experimental results

Load-elongation curves for three different corroded specimens and one corrosion-free plate are shown in Figure 6. FT-22 and FT-18 have comparatively larger minimum thickness ratio ($\mu = 0.827$ and 0.632 respectively) and the specimen FT-15 has comparatively lesser value of it ($\mu = 0.469$). Further it can be seen that the steel plate FT-5, in which the corrosion progression was more severe, the minimum thickness ratio is also diminutive ($\mu$ =0. 231).

Herein, the specimen (FT-22) with minor corrosion has the almost same mechanical properties (such as apparent yield strength and load-elongation behavior etc.) as the corrosion-free specimen (FM-5). On the other hand, the moderately corroded specimen (FT-18) and the severe corroded (in this case, locally) specimen (FT-15) show obscure yield strength (Figure 6). And the elongation of the specimen FT-15 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 moderate and severe corrosion members to elongate locally and reach to the breaking point.

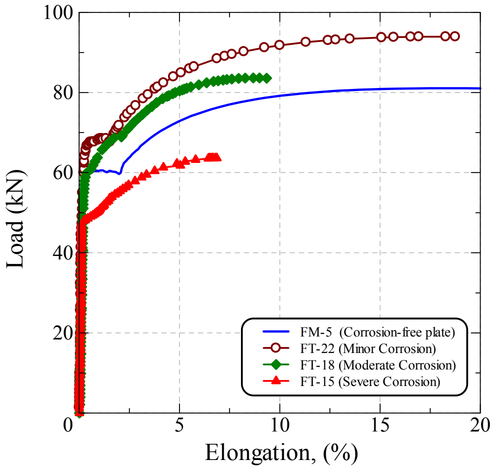


*Fig. 6. Load-elongation curves*

Further, it was noted that the most of the corroded specimens had been broken either in a section of minimum thickness ($t_{min}$) or near the smallest average thickness ($t_{sa}$). Therefore, the local statistical parameters with the influence of stress concentration should be used for the yield and tensile strength estimations.

*Table 2: Measurement, experimental results and categorization of specimens*

| **Member** | **$t_{avg}$ /(mm)** | **$t_{min}$ /(mm)** | **$t_{sa}$ /(mm)** | **$\sigma_{st}$ /(mm)** | **Experimental Results** | | **$\mu$ ($t_{min}/t_0$)** | **Corrosion Type** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **$P_y$ /(kN)** | **$P_b$ /(kN)** | | |
| FT-1 | 9.25 | 7.90 | 9.03 | 0.21 | 60.89 | 92.20 | 0.752 | Minor |
| FT-2 | 9.86 | 9.04 | 9.73 | 0.21 | 67.82 | 96.08 | 0.861 | Minor |
| FT-5 | 7.54 | 2.43 | 4.10 | 2.01 | 26.78 | 35.82 | 0.231 | Severe |
| FT-6 | 9.25 | 6.90 | 8.69 | 0.56 | 59.57 | 87.19 | 0.657 | Moderate |
| FT-8 | 9.16 | 8.47 | 9.02 | 0.20 | 64.10 | 91.39 | 0.807 | Minor |
| FT-9 | 9.39 | 8.34 | 9.16 | 0.26 | 62.32 | 91.04 | 0.794 | Minor |
| FT-10 | 9.03 | 8.29 | 8.88 | 0.21 | 65.75 | 91.24 | 0.790 | Minor |
| FT-11 | 8.97 | 7.50 | 8.41 | 0.47 | 61.88 | 87.42 | 0.714 | Moderate |
| FT-12 | 8.73 | 8.00 | 8.51 | 0.18 | 64.83 | 91.29 | 0.762 | Minor |
| FT-13 | 8.76 | 7.93 | 8.50 | 0.27 | 61.40 | 89.92 | 0.755 | Minor |
| FT-14 | 8.82 | 7.97 | 8.53 | 0.23 | 62.50 | 89.52 | 0.759 | Minor |
| FT-15 | 7.77 | 4.92 | 6.50 | 0.97 | 47.09 | 63.64 | 0.469 | Severe |
| FT-18 | 9.01 | 6.64 | 7.72 | 0.60 | 59.85 | 83.64 | 0.632 | Moderate |
| FT-22 | 9.40 | 8.68 | 9.25 | 0.11 | 67.75 | 93.96 | 0.827 | Minor |
| WT-1 | 9.26 | 8.42 | 8.89 | 0.22 | 63.91 | 89.54 | 0.842 | Minor |
| WT-2 | 9.41 | 8.31 | 8.96 | 0.37 | 65.45 | 90.53 | 0.831 | Minor |
| WT-3 | 9.46 | 8.07 | 9.24 | 0.27 | 65.41 | 91.38 | 0.807 | Minor |
| WT-4 | 9.26 | 8.35 | 9.00 | 0.20 | 64.46 | 92.00 | 0.835 | Minor |
| WT-5 | 9.16 | 7.88 | 8.71 | 0.31 | 62.87 | 91.21 | 0.788 | Minor |

| **Member** | **$t_{avg}$ /(mm)** | **$t_{min}$ /(mm)** | **$t_{sa}$ /(mm)** | **$\sigma_{st}$ /(mm)** | **Experimental Results** | | **$\mu$ ($t_{min}/t_0$)** | **Corrosion Type** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **$P_y$ /(kN)** | **$P_b$ /(kN)** | | |
| WT-6 | 9.48 | 8.55 | 9.22 | 0.22 | 64.75 | 91.68 | 0.855 | Minor |
| WT-7 | 9.32 | 7.86 | 9.04 | 0.43 | 64.23 | 87.19 | 0.786 | Minor |
| WT-8 | 9.27 | 7.92 | 8.89 | 0.25 | 64.78 | 91.19 | 0.792 | Minor |
| WT-9 | 9.09 | 8.11 | 8.87 | 0.29 | 61.30 | 87.00 | 0.811 | Minor |
| WT-11 | 9.31 | 8.13 | 8.90 | 0.25 | 63.24 | 90.96 | 0.813 | Minor |
| WT-12 | 9.31 | 8.47 | 9.00 | 0.18 | 64.15 | 92.72 | 0.847 | Minor |
| WT-13 | 8.82 | 7.61 | 8.33 | 0.29 | 63.74 | 90.78 | 0.761 | Minor |
| WT-15 | 9.22 | 8.14 | 9.01 | 0.24 | 61.86 | 88.71 | 0.814 | Minor |
| WT-16 | 9.02 | 8.14 | 8.79 | 0.24 | 62.78 | 89.36 | 0.814 | Minor |
| WT-17 | 9.13 | 8.18 | 8.94 | 0.24 | 62.16 | 90.03 | 0.818 | Minor |
| WT-18 | 9.17 | 8.20 | 8.94 | 0.16 | 65.23 | 92.03 | 0.820 | Minor |
| WT-19 | 8.86 | 7.70 | 8.49 | 0.38 | 63.46 | 87.41 | 0.770 | Minor |
| WT-21 | 9.16 | 8.03 | 8.89 | 0.19 | 69.64 | 91.03 | 0.803 | Minor |

Even though 42 specimens were tested in this study some of the specimens were broken outside the gauge length. Therefore only the successful specimens were considered for this research study and their corroded surface measurements, experimental yield and tensile loads and corrosion level classification are shown in Table 2. There, the initial thickness($t_0$) of the flange specimens and web specimens are 10.5mm and 10.0 mm respectively.

## 4. Residual Strength Estimation

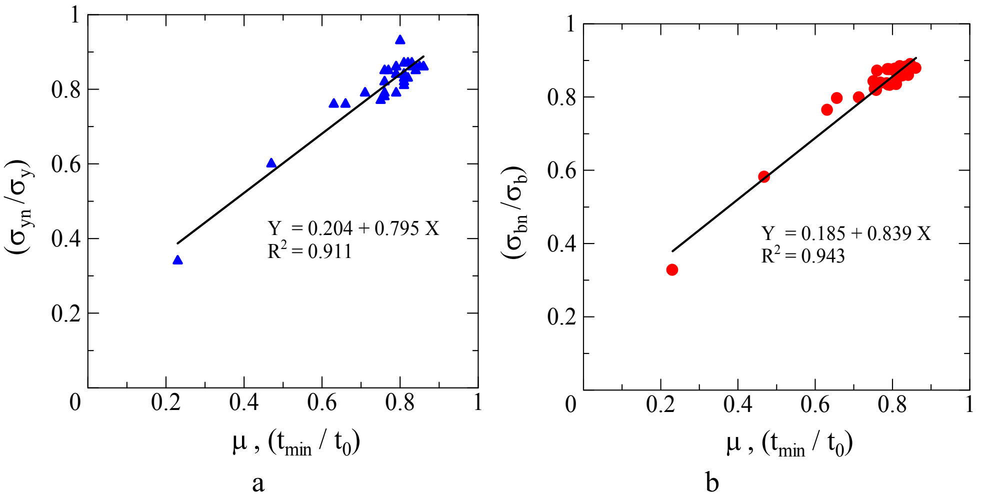
### 4.1 Estimation of Yield and Tensile Strength

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:

$$t_{e\_y} = \left( \frac{P_y}{B \cdot \sigma_y} \right) \tag{3}$$

$$t_{e\_b} = \left( \frac{P_b}{B \cdot \sigma_b} \right) \tag{4}$$

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.



a b

*Fig. 7. Relationship of (a) yield stress ratio, (b) tensile stress ratio and minimum thickness ratio (μ)*

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 measureable statistical parameters (such as average thickness $t_{avg}$, minimum thickness $t_{min}$, standard deviation of thickness $\sigma_{st}$ etc.) were examined and a better relationship was found with the minimum thickness. 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 condition of corrosion in the process of estimating remaining strength capacities.

The x-axis of Fig. 7 is the minimum thickness ratio (μ) and the y-axis shows the nominal stress ratio normalized by yield stress ($\sigma_{yn}/\sigma_y$) in Figure 7(a) and tensile stress ($\sigma_{bn}/\sigma_b$) in Figure 7(b) respectively. Figures 7(a) and 7(b) shows a good linear relationship between the minimum thickness ratio in both yield and tensile stress conditions. Also it is noted that an average unique relationship for both yield and tensile stress conditions can be obtained. From this relationship, a formula for representative effective thickness ($t_{eff}$) can be obtained as described below.

From Figure 7(a),

$$\frac{\sigma_{yn}}{\sigma_y} = 0.204 + 0.795\mu$$

$$t_{eff} = 0.204t_0 + 0.795t_{min} \tag{5}$$

In same way from Figure 7(b),

$$t_{eff} = 0.185t_0 + 0.839t_{min} \tag{6}$$

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 teff should be equal to $t_0$ as well, can be expressed as:

$$t_{eff} = \lambda t_0 + (1-\lambda)\ t_{min} \tag{7}$$

Considering both yield and tensile stress conditions, it was fount that the $\lambda$=0.2 gives the best agreement and hence the representative effective thickness parameter can be defined as:

$$t_{eff} = 0.2\ t_0 + 0.8\ t_{min} \tag{8}$$

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

$$t_{c,max} = t_0 - t_{min} \tag{9}$$

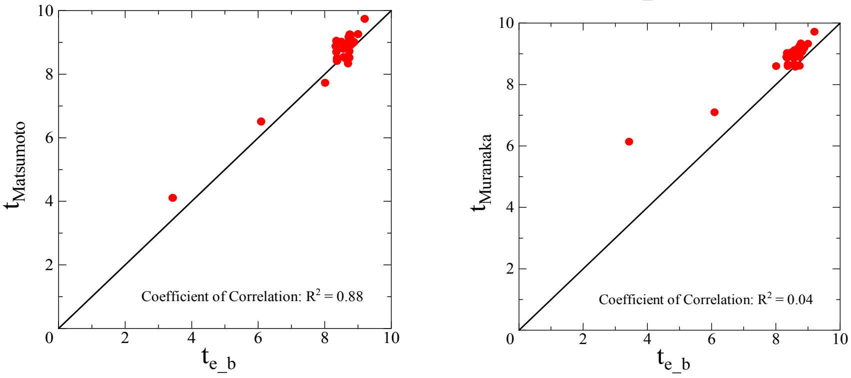
So, considering Eq. 8 and Eq. 9, the following relationship can be obtained for representative effective thickness (teff), which can be used to estimate the remaining yield and tensile strengths of a corroded steel plate.

$$t_{eff} = t_0 - 0.8\ t_{c,max} \tag{10}$$

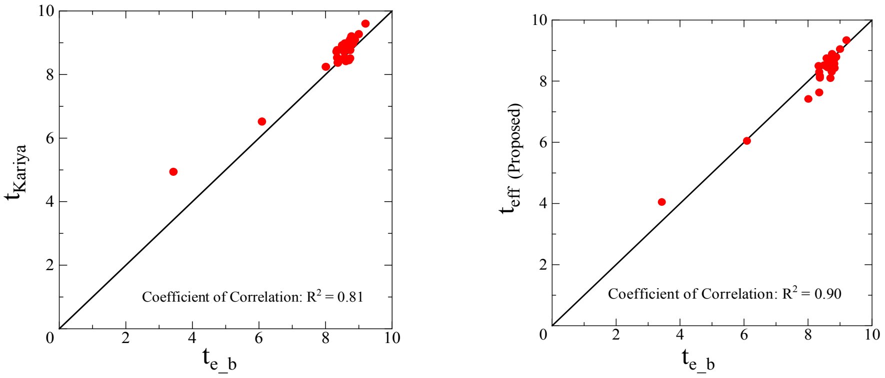
A further detailed study comprises with experimental and numerical analysis of more specimens with moderate and severe corrosion is deemed necessary to understand the significance of this λ value and verify this for different corrosion levels and environmental conditions.

### 4.2 Comparison of Proposed Effective Thickness

The experimentally predicted thickness (Eq. 3 and Eq. 4) and the representative thickness which were valued by different methods were examined and compared to understand the effectiveness of the proposed method of estimating the remaining strength capacities of corroded steel plates. The following Figure 8 shows the behavior of representative thickness, valued by different methods and the experimental tensile effective thickness ($t_{e\_b}$).



(a) Matsumoto *et al.* 1989 (b) Muranaka *et al.* 1998



(c) Kariya et al. 2003 (d) Proposed

*Figure 8: Relation between different predicted effective thickness parameters with* $t_{e\_b}$

Figure 8 shows that the strength estimations obtained by the effective thickness values proposed by all Matsumoto et al 1989, Muranaka et al 1998 and Kariya et al 2003 are rather overestimated. So, this could lead the corroded structures on risk as their actual remaining capacities are lesser than that of the predicted. But, the proposed method is much closer to the actual conditions.

*Table 3. Comparison of correlation coefficients of different representative thickness prediction methods*

| **Method** | | **Matsumoto *et al.* 1989** | **Muranaka *et al.* 1998** | **Kariya *et al.* 2003** | **Proposed, $t_{eff}$** |
|---|---|---|---|---|---|
| **Equation of thickness** | | $t_{sa}$ | $t_{avg} - 0.7\sigma_{st}$ | $t_{avg} - 1.3\sigma_{st}$ | $t_0$ - 0.8 $t_{c,max}$ |
| **Correlation Coefficient** | Yield | - | - | - | 0.89 |
| | Tensile | 0.88 | 0.04 | 0.81 | 0.90 |

The Table 3 shows the coefficient of correlation values of the available different methods and the proposed method of effective thickness in estimating remaining yield and tensile strengths. It clearly shows that the proposed effective thickness parameter gives more reliable and better prediction with the experimentally analyzed results than other available methods.

## 5. Conclusions

The 42 specimens taken out of the scrapped plate girder which had been used for about 100 years with severe corrosion, was used to perform the tensile tests to clarify the relationship between the representative effective thickness ($t_{eff}$) to estimate the mechanical properties of corroded plates and their level of corrosion. A representative effective thickness equation derived by using initial thickness and maximum corroded thickness (derived with minimum thickness) to estimate their remaining yield and tensile strengths is discussed from those experimental results.

The main conclusions are as follows:

1. The corrosion causes strength reduction of steel plates and minimum thickness ratio ($\mu$) can be used as a measure of the level of corrosion and their strength degradation. Therefore, three basic corrosion categories can be defined, Minor Corrosion ($\mu \geq 0.75$), Moderate Corrosion ($0.75 > \mu > 0.5$) and Severe Corrosion ($\mu \leq 0.5$) according to their severity of corrosion.
2. A representative effective thickness ($t_{eff}$), based on the initial thickness ($t_0$) and maximum corroded thickness ($t_{c,max}$) can be used to estimate the remaining yield and tensile strength of corroded steel plates. In estimation of both remaining yield strength and tensile strength, the proposed relationships revealed a good comparison with the experimental results and the derived equations are as follows:

$$t_{eff} = t_0 - 0.8\ t_{c,max}$$

As the proposed effective thickness equation has only a single variable, maximum corroded thickness ($t_{c,max}$), 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. Also it is necessary to note that the $t_{max}$ should be applied for very old bridges which $t_0$ could be unknown in very rare situations. Further this method is simple and gives more reliable and closer results compared to the other available methods.

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