Steel and Composite Structures, Vol. 12, No. 5 (2012) 379-393
DOI: http://dx.doi.org/10.12989/scs.2012.12.5.379

An enhanced method of predicting effective thickness of corroded steel plates

Tatsumasa Kaita[1], J.M. Ruwan S. Appuhamy[2], Mitao Ohga*[2] and Katashi Fujii[3]

[1]*Department of Civil Engineering & Architecture, Tokuyama College of Technology, Japan*
[2]*Department of Civil & Environmental Engineering, Ehime University, Japan*
[3]*Department of Social & Environmental Engineering, Hiroshima University, Japan*

(Received November 09, 2010, Revised February 22, 2012, Accepted February 27, 2012)

Abstract. Many steel bridge infrastructures in the world are getting older, and a large number of these structures are in need of maintenance, rehabilitation or replacement. Most of them are subjected to corrosion due to exposure to aggressive environmental conditions and inadequate maintenance, causing reduction of their carrying capacities. In order to have an adequate bridge management, it is of paramount importance to develop an efficient, accurate and rapid condition assessment method which can be used to make reliable decisions affecting the cost and safety. Therefore, a simple and accurate method of calculating remaining yield and tensile strength by using a concept of representative effective thickness with correlation of initial thickness and maximum corroded depth is proposed in this study, based on the results of many tensile coupon tests of corroded plates obtained from a steel plate girder with severe corrosion, used for about 100 years. Furthermore, a strength reduction diagram which will be very useful for bridge inspection engineers to make rational decisions about the maintenance management of aged steel bridge infrastructures is presented.

Keywords: bridge maintenance; corrosion; effective thickness; remaining strength; tensile test.

1. Introduction

Corrosion is one of the most important causes of deterioration of steel girder bridges and a major problem currently facing the transportation engineering community in the world. The results of this deterioration generally range from progressive weakening of a steel structure over a long time, to rapid structural failure. The consequence of corrosion is a reduction in member cross-sectional area and, in turn, strength; a reduction of carrying capacity and structural safety (Zahrai *et al.* 2003). It has been reported that more than 35% of steel bridges in the USA are structurally deficient because of structural degradations (Chen *et al.* 2009). Over the past few decades there have been many damage examples of older steel bridge structures due to corrosion around the world. The catastrophic collapses of the Silver Bridge (Point Pleasant, WV) in 1967 and the Mianus River Bridge (Connecticut) in 1983, USA (NSBA *et al.* 2006) indicated the paramount importance of attention to the condition of older bridges, leading to intensified inspection protocols and numerous eventual retrofits or replacements.

In recent years, damage due to corrosion is one of the major factors in repair, reinforcement and replacement of steel bridges (Natori *et al.* 2001 and Kitada *et al.* 2006). Since, corrosion will deteriorate

* Corresponding author, Professor, E-mail: oga.mitao.mj@ehime-u.ac.jp

the performance of steel structures with time and it's a very difficult task to retrofit or rebuild those aged bridges at the same time, careful evaluation of existing structures for the feasibility of current usage and estimate the necessity of retrofitting of some selected corroded members are essential. Therefore, understanding of the influence of damage due to corrosion on remaining load-carrying capacities is of high concern among the bridge maintenance engineers at present.

Further, the lack of information concerning the behavior of corroded web panels makes difficult the civil engineer's task of evaluating the deteriorated member. An in-depth study in front of serviceability and ultimate limit states is necessary to develop efficient techniques to evaluate the structural integrity and safety. The ultimate strength of existing steel railway bridges varies widely depending on their structural form and the degree of corrosion (Sugimoto *et al.* 2006). It has been pointed out that the corrosion can lead to cracking (fracture), yielding or buckling of members which can result in stress concentration, changes in geometric parameters and a build-up of the corrosion products. These parameters are critical for the member's ability to resist load effects (Sharifi *et al.* 2010). Furthermore, it is known that the corrosion wastage and stress concentration caused by the surface irregularity of corroded steel plates influence the remaining strength of corroded steel plates (Kariya *et al.* 2005). Therefore, evaluation of the effect of different forms of corrosion to the remaining strength capacities of existing structures is a vital task for maintenance management of steel highway and railway infrastructures.

Literature review reveals that quite a few numbers of experimental loading tests were carried out in past few years, in order to investigate the remaining strength of corroded tensile plates. Namely, Matsumoto *et al.* (1989) investigated the tensile strength, using tensile coupons with corrosion. They predict the remaining tensile strength of corroded plates, using minimum value of average thickness (t_{sa}) of the cross section perpendicular to the loading axis as a representative thickness. Furthermore, Bruneau *et al.* (1997) and Zahrai *et al.* (2003) conducted some tensile and cyclic tests of corroded specimens to investigate the non-cyclic ductility, cyclic ductility and hysteretic energy dissipation capacity of structural steel. They too proposed that minimum average thickness would be a good parameter to estimate remaining tensile strength. 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. Furthermore, Khedmati *et al.* (2011) conducted many FEM analyses and proposed an effective thickness parameter with a correlation of average thickness and standard deviation of thickness, to estimate the ultimate strength and post buckling behavior of randomly corroded steel plates under uniaxial compression. Thus, it is very clear that, many researchers usually use representative thickness based on several statistical parameters to estimate the remaining strength of corroded steel members.

2. Objective

It was noticed that the widths of above mentioned test specimens are very small (less than 30 mm). But, during the preliminary investigation it was found that many corrosion pits with more than 30 mm 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, 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 actual size of 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, all above described representative thickness methods 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, 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, it will be a tough task for the bridge maintenance engineers to attend on detail investigations for all these structures in regular basis. But, it is necessary to assure the safety of these structures and determine the necessary maintenance regularly. Therefore, a simple and more accurate method to predict their remaining yield and tensile strength capacities with easily measurable statistical thickness parameters, such as: initial thickness (t_0) and the maximum corroded depth ($t_{c,max}$), is proposed and compared with the other available remaining strength estimation methods.

3. Corroded test specimens

3.1 Test specimen configuration and material properties

A steel girder from the Ananai River Bridge in Kochi prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years, was used for this experimental study. 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. All plate girders were constructed by rivet joints and were exposed to high airborne salt environment by strong sea wind for a long time. 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 = 10.5 mm) and web plate (initial thickness = 10.0 mm) respectively.

Before conducting the thickness measurements, all rusts over both surfaces were removed carefully by using electric wire brushes and punches. Then, two new SM490A plates (t = 16 mm) were jointed to both sides of specimen by the butt full penetration welding for grip parts to loading machine, as shown in Fig. 1. Here, the flange and web specimens have the widths ranged from 70-80 mm and 170-180 mm respectively. In addition, 4 corrosion-free specimens (JIS5 type) were made of each two from flange and web, and then 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.

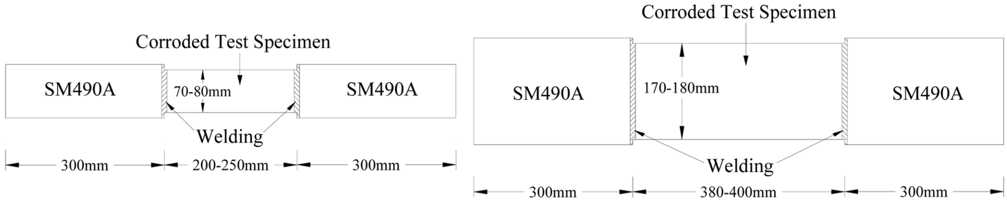

Fig. 1 Dimensions of test specimens

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	-

3.2 Measurement of corrosion surface

Accuracy and convenience are highly demanded in the measurement of corroded 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 test specimens (Kaita *et al.* 2005). Before the measurement, a global coordinate system with an original point was setup. The advantage of this device is the coordinate values of an arbitrary surface point can be easily given by using the coordinate system set up initially, even though the device is moved to another position from its initial position.

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 Fig. 2. Since this probe irradiates the steel surface with a laser beam, which has about 100 mm width, the large number of 3-dimensional coordinate data can be obtained easily at a time. 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 0.5 mm 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. Then, 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 the measurement results.

Fig. 2 Condition of thickness measurement

4. Tensile test of corroded specimens

4.1 Classification of corrosion sates

It is necessary to categorize the different corrosion conditions which can be seen in actual steel structures, into few general types for better understanding of their remaining strength capacities considering their visual distinctiveness and the features of histograms, amount of corrosion and their expected mechanical and ultimate behaviors. Fig. 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

$$\mu = \frac{t_{min}}{t_0} \tag{1}$$

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

Further, Fig. 4 shows three tensile test specimens with above three classified corrosion types. In minor corrosion type, it can be seen that many small corrosion pits were spread on all over the plate surface and an example of this corrosion type (F-14) is shown in Fig. 4(a). When the corrosion is more progressed, the moderate corrosion type can be seen where few considerable corroded pits exist in some places. An example of this corrosion type (F-13) is shown in Fig. 4(b). Further, as the corrosion is more progressed than the moderate corrosion condition, 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 25 mm) on the member. One example of severe corrosion type (F-19) is shown in Fig. 4(c). The Table 2 shows the corroded surface measurement data and the classification of each specimen

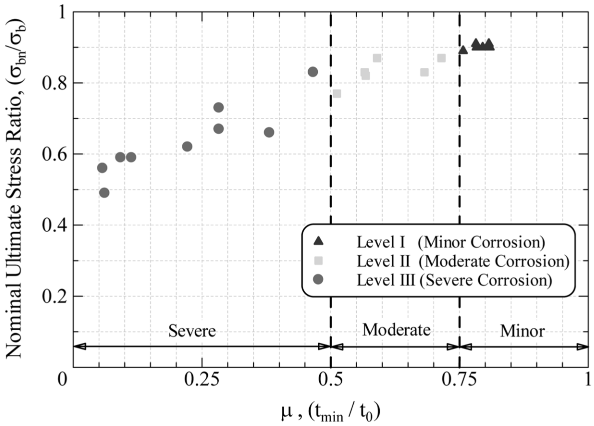

Fig. 3 Relationship of ultimate stress ratio & minimum thickness ratio (μ)

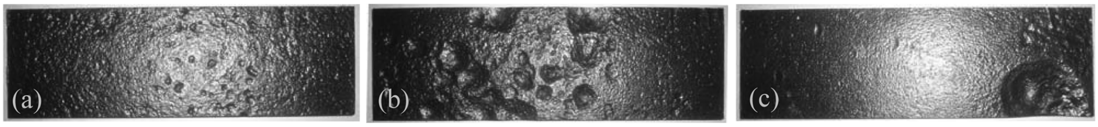

Fig. 4 Plates with (a) minor corrosion (F-14), (b) moderate corrosion (F-13) and (c) severe corrosion (F-19)

Table 2 Measurement, experimental results and categorization of specimens

Member	t_{avg} (mm)	t_{min} (mm)	t_{sa} (mm)	σ_{st} (mm)	Experimantal results		μ (t_{min}/t_0)	Corrosion type
					P_y (kN)	P_b (kN)		
F-1	9.06	2.98	7.95	1.14	167.24	224.26	0.283	Severe
F-2*	10.08	6.81	9.84	0.24	-	-	0.648	Moderate
F-3	9.27	5.97	8.45	0.69	186.81	289.32	0.568	Moderate
F-4*	10.07	7.34	9.65	0.23	-	-	0.699	Moderate
F-5	7.78	1.19	7.13	1.31	143.59	196.53	0.113	Severe
F-6	9.55	7.16	9.30	0.42	196.60	288.60	0.682	Moderate
F-7	9.87	7.51	9.58	0.40	204.40	306.00	0.715	Moderate
F-8	10.22	8.49	9.97	0.24	213.60	319.60	0.809	Minor
F-9	9.92	4.90	9.25	0.59	194.60	294.40	0.466	Severe
F-10*	6.72	0.00	3.81	2.36	-	-	0.000	Severe
F-11	8.05	0.96	6.97	1.55	147.24	203.78	0.092	Severe
F-12	9.25	2.97	8.29	0.75	178.20	247.60	0.283	Severe
F-13	9.70	5.38	8.48	0.71	192.79	273.54	0.512	Moderate
F-14	10.09	8.22	9.92	0.25	210.20	319.00	0.783	Minor
F-15	9.21	4.00	7.74	1.01	152.52	225.00	0.381	Severe
F-16	10.06	6.20	9.12	0.36	206.20	306.40	0.590	Moderate
F-17	9.17	2.33	7.27	1.44	154.90	219.00	0.222	Severe
F-18	8.59	0.60	6.67	1.41	137.49	190.26	0.057	Severe
F-19	9.51	0.64	6.95	1.57	160.40	174.20	0.061	Severe
F-20*	7.08	0.45	4.89	1.86	-	-	0.043	Severe
F-21	10.09	8.22	9.69	0.25	215.50	321.40	0.782	Minor
W-1	9.51	5.66	9.00	0.41	477.00	671.50	0.566	Moderate
W-2	9.57	7.95	9.43	0.24	487.50	727.50	0.795	Minor
W-3	9.64	8.07	9.45	0.21	497.69	735.69	0.807	Minor
W-4	9.38	7.57	9.22	0.23	496.00	719.50	0.757	Minor
W-5*	9.50	7.38	9.15	0.31	-	-	0.738	Moderate

*Breaking section is out of gauge length/ test is not successful

according to the level of corrosion.

The Fig. 5 shows the thickness histograms of three members which are classified in to the above mentioned corrosion categories. There, the significance of these three corrosion categories can be

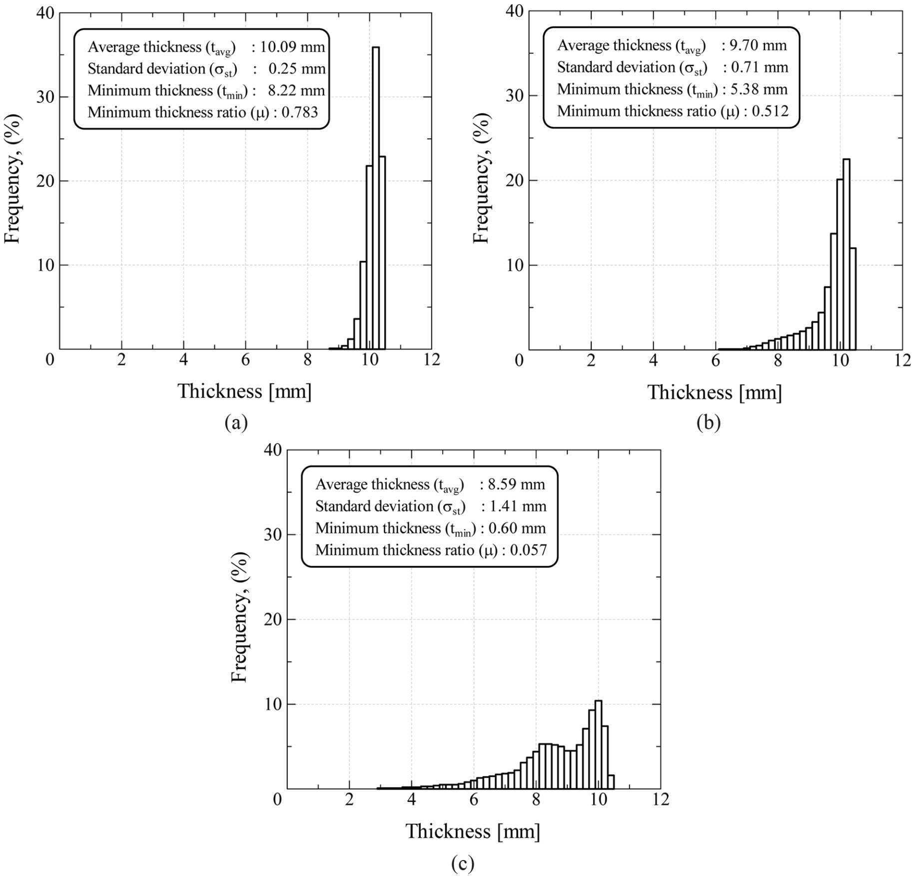

Fig. 5 Thickness histograms of (a) minor corrosion type (F-14), (b) moderate corrosion type (F-13) and (c) severe corrosion type (F-18)

recognized from the features of those thickness histograms as well. Fig. 5(a) shows 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 Fig. 5(b), it can be seen that the thickness distribution of the moderate corrosion specimen is larger than that of the minor corrosion members and the peak of thickness histogram is not same as the average thickness of the member. Usually in severe corroded members, few peaks of the thickness histogram can be seen as shown in Fig. 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.

4.2 Experimental setup and loading conditions

Tensile loading tests were carried out at constant velocity under loading control by using a hydraulic loading test machine (maximum load: 2940 kN) for all 26 specimens with different corrosion conditions. Fig. 6(a) shows the loading machine used for this experimental analysis. The loading velocity was set to 200 N/sec for minor corroded specimens and 150 N/sec for moderate and severe

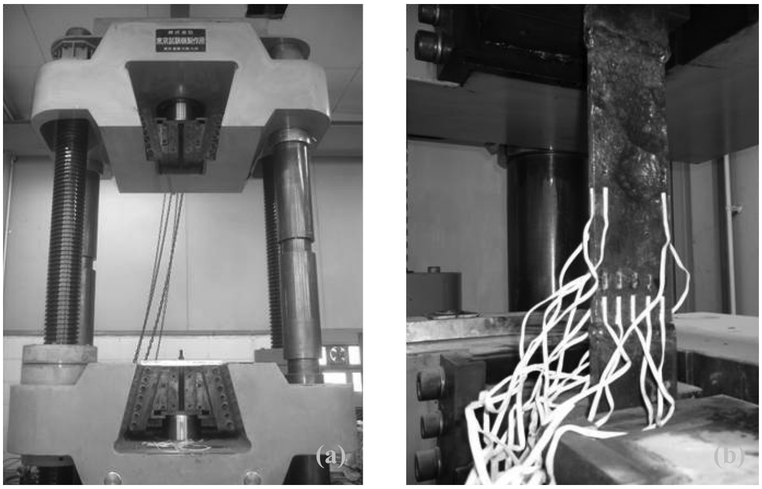

Fig. 6 (a) Loading test machine and (b) specimen prepared for the tensile test

corroded specimens.

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 Fig. 6(b). 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.

4.3 Experimental results and discussion

Fig. 7 shows the load-elongation curves for three different corroded specimens with 3 corrosion types. 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 severe corroded specimen (F-19) show

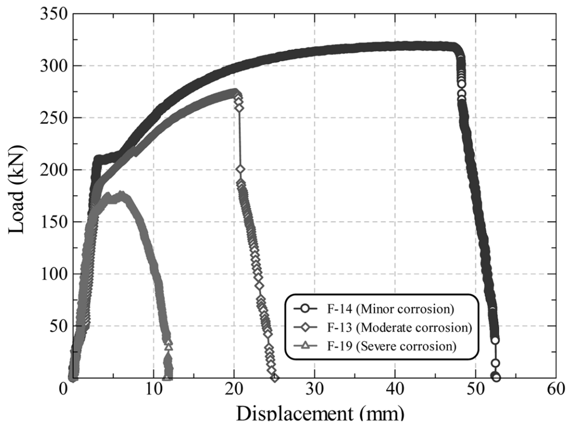

Fig. 7 Load-displacement curves

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 the breaking point.

Even though the relation between the breaking section and the thickness distribution is not exactly clarified yet, it can be seen that most of minor corrosion members are failed in a section corresponds to a minimum thickness point (t_{min}) or a minimum average thickness point (t_{sa}) for the members with the thickness variation is very small. Also, it was noted that the breaking point of moderate and severe corrosion members are corresponds to a section of the minimum thickness point. The breaking states of severe corroded specimen (F-1) are shown in Fig. 8. It can be seen in Fig. 8(a), crack occurred at the minimum thickness point (left side of specimen). Further it was noticed that, when this crack initiation happens, the specimen has reached to its maximum remaining strength, and then the load will begin to decrease rapidly. The progression of the crack can be seen to the right angle direction of load axis as shown in Fig. 8(b) and Fig. 8(c), depending on the surface irregularities. Therefore, these facts revealed the importance of identifying the breaking trigger point from thickness measurement results for more accurate tensile strength estimation method in order to apply for the maintenance management of actual steel structures.

5. Remaining strength estimation

The two basic definitions of the experimental effective thickness (t^*_{eff}) for the yield and tensile strength estimations can be expressed as follows

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

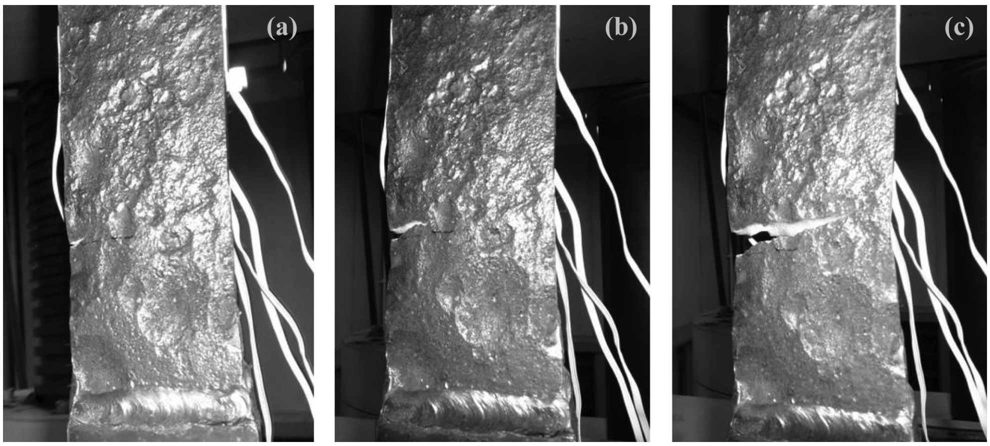

Fig. 8 (a) Crack initiation; (b) and (c) propagation of the crack

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 stresses 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: minimum thickness, average thickness, minimum average thickness and standard deviation of thickness etc.) with a high correlation with the experimental effective thickness will be essential for remaining strength estimation of those structures. Therefore, in this study, more attention was paid on developing a simple, accurate and brisk assessment method to estimate the remaining strength capacities of steel bridge structures.

5.1 Estimation of yield and tensile strengths

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 condition of corrosion in the process of estimating remaining strength capacities. Fig. 9(a) and Fig. 9(b) show the relationships obtained for yield and tensile stress conditions. 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 Fig. 9(a)

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

$$t_{eff} = 0.631\ t_0 + 0.372\ t_{min} \tag{3}$$

In same way from Fig. 9(b)

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

$$t_{eff} = 0.531\ t_0 + 0.483\ t_{min} \tag{4}$$

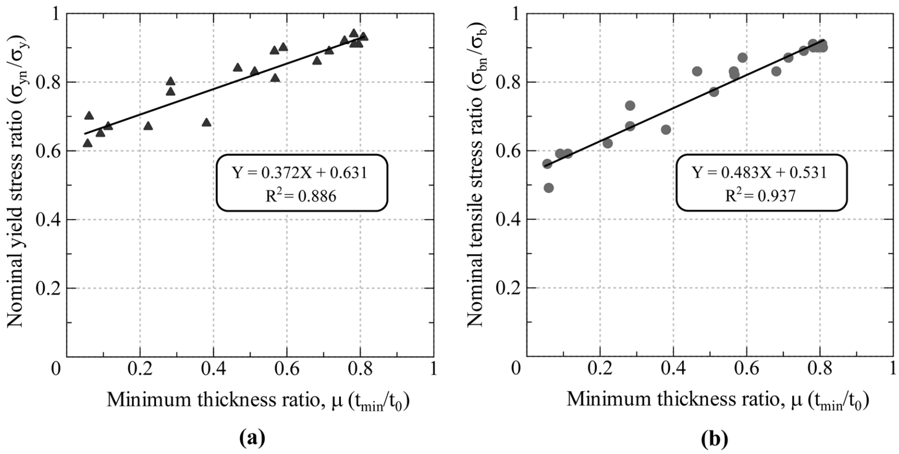

Fig. 9 Relationship of (a) yield stress ratio, (b) tensile stress ratio and minimum thickness ratio (μ)

It can be seen that both Eqs. (3) and (4) have a negligible error (0.003 and 0.014 in yield and tensile states respectively) in satisfying the non corrosion condition, which may be caused due to the unavoidable experimental deficiencies. 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

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

Fig. 10 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

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

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

$$t_{c,\,max} = t_0 - t_{min} \tag{7}$$

Therefore, considering Eqs. (6) and (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.

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

Since the proposed effective thickness equations have only a single variable, maximum corroded

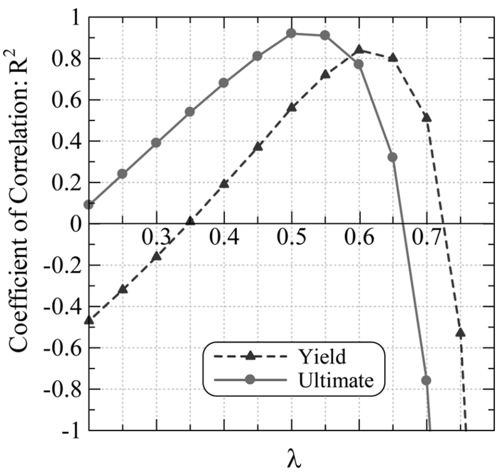

Fig. 10 Estimation of coefficient, λ

depth ($t_{c,max}$), 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 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 measureable thickness measurements.

5.2 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 (Eq. (2)) to understand the effectiveness of the proposed method of estimating remaining strength capacities for corroded steel plates. Fig. 11 shows the behavior of representative thickness, valued by different methods and the experimental tensile effective thickness (t^*_{eff}).

It can be seen from Figs. 11(a), 11(b) and 11(c), that the strength estimations obtained by the effective thickness values proposed by all available methods (Matsumoto *et al.* 1989, Muranaka *et al.* 1998 and

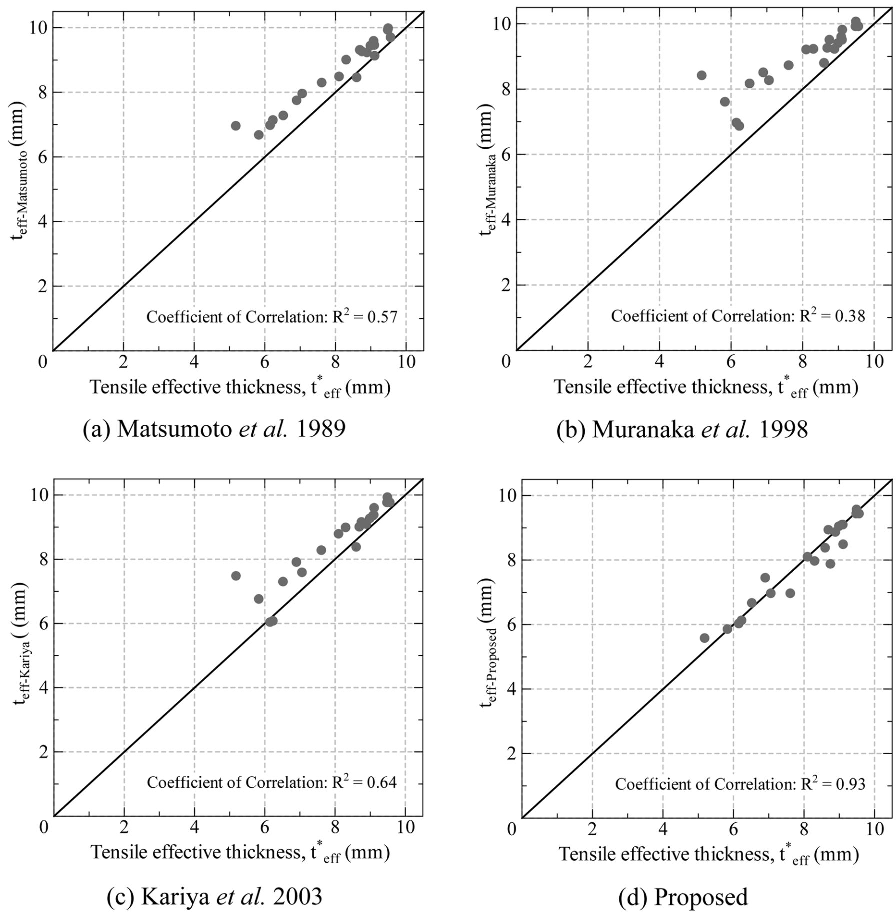

Fig. 11 Relation between different predicted effective thickness parameters with t^*_{eff}

Table 3 Comparison of correlation coefficients of different effective thickness prediction methods

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

Kariya *et al.* 2003) give rather overestimated result. One reason for this can be the all available methods are based on average thickness (t_{avg}) of the corroded surface and it was found that t_{avg} tends to become larger than effective thickness, as the influence of stress concentration due to corrosion will not be able to consider carefully. Therefore, use of those effective thickness estimations could lead the corroded structures on risk regarding the decision taken on their maintenance management plan, as their actual remaining strength capacities are lesser than that of the predicted. But, as it can be seen from Fig. 11(d), the proposed effective thickness gives more accurate and better remaining strength estimation. Further, the Table 3 shows the coefficient of correlation values of available different methods and the proposed effective thickness estimation method, which can be used to estimate the remaining yield and tensile strengths of corroded steel plates. It clearly shows that the proposed effective thickness parameter gives more reliable and better prediction with the experimentally analyzed results than other available methods.

5.3 Strength reduction diagram

Current assessment methods of corrosion damaged steelwork involve visual inspection which tends to be used very conservatively. Basically, regular inspections have significant influence on the load capacity rating, the remaining fatigue life evaluation, on reliable and safe transportation, and on the development of meaningful short and long-term recommendations for the continuing health of bridges. Therefore use of reliable '*strength reduction diagram*' will be very useful to bridge inspection engineers in rapid assessment of corroded steel bridge structures and to plan the required retrofitting or replacements to be conducted immediately. Here, the percentage strength reduction [SR (%)] can be calculated as

$$SR(\%) = \left(1 - \frac{t_{eff}}{t_0}\right)100 \tag{9}$$

By considering the Eq. 9 for the tensile strength, the SR (%) can be expressed as

$$SR(\%) = 50(1 - \mu) \tag{10}$$

Fig. 12(a) shows the relation between proposed tensile effective thickness and the minimum thickness ratio (μ) for three different initial thickness values; $t_0 = 10.0$ mm, 10.5 mm and 11.0 mm respectively. Further, Fig. 12(b) shows the relationship between the percentage tensile strength reduction and minimum thickness ratio (μ). There, the significance of the corrosion levels and the percentage reduction of tensile strength of corroded steel members can be clearly identified as

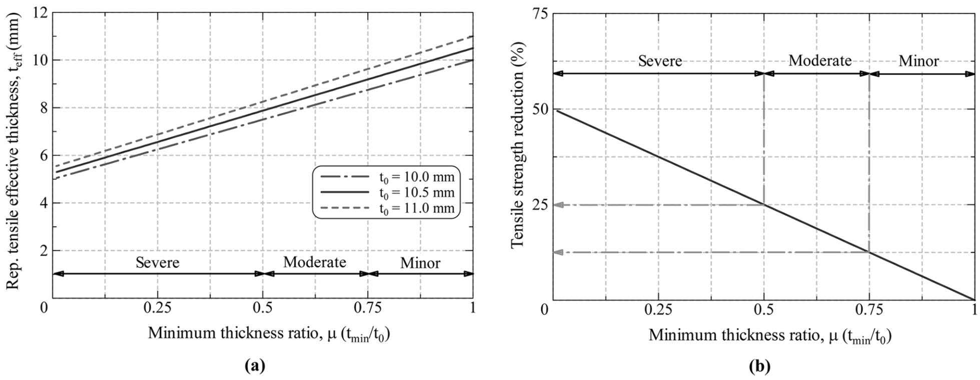

Fig. 12 Relationship of (a) representative tensile effective thickness (teff), (b) tensile strength reduction and minimum thickness ratio (μ)

SR(%) < 12.5	; Minor Corrosion
12.5 ≤ SR(%) ≤ 25	; Moderate Corrosion
SR(%) > 25	; Severe Corrosion

Since the strength reduction diagram Fig. 12(b) gives a good indication about the percentage tensile strength reduction according to the severity of corrosion, the bridge engineers would be able to decide whether the infrastructure requires any initial corrosion prevention precautions such as painting etc., or retrofitting of some selected members or replacement of some critical members in order to assure the adequate safety of the existing structure.

6. Conclusions

The steel surface measurements and tensile tests were conducted on many wide specimens taken out of the scrapped plate girder which had been used for about 100 years with severe corrosion to clarify the relationship between the representative effective thickness (t_{eff}) which can be used to estimate the mechanical properties of corroded plates and their level of corrosion. The main conclusions of this study can be summarized as

(1) The remaining yield and tensile strengths of corroded steel plates can be estimated by using the representative effective thickness defined as

$$t_{eff} = \begin{cases} t_0 - 0.4t_{c,\,max} & \text{; Yield strength} \\ t_0 - 0.5t_{c,\,max} & \text{; Tensile strength} \end{cases}$$ with high accuracy.

(2) The three classified corrosion categories give a good indication about their percentage tensile strength reduction, whereas: minor corrosion; SR(%) < 12.5, moderate corrosion; 12.5 ≤ SR(%) ≤ 25 and severe corrosion; SR(%) > 25 respectively.

(3) Minimum thickness ratio (μ), which is an easily measurable parameter, can be used as a measure of the level of corrosion and their strength degradation.

Further, the proposed strength estimation method is simple and gives more reliable and better results compared to the other available methods.

Acknowledgements

The authors would like to thank the technical staffs of Mitutoyo Corporation (Japan) for their assistance in surface measurement of corroded specimens and Mr. Y. Tanabe, Mr. H. Ikeda and Mr. K. Itogawa for their support extended during the experimental work.

References

Bruneau, M. and Zahrai, S.M. (1997), "Effect of severe corrosion on cyclic ductility of steel", *J. Struct. Eng.*, **123**(11), 1478-1486.

Chen, M. and Das, S. (2009), "Experimental study on repair of corroded steel beam using CFRP", *Steel. Compos. Struct.*, **9**(2), 103-118.

Kaita, T., Fuji, K., Miyashita, M., Uenoya, M., Okumura, M. and Nakamura, H. (2005), "A simple estimation method of bending strength for corroded plate girder", *Collaboration and Harmonization in Creative Systems*, **1**, 89-97.

Kariya, A., Tagaya, K., Kaita, T. and Fujii, K. (2003), "Basic study on effective thickness of corroded steel plate and material property", *Annual conference of JSCE*, 967-968. (In Japanese)

Kariya, A., Tagaya, K., Kaita, T. and Fujii, K. (2005), "Mechanical properties of corroded steel plate under tensile force", *Proceedings of the 3rd International Structural Engineering and Construction Conference (ISEC-03)*, Japan, 105-110.

Khedmati, M.R., Nouri, Z.H.M.E. and Roshanali, M.M. (2011), "An effective proposal for strength evaluation of steel plates randomly corroded on both sides under uniaxial compression', *Steel. Compos. Struct.*, **11**(3), 183-205.

Kitada, T. (2006), "Considerations on recent trends in, and future prospects of, steel bridge construction in Japan", *J. Constr. Steel. Res.*, **62**, 1192-1198.

Matsumoto, M., Shirai, Y., Nakamura, I. and Shiraishi, N. (1989), "A proposal of effective thickness estimation method of corroded steel member", *Bridge Foundation Engineering,* **23**(12), 19-25. (In Japanese)

Muranaka, A., Minata, O. and Fujii, K. (1998), "Estimation of residual strength and surface irregularity of the corroded steel plates", *J. Struct. Eng.*, **44A**, 1063-1071. (In Japanese)

Natori, T., Nishikawa, K., Murakoshi, J. and Ohno, T. (2001), "Study on characteristics of corrosion damages in steel bridge members", *J. Struct. Mech. and Earthq. Eng.*, **668**(54), 299-311. (In Japanese)

NSBA. (2006), "Corrosion protection of steel bridges", *Steel Bridge Design Handbook*, Chapter 23, National Steel Bridge Alliance.

Sharifi, Y. and Rahgozar, R. (2010), "Remaining moment capacity of corroded steel beams", *Int. J. Steel. Struct.*, **10**(2), 165-176.

Sugimoto, I., Kobayashi, Y. and Ichikawa, A. (2006), "Durability evaluation based on buckling characteristics of corroded steel deck girders", *QR of RTRI*, **47**(3), 150-155.

Zahrai, S.M. (2003), "Cyclic strength and ductility of rusted steel members", *Asian J. Civil. Eng.*, **4**(2-4), 135-148.

CC