Analytical Study on Significance of Corroded Surface Measurement on Residual Strength Prediction

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Abstract

The maintenance and safety of the existing bridges is an important concern of all highway and railroads. To assure adequate safety and determine the ongoing maintenance needs, thorough regular inspections are required. These inspections should form the essential source of information for carrying out a comprehensive evaluation of its current capacity. But 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. Most of these structures are subjected to corrosion due to environmental exposure which can reduce their carrying capacities. So, there is a need of more brisk and accurate assessment method which can be used to make reliable decisions affecting the cost and safety.

In modern practices, numerical simulation is being used to replace the time-consuming and expensive experimental work and to comprehend on the lack of knowledge of mechanical behavior, stress distribution, ultimate behavior and so on. Therefore, using of numerical analysis method will give important knowledge not only for the strength estimation but also for subsequent repair and retrofitting plan. This paper presents the results of non-linear FEM analyses and compares them with their respective tensile tests of corroded plates which are obtained from a steel plate girder used for about 100 years with severe corrosion condition. Further, the effect of number of measuring points on the remaining strength estimation is studied to establish an analytical methodology to predict the residual strength capacities of a corroded steel member by measuring lesser number of points with an acceptable accuracy level.

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1. INTRODUCTION

In Japan, many bridges were intensively constructed in the 1960s–80s, during the period of high economic growth, with the number of bridges constructed per year decreasing recently to half of the overall peak. More specifically, the steel bridge industry reached the golden age in the latter half of the 1960s. Recently, it is observed that various kinds of damage have occurred to many bridges mainly constructed in the 1960s. Nowadays, many existing steel bridges exhibit some form of deterioration, such as the corrosion of steel members, fatigue cracks in RC slabs, steel decks and steel members due to the passage of many overweight vehicles, much heavier than those specified in the 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 (LCC). As a result, many bridges require substantial strengthening and repair works. Instead of the construction of large and long-span bridges, the retrofitting, strengthening, repair and maintenance of existing steel bridges already constructed will take an increasingly important part of the future steel bridge market in Japan. But, it is very difficult to retrofit or rebuild those aged or damaged bridges at the same time. Therefore, it is important to 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.

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 steel plates. But, to develop a more reliable strength estimation technique, only experimental approach is not enough as actual corroded surfaces are different from each other. Further, performing of experimental analyses for each and every aged bridge structure is not possible due to the time and economic constraints. Therefore, nowadays, use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry.

Further, it is not easy to measure several thousands of points, to accurately reproduce the corroded surface by numerical methods and to predict the behavior of that corroded member with more precisely. Therefore, study the effect of corroded surface data measurement intensity on their present load carrying capacities and investigation of the possibility of establishing 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 would be a vital task for the maintenance management of steel highway and railway infrastructures.

2. CORROSION LEVEL CLASSIFICATION

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, amount of corrosion and their expected mechanical and ultimate behaviors. In this study, 42 specimens (21 each from flange and web; denoted as FT and WT respectively) cut out from a steel bridge girder of Ananai River in Kochi Prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years. Then the thicknesses of all scratched specimens were measured by using a laser displacement gauge and the tensile tests were performed in order to clarify their remaining strength capacities.
The Figure 1 shows the relationship between the nominal ultimate stress ratio \( \frac{\sigma_{bn}}{\sigma_b} \) 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:

\[
\mu = \frac{t_{\text{min}}}{t_0}
\]

There, the initial thickness \( t_0 \) of the flange specimens and web specimens are 10.5mm and 10.0 mm 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

3. NUMERICAL INVESTIGATION

3.1. Analytical Model

The 3D isoparametric hexahedral solid element with eight nodal points (HX8M) and updated Lagrangian method based on incremental theory were adopted in these analyses. Non linear elastic-plastic material, Newton-Raphson flow rule and Von Mises yield criterion were assumed for material properties. Further, an automatic incremental -iterative solution procedure was performed until they reached to the pre-defined termination limit.
The analytical models with length and width dimensions of 70mm x 25mm (Figure 2) were modeled with different corrosion conditions for respective specimens. One edge of the member’s translation in X, Y and Z directions were fixed and only the Y and Z direction translations of the other edge (loading edge) were fixed to simulate with the actual experimental condition. Then the uniform incremental displacements were applied to the loading edge as shown in Figure 2. Yield stress $\sigma_y = 299.9$ [MPa], Elastic modulus $E = 195.8$ [GPa], Poisson’s ratio $\nu = 0.278$ were applied to all analytical models, respectively.

3.2. Ductile Fracture Criterion

The “Stress Modified Critical Strain Model (SMCS)” was proposed by Kavinde et al. (2006), to evaluate the initiation of ductile fracture as a function of multiaxial plastic strains and stresses. This method was adopted in this analytical study. In SMCS criterion, the critical plastic strain ($\varepsilon_{p,\text{Critical}}$) is determined by the following expression:

$$\varepsilon_{p,\text{Critical}} = \alpha \cdot \exp \left(-1.5 \frac{\sigma_m}{\sigma_e} \right)$$

(2)

where, $\alpha$ is toughness index and the stress triaxiality $T = (\sigma_m / \sigma_e)$, a ratio of the mean or hydrostatic stress ($\sigma_m$) and the effective or von Mises stress ($\sigma_e$). The toughness index $\alpha$ is a fundamental material property and hence obtained from the tensile test conducted for the non corroded specimen and obtained as follows:
\[ \alpha = \frac{\varepsilon_{\text{Critical}}}{\text{Exp}( -1.5 \frac{\sigma_{m}}{\sigma_e})} \]  

The ultimate strength of each corroded specimen was calculated accordingly by using the SMCS criterion and compared with their experimental ultimate capacities to understand the feasibility of the numerical modeling approach for remaining strength estimation of corroded steel plates with different corrosion conditions.

### 3.3. Analytical Results

The yield and ultimate strength in analytical prediction was estimated and compared with that of the experimentally obtained values to evaluate the accuracy of the used analytical model. The percentage error in yield and tensile strength in analytical predictions are calculated respectively as follows:

\[ \% \text{ Error in } P_y = \frac{P_y[\text{Analytical}] - P_y[\text{Experimental}]}{P_y[\text{Experimental}]} \cdot 100 \]  

\[ \% \text{ Error in } P_b = \frac{P_b[\text{Analytical}] - P_b[\text{Experimental}]}{P_b[\text{Experimental}]} \cdot 100 \]

Non corroded specimen was modeled at first, with the above described modeling and analytical features to understand the accuracy of the procedure adopted. It was found that the analytical model results were almost same as the experimental results with having a negligible percentage error of 0.03% and 0.02% in yield and tensile strength respectively. Then, all other experimentally successful specimens were modeled accordingly and their yield and ultimate strengths were compared with the experimentally obtained values.

The Figure 3(a) shows a very good comparison of experimental and analytical load-elongation behaviors for all three classified corrosion types. Here, the percentage errors in yield and tensile strength predictions
of the analytical models of three corrosion types are 2.11% and 0.56% in FT-22, 0.84% and 0.49% in FT-18 and 0.19% and 4.48% in FT-15 respectively. Further, the Figure 3(b) shows the comparison of ultimate load capacities of all specimens in experimental and numerical analyses. Having a coefficient of correlation of $R^2 = 0.963$ indicate the accuracy and the possibility of numerical investigation method to predict the tensile strength of actual corroded specimens.

4. EFFECT OF CORRODED SURFACE MEASUREMENT INTENSITY

Even though, it is an exigent task to conduct detail investigations of all existing steel structures as the number of steel structures are steadily increasing in the world, it is necessary to assess those structures in regular basis to ensure their safety and determine necessary maintenance. Hence, development of an accurate and brisk method of evaluating remaining strength capacities of existing steel structures is an imperative task in bridge maintenance engineering.

4.1. Analytical Models

The 6 different finite element models, as shown in Figure 4 were modeled and analyzed for each corroded specimen and compared them with the results of Model 1 with 1mm mesh data to understand the effect of corroded surface data intensity with their remaining yield and tensile strength capacities. Total measuring points of 1846, 504, 90, 32, 18 and 8 are consist of the Models 1, 2, 3, 4, 5 and 6 respectively. The same modeling features and analytical procedure as described in chapter 3 were adopted.

4.2. Analytical Results and Discussion

Non-linear finite element analyses were performed for all six models of minor, moderate and severe corroded specimens and their load-elongation behaviors, yield and tensile load capacities and ultimate
behaviors were compared with the 1mm model to understand the effect of coarseness of the surface measurement.

Figure 5: Comparison of load-elongation curves of different models: (a) minor corrosion member FT-22, (b) moderate corrosion member FT-18 and (c) severe corrosion member FT-15

Figure 6: Stress distributions of different models of three corroded specimens at ultimate load
The Figure 5 shows the load-elongation behavior of three specimens, FT-22, FT-18 and FT-15 with different no of measuring points. It can be seen that the load-elongation behavior is almost same in all models [Figure 5(a)], irrespective of the intensity of corroded surface measurement for minor corrosion members. But, Figure 5(b) and Figure 5(c) show that the load-elongation behaviors are affected by the coarseness of the measuring points for moderate and severe corrosion members. The Figure 6 shows the ultimate stress distribution of different models of three members FT-22, FT-18 and FT-15 with minor, moderate and severe corrosion conditions respectively. It shows that, even though the stress distributions and the stress concentration effects are almost same in minor corrosion specimen models, it significantly varies in models with lesser no of measuring points of moderate and severe corroded specimens. Further, the Table 1 shows the yield and tensile strength estimations of different models of those specimens and it shows that the data intensity for minor corrosion members is not very significant for their remaining strength estimation. This fact can be comprehended as the overall amount of corrosion or the corrosion attack for a particular location is very small in minor corrosion members. But, it can be noted that the percentage errors in both yield and tensile strength estimations are increased with the reduction of the intensity of corroded surface measurement points in moderate and severe corrosion members. The reason for this could be the missing of the maximum corroded location or some severe corroded portions during this kind of regular data measurement. So the effect of stress concentration will diminish in some of the models considered in this study, which are having smaller number of measuring points. So the remaining strengths are over estimated with the increase of coarseness of the data measurement, and this could lead the infrastructure in danger with decision taken regarding its maintenance management plan.

### Table 1: Yield and tensile strength predictions of different analytical models

| Model No | Yield Load, $P_y$/(kN) | Tensile Load, $P_b$/(kN) |
|----------|------------------------|-------------------------|
|          | FT-22                  | FT-18                  | FT-15                  | FT-22                  | FT-18                  | FT-15                  |
| 1        | 69.18 (-)              | 60.35 (-)              | 47.18 (-)              | 93.43 (-)              | 83.23 (-)              | 66.49 (-)              |
| 2        | 69.25 (0.10%)          | 60.09 (0.43%)          | 47.48 (0.63%)          | 93.24 (0.20%)          | 82.77 (0.55%)          | 65.69 (1.20%)          |
| 3        | 68.88 (0.43%)          | 60.71 (0.60%)          | 46.63 (1.16%)          | 93.09 (0.37%)          | 82.60 (0.75%)          | 67.36 (1.32%)          |
| 4        | 69.27 (0.13%)          | 61.73 (2.29%)          | 46.36 (1.74%)          | 93.44 (0.00%)          | 82.34 (1.06%)          | 67.85 (2.06%)          |
| 5        | 69.18 (0.00%)          | 62.47 (3.51%)          | 48.34 (2.44%)          | 93.48 (0.05%)          | 82.02 (1.45%)          | 68.22 (2.61%)          |
| 6        | 70.01 (1.20%)          | 62.78 (4.03%)          | 44.92 (4.79%)          | 93.98 (0.58%)          | 87.18 (4.74%)          | 70.52 (6.08%)          |

( ) - % Error in strength estimation

### 5. CONCLUSIONS

The surface irregularity measurement, tensile testing and non linear FEM analyses were conducted for corroded steel specimens and the following conclusions can be made from this study. 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. A very good agreement between the experimental and analytical results can be seen for all three classified corrosion types. So, the adopted numerical modeling technique can be used to predict the remaining strength capacities of actual corroded members accurately. Though the intensity of corroded surface measurement is not very significant for minor corrosion members, it was found that it affects for moderate and severe corrosion members considerably in prediction of their remaining strength capacities. So, a regular coarse surface measurement would be...
sufficient for minor corrosion members. But, a special surface measurement method with few data points, concerning the severity of corrosion and stress concentration is required and this will be investigated for moderate and severe corrosion members in future studies.

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