Investigation of Brisk Finite Element Analytical Model for Prediction of Remaining Strength Capacities of Corroded Steel Plates

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1. Introduction

Many bridge infrastructure systems are getting older, and a large number of these structures are in need of maintenance, rehabilitation or replacement. Corrosion and fatigue cracking may be the two most important types of damage in aging structures. 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, during past few decades. Due to economic constraints, it is not possible to conduct tests for each and every aged bridge structure within their bridge budgets. Therefore, nowadays, use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry.

This paper comprises non-linear FEM analysis results of many actual corroded plates with different corrosion conditions and comparison of these with the respective tensile coupon tests results, to develop an analytical method to predict the behavior of corroded steel bridge plates. Further, as it is not easy to measure several thousands of points, to accurately reproduce the corroded surface by numerical methods and to predict their yield and ultimate behaviors, a simple and reliable analytical model is proposed to estimate the remaining strength capacities of actual corroded members more precisely.

2. Classification of Corrosion States

In this study, 26 specimens (21-flange and 5-web) 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 100 years. Then the thicknesses of all scratched specimens were measured by using a 3D laser scanning device and the tensile tests were performed in order to clarify their remaining strength capacities. As it is necessary to categorize the different corrosion conditions into few general types for better understanding of their remaining strength capacities, 3 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

Here, the minimum thickness ratio (μ) is defined as:

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

3. Numerical Analysis

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 different length and width dimensions (according to the configurations of actual specimens) were modeled with their respective corrosion conditions. 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. Yield stress σ_y = 294.7 [MPa], Elastic modulus E = 191.6 [GPa], Poisson's ratio ν = 0.276 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 iniation of ductile fracture as a fuction of multiaxial plastic strains and stresses. This method was adopted in this analytical study. In SMCS criteion, the critical plastic strain ($\varepsilon_P^{Critical}$) is determined by the following expression:

$$\varepsilon_P^{Critical} = \alpha \cdot \mathrm{Exp}\left(-1.5\frac{\sigma_m}{\sigma_e}\right) \tag{2}$$

Where, α is toughness index and the stress triaxiality T = (σ_m/σ_e), a ratio of mean or hydrostatic stress (σ_m) and the effective or von Mises stress (σ_e). The toughness index α is a fundamental material property and hence obtained from the tensile test conducted for the non corroded specimen.

3.3 Analytical Results

Non corroded specimen was modeled at first, with the above described modeling and analytical features and 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. Figure 1 shows a very good comparison of experimental and analytical load-elongation behaviors for

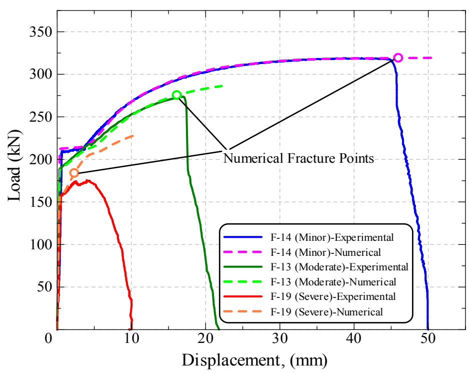

Figure 1: Comparison of experimental and analytical load-elongation curves

all 3 classified corrosion types. Here, the percentage errors in yield and tensile strength predictions of the analytical models of three corrosion types are 0.53% and 0.03% in F-14, 2.96% and 0.70% in F-13 and 3.20% and 5.53% in F-19 respectively. Therefore, this analytical method can be used to predict the yield and tensile strength of actual corroded specimens more precisely.

4. Development of Brisk Analytical Method

4.1 Corrosion Condition Modeling (CCM) Parameters

Since it is an exigent task to conduct detail corroded surface measurements for all aged steel infrastructures, a simple and accurate method is deemed necessary to model different corroded surfaces numerically and predict their yield and ultimate behaviors. Therefore two parameters were defined to model the corroded surface considering the stress concentration effect and to obtain the yield and ultimate behaviors more accurately. The following Figure 2 shows the variation of diameter of the maximum corroded pit (D) and average thickness (t_{avg}) vs. maximum corroded depth ($t_{c,max}$).

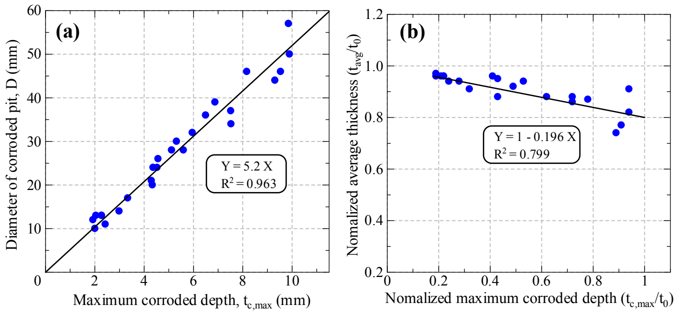

Figure 2: Relationship of (a) D vs. $t_{c,max}$ and (b) normalized t_{avg} vs. $t_{c,max}$

Therefore the two equations for the corrosion condition modeling (CCM) parameters can be defined as:

$$D^* = 5.2\ t_{c,max} \quad (3)$$

$$t^*_{avg} = t_0 - 0.2\ t_{c,max} \quad (4)$$

where D^* and t^*_{avg} are the representative diameter of maximum corroded pit and representative average thickness respectively.

4.2 Analytical Model

An analytical model is developed with the above CCM parameters for each corroded specimen with different corrosion conditions as shown in Figure 3. The same modeling features and analytical procedure as described in section 3 were adopted for the analyses. Then the results of this model were compared with the experimental results to understand the effectiveness of the proposed model.

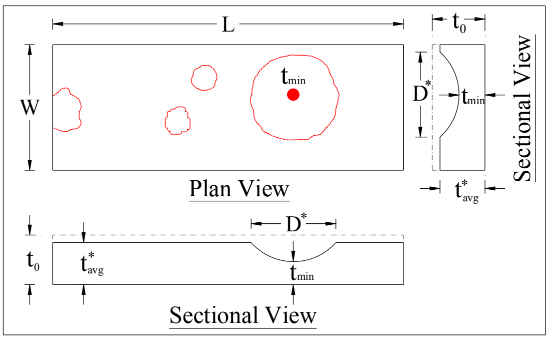

Figure 3: Analytical model with CCM parameters

4.3 Analytical Results and Discussion

The load-elongation behavior of 3 members with different corrosion conditions are shown in Figure 4 bellow. A very good comparison of the load-elongation behavior can be seen for the all three classified corrosion types. Here, the percentage errors in yield and tensile strength predictions of the proposed analytical model for the three corrosion types are 0.13% and 0.83% in F-14, 0.38% and 1.01% in F-13 and 3.51% and 2.69% in F-19 respectively. Since these models are developed by considering the loss of steel volume through the use of representative average thickness and stress concentration effect, better prediction of yield and ultimate behaviors and failure surfaces can be obtained. Further, since these models require only the measurement of maximum corroded depth ($t_{c,max}$), which can be easily identified through a careful visual inspection of the corroded surface, this method can be used as a simple, reliable and brisk analytical method for the maintenance management of steel infrastructures.

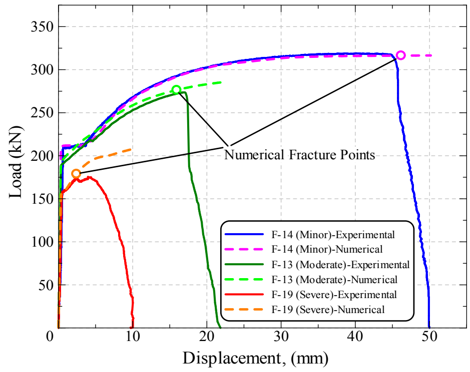

Figure 4: Comparison of load - elongation curves of proposed analytical model

5. Conclusions

1. 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.
2. Proposed analytical model with CCM parameters showed a very good agreement with the experimental results for all three classified corrosion types. Further, the proposed method is simple and gives more accurate remaining strength estimation of corroded steel plates.

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