DEVELOPMENT OF BRISK FINITE ELEMENT ANALYTICAL METHOD OF PREDICTING TENSILE STRENGTH REDUCTION DUE TO CORROSION

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ABSTRACT

Steel girder bridges, like other structures, deteriorate over time due to environmental effects, material fatigue, and overloading. Corrosion becomes one of the major causes of deterioration of steel bridges and there have been many damage examples of older steel bridge structures due to corrosion around the world during past few decades. Therefore, designing of bridge infrastructure systems for a particular service life and maintaining them in a safe condition during their entire service life have been recognized as very critical issues worldwide. It is an exigent task to conduct tests for each and every aged bridge structure within their bridge budgets and hence nowadays, the finite element analysis method has become the most common, powerful and flexible tool in rational structural analysis and makes it possible to predict the strength of complex structures more accurately than existing classical theoretical methods. Further, since 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 by measuring only the maximum corroded depth ($t_{c,max}$), in order to estimate the remaining strength capacities of actual corroded members more precisely.

***Key words*:** Corrosion, Steel bridges, Remaining strength, FEM analysis, Maintenance management

1. INTRODUCTION

Major steel bridges are usually the crucial elements of the road and railway infrastructures. Very often they constitute a part of critical links between highly habited areas. As a consequence, their closure or traffic capacity reduction causes major inconveniences for the users and result in significant losses to the economy. With aging, Corrosion becomes one of the major causes of deterioration of steel bridges, and its' damages seriously affect on their durability [1]. It is very difficult to retrofit or rebuild those aged 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.

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 [2]. 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 [3]. 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.

Several experimental studies of corroded surfaces were done by some researchers during past few decades, in order to introduce methods of estimating remaining strengths of corroded steel plates [4-6]. But, to develop a more reliable strength estimation technique, only experimental approach is not enough as actual corroded surfaces are different from each other. Therefore, nowadays, use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry. The analytical results and their comparison with respective experimental results are presented in this paper, in order to investigate the applicability of numerical modeling approach for residual strength estimation of corroded steel members. Further, the feasibility of establishing of a simple, accurate and reliable analytical method to predict the residual strength capacities of a corroded steel member by measuring only the maximum corroded depth is also discussed.

2. EXPERIMENTAL ANALYSIS

2.1 Corroded Test Specimens

The tensile test specimens 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 100 years. There, 21 (F1-F21) and 5 (W1-W5) test specimens were fabricated from the cover plate on upper flange and web plate respectively. 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.

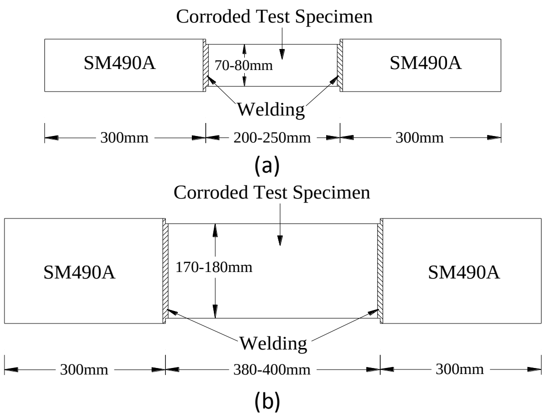


Figure 1: Dimensions of (a) flange and (b) web test specimens

Table 1: Material properties

Specimen	Elastic modulus /(GPa)	Poisson's ratio	Yield stress /(MPa)	Tensile strength /(MPa)	%Elongation @break
Flange-no corrosion	187.8	0.271	281.6	431.3	40.19
Web-no corrosion	195.4	0.281	307.8	463.5	32.87
SS400 JIS	200.0	0.300	245~	400~ 510	–

In this study, all specimens were categorized into typical 3 corrosion types concerning their corrosion conditions and minimum thickness ratio, μ (minimum thickness/initial thickness). The corrosion conditions with $\mu > 0.75$ are defined as '*minor corrosion*'. And the '*moderate corrosion*' type is defined when $0.75 \geq \mu \geq 0.5$. Further, the 3rd corrosion type $\mu < 0.5$ is defined as '*severe corrosion*' [6]. The initial thicknesses of flange and web specimens are 10.5mm &10.0mm.

2.2 Experimental Results

Figure 2 shows the load-displacement curves for three corroded specimens (F-14, F-13 and F-19) with 3 corrosion types. Herein, the specimen (F-14) with minor corrosion has almost same mechanical properties as the corrosion-free specimen. On the other hand, the moderate corroded specimen (F-13) and the severe 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 to elongate locally and reach to the breaking point.

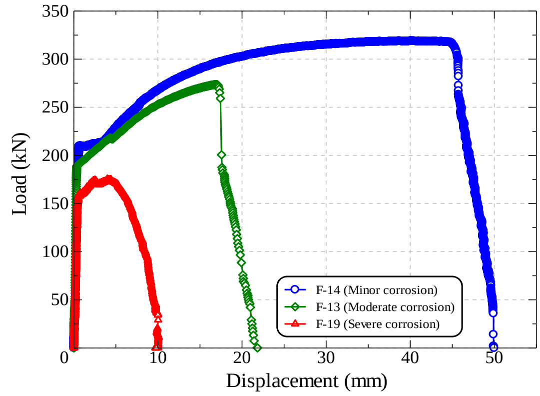


Figure 2: Load-displacement curves

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. 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.

3.2 Ductile Fracture Criterion

The "*Stress Modified Critical Strain Model (SMCS)*" proposed by Kavinde *et al.* [7], to evaluate the initiation of ductile fracture as a function of multiaxial plastic strains and stresses was adopted in this analytical study. In SMCS criterion, the critical plastic strain ($\varepsilon_p^{critical}$) is determined by the following expression:

$$\varepsilon_P^{Critical} = \alpha \cdot \mathrm{Exp}\left(-1.5\frac{\sigma_m}{\sigma_e}\right) \qquad (1)$$

Where, α is toughness index and the stress triaxiality T = (σ_m/σ_e), a ratio of the mean stress (σ_m) and the effective stress (σ_e).

3.3 Analytical Results

Figure 3 shows the comparison of experimental and analytical load-displacement curves of F-14, F-13 and F-19. There, it can be seen that a very good agreement of experimental and analytical load-displacement behaviors for all 3 classified corrosion types can be obtained. Here, the percentage errors in yield and tensile strength predictions of analytical models of 3 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, it is revealed that this analytical method is accurate and hence can be used to predict the yield and tensile behaviors of actual corroded specimens more precisely.

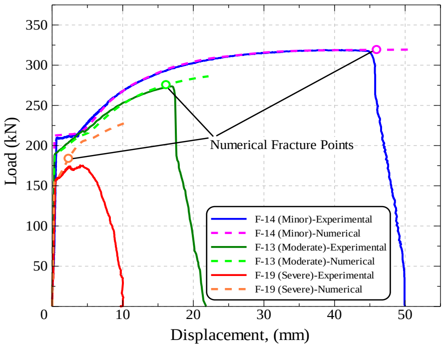


Figure 3: Comparison of experimental and analytical load-displacement curves

4. BRISK ANALYTICAL METHOD

4.1 CCM Parameters

Two parameters were defined to model the corroded surface considering the material loss and stress concentration effect, and to obtain the yield and ultimate behaviors accurately. Figure 4 shows the variation of diameter of the maximum corroded pit (D) and average thickness (t_{avg}) vs. maximum corroded depth ($t_{c,max}$).

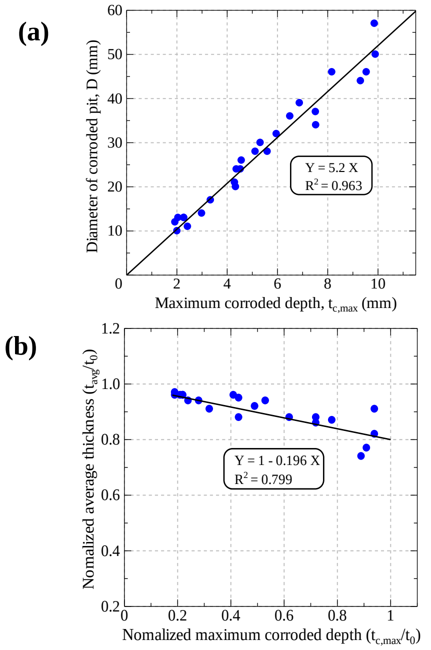


Figure 4: Relationship of (a) D vs. $t_{c,max}$ and (b) normalized t_{avg} vs. $t_{c,max}$

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

$$D^* = 5.2\ t_{c,max} \quad (2)$$

$$t^*_{avg} = t_0 - 0.2\ t_{c,max} \quad (3)$$

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

4.2 Brisk Analytical Model

An analytical model is developed with the above CCM parameters for each corroded specimen with different corrosion conditions as shown in Figure 5. 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.

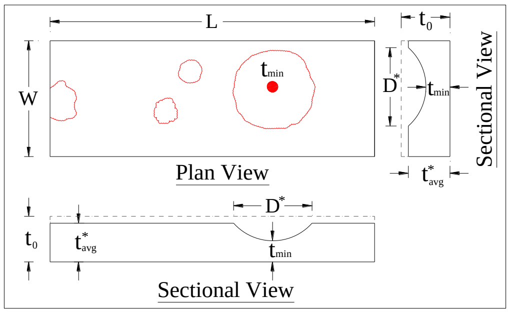
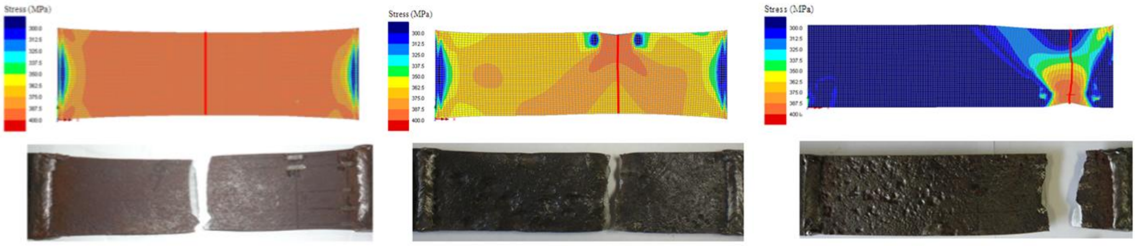


Figure 5: Analytical model with CCM parameters

4.3 Analytical Results and Discussion

The stress distribution and failure surfaces of 3 specimens with proposed analytical model at ultimate load are shown in Figure 6. There, it was noticed that a very good agreement of the failure surfaces of experimental and proposed model can be obtained. Further, Figure 7 shows that a very good comparison of the load-elongation behavior can be seen for the all three classified corrosion types. Here, the %errors in yield and tensile strength predictions of proposed analytical model



(a) F-14 [Minor corrosion] (b) F-13[Moderate corrosion] (c) F-19 [Severe corrosion]

Figure 6: Ultimate stress distribution of different specimens with proposed analytical model

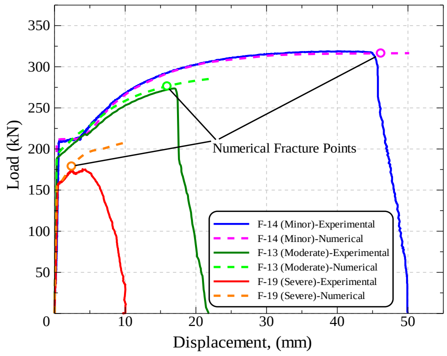


Figure. 7: Comparison of load - elongation curves of proposed analytical model

for the 3 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.

5. CONCLUSIONS

A very good agreement between experimental and non linear FEM 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.

Two good relationships for the corrosion condition modeling (CCM) parameters can be defined as:

$$D^* = 5.2\, t_{c,max}$$
$$t^*_{avg} = t_0 - 0.2\, t_{c,max}$$

And the proposed analytical model with CCM parameters showed a very good agreement with the experimental results for all three classified corrosion types.

Further, the proposed analytical method is simple and gives more accurate remaining strength estimation of corroded steel plates and hence this analytical model can be used as a reliable and brisk method for the maintenance management of corroded steel infrastructures.

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