NUMERICAL STUDY ON REMAINING STRENGTH PREDICTION OF CORRODED STEEL BRIDGE PLATES

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Abstract

Corrosion causes strength deterioration of aged steel infrastructures and hence careful evaluation of their remaining load-carrying capacities are of high importance in maintenance engineering. To develop a more reliable strength estimation technique, only experimental approach is not enough as actual corroded surfaces are different from each other. However 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 strength estimation but also for subsequent repair and retrofitting plan. The results of non-linear FEM analysis of many actual corroded plates with different corrosion conditions and comparison of them with the respective tensile coupon tests results are presented in this paper. Further, the feasibility of establishing of an analytical methodology to predict the residual strength capacities of a corroded steel member with fewer number of measuring points are also discussed.

Keywords: Corrosion, Numerical analysis, Strength estimation, Tensile test

1. Introduction

Many steel bridge infrastructures of the world are getting old and 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. Therefore it is important to develop advanced technologies which can be used to assist proper management and control of such age-related deterioration as many of these structures are currently in need of maintenance, rehabilitation or replacement.

Detailed regular inspections are necessary in order to assure adequate safety and determine maintenance requirements, in bridge infrastructure management. 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.

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Usually, the accurate predictions are based on how accurately statistical parameters are estimated and therefore mainly depends on experimental and field data. In the past few decades, 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, due to economic constraints, it is not possible to conduct tests for each and every aged bridge structure within their bridge budgets. Therefore, bridge engineers are faced with the lack of experimental and field data. 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. Preliminary Investigation of Corroded Specimens

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. 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 in order to care not to change the condition of the corrosion irregularity. 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 JIS No.5 test specimen is shown in Figure 1.

As the corrosion conditions in actual steel structures are different from each other, it is necessary to

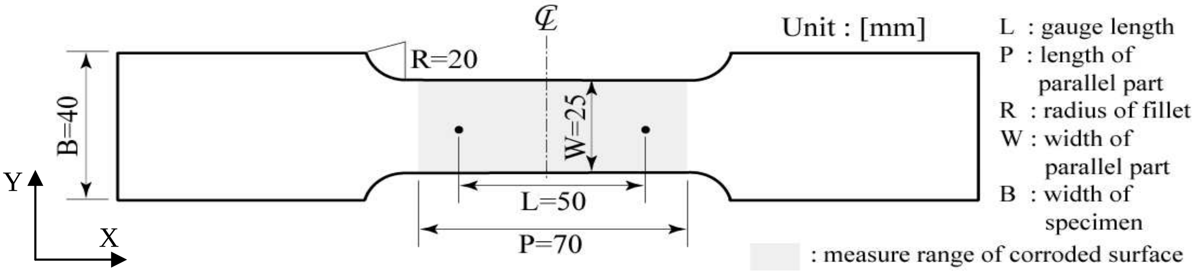

Figure 1: JIS No.5 Specimen for tensile test

categorize them 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. Therefore, 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 the minimum thickness ratio, $\mu > 0.75$ are defined as 'minor corrosion'. And the 'moderate corrosion' type is defined when the minimum thickness ratio, $0.75 \geq \mu \geq 0.5$. Further, the 3rd

Figure 2: Plates with (a) minor corrosion [FT-22], (b) moderate corrosion [FT-18] and (c) severe corrosion [FT-15]

corrosion type with the minimum thickness ratio, $\mu < 0.5$ is defined as 'severe corrosion'. There, the initial thickness (t_0) of flange specimens and web specimens are 10.5mm and 10.0 mm. Three specimens; FT-22, FT-18 and FT-15 with minor, moderate and severe corrosion conditions respectively are shown in Figure 2.

The significance of three proposed corrosion conditions can be identified even with the visual examination of those members, as members with minor corrosion have tiny corrosion pits (less than 3mm depth) throughout the member, members with moderate corrosion have few considerable corroded pits (depth of 3-5 mm) in some places while many non-corroded portions also remain widely and members with severe corrosion have several extensive corroded regions (maximum corrosion depth over 5mm).

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 length and width dimensions of 70mm x 25mm (X and Y directions) 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 = 299.9 [MPa], Elastic modulus E = 195.8 [GPa], Poisson's ratio ν = 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 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 starin ($\varepsilon_P^{Critical}$) 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 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. 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.

3.3. Analytical Results

Non corroded specimen was modeled at first, with the above described modeling and analytical features to understand the accuracy of the adopted procedure. 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 Figures 3(a), 3(b) and 3(c) show 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 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(d) shows the comparison of ultimate load capacities of all 32 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.

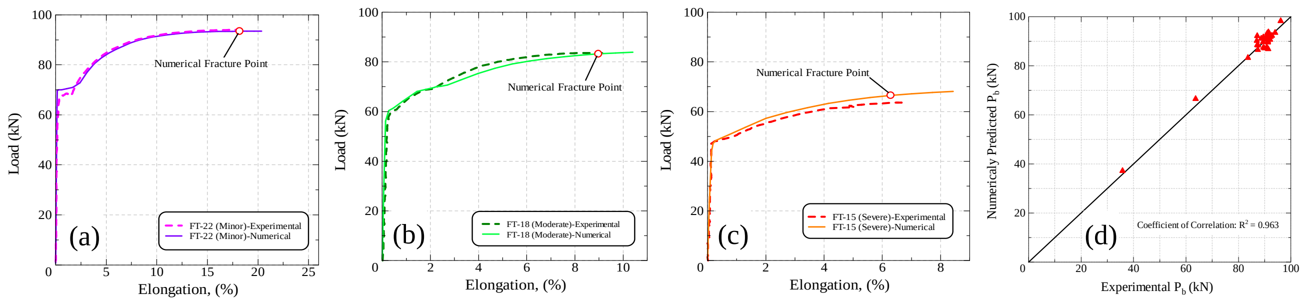

Figure 3: Comparison of experimental and analytical load-elongation curves of specimens with; (a) minor corrosion [FT-22], (b) moderate corrosion [FT-18], (c) severe corrosion [FT-15] and (d) comparison of experimental and analytical ultimate load capacities

4. Effect of Measuring Points

It is necessary to conduct regular assessments of each and every structure to ensure their safety and determine maintenance needs. But, it wouldn’t be an easy task as the number of highway and railway steel structures are steadily increasing in the world. So, developing a rapid and accurate methodology to estimate the remaining strength capacities of steel infrastructures is a vital task in maintenance engineering.

4.1. Numerical Modeling with Regular Corroded Surface Measurements (RCSM) Methods

4.1.1. Analytical Models

Table 1: Data interval and total no. of measuring points

Model No.	Maximum Data Interval /(mm)	Total measuring points
1	1	1846
2	2	504
3	5	90
4	10	32
5	15	18
6	25	8

Six different finite element models with different corroded surface measurement intervals in X and Y directions 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. The Table 1 shows the maximum data measurement interval and total number of measuring points in each model. The same modeling features and analytical procedure as described in chapter 3 were adopted for all analyses.

4.1.2. Analytical Results and Discussion

The Figure 4 shows the percentage errors in yield and tensile strength estimations of different RCSM models for three members FT-22, FT-18 and FT-15 with minor, moderate and severe corrosion conditions respectively. It can be seen 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

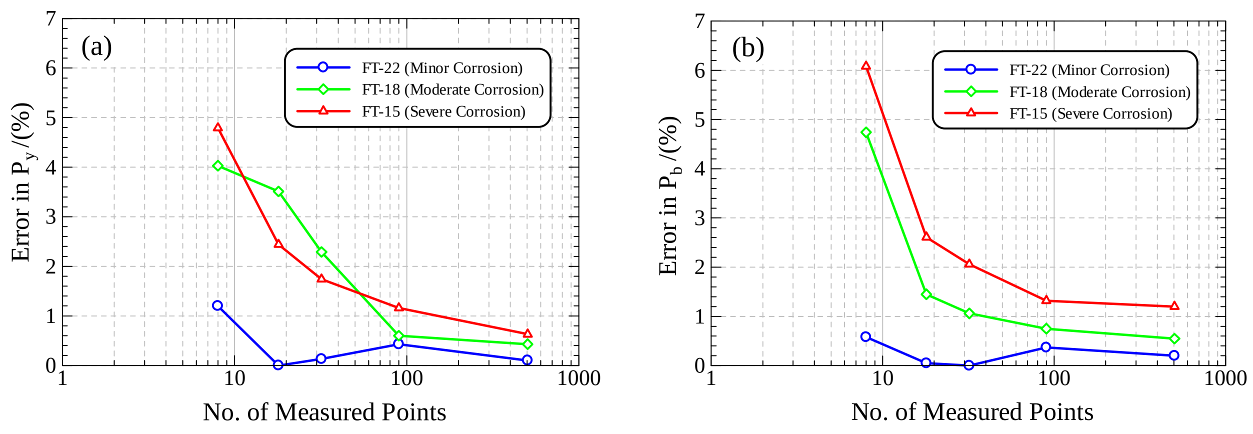

Figure 4: Comparison of %errors in (a) yield and (b) tensile strength estimation

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. So, a special surface measurement method with few data points, concerning the severity of corrosion and stress concentration is required for moderate and severe corrosion members.

4.2. Numerical Modeling with Special Corroded Surface Measurements (SCSM) Methods

4.2.1. Analytical Models

Five different models were created by considering the irregularity of the corroded surface and stress concentration effect and their analytical results were compared with the model with 1mm corroded surface data (Model-1). The Figure 5 shows different SCSM analytical models used in this study. The outer edges were taken as the initial thickness (t_0) in all models except the Model-1. The Model-2 consists only the measurement of minimum thickness point (t_{min}) and linear variation was considered between t_{min} point and edges of the plate. The Model-3 and Model 4 were created with t_{min} point and two other thickness measurements taken at the edges of the corroded pit in longitudinal direction and width direction respectively. These models also were created by considering the linear variation among measured points and plate boundaries. The Models 5a and 5b consists five corroded surface measurements of the corroded pit including its t_{min} and two points each in longitudinal and width directions. Then, linear and Spline variations were used to model the corroded portion in Model-5a and Model-5b respectively. Further, linear variation between the corroded pit and plate edges were used in both models.

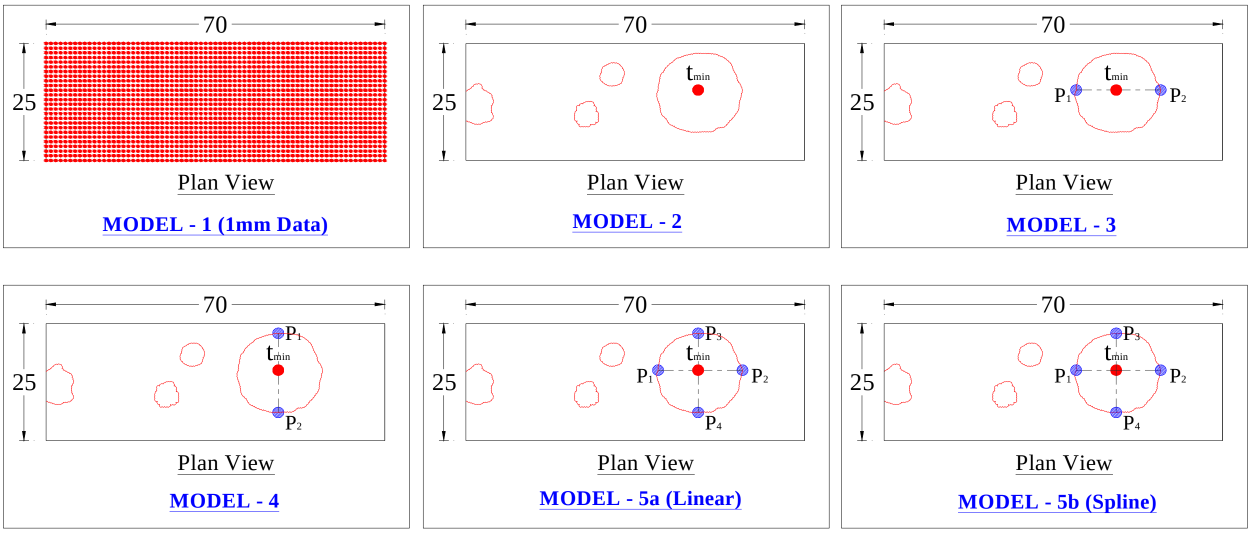

Figure 5: Analytical models with special corroded surface measurement points

Same modeling features, non-linear elastic-plastic material properties and analytical proceedure were adopted for all above models and the analysis was continuied untill they reach to their predefined termination limits. Then, their load-elongation behaviours, yield and tensile strengths and ultimate behaviors were compared with the Model-1 with 1mm corroded surface data, to understand the effect of special corroded surface data measurement methods having fewer number of measuring points.

4.2.2. Analytical Results and Discussion

The Figure 6(a) and Figure 6(b) show the ultimate stress distributions of different SCSM models of moderate corrosion member (FT-18) and severe corrosion member (FT-15) respectively. The stress concentration effect can be seen in all these SCSM models, as all of them were developed including the minimum thickness point (t_{min}). But, the differences in stress distribution can be seen in different models as the irregularity of each

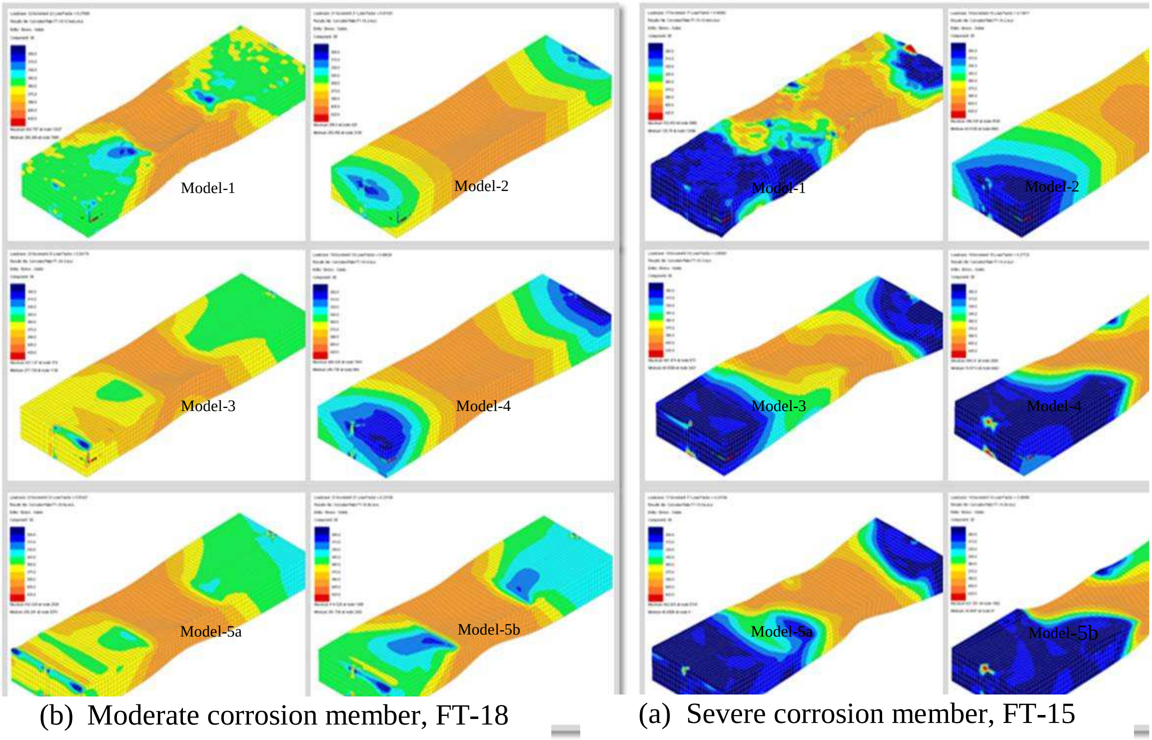

Figure 6: Stress distributions of different special analytical models at ultimate load

model is different. Further, more similar stress distribution can be seen in Model-5a and Model-5b with the results of their 1mm data model. The percentage errors in yield and tensile strength estimations of different SCSM models for members FT-18 and FT-15 are shown in Figure 7. There, it can be seen that the %errors of moderate corrosion specimen (FT-18) are very small in Models 5a and 5b. Further, it can be seen that even though the %errors of severe corroded specimen (FT-15) in Models 5a and 5b are comparatively smaller than the other models, those errors are quite significant too. Therefore, more SCSM models to be developed to represent the corroded surface irregularity more accurately for severe corroded members in future studies.

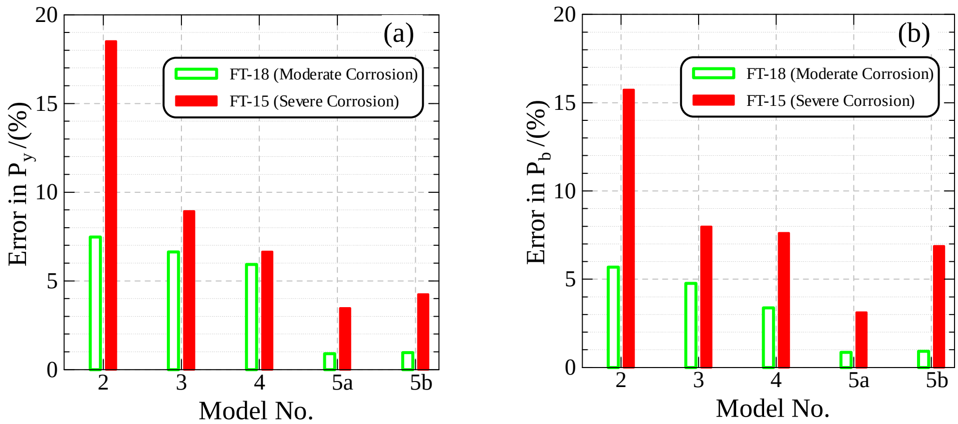

Figure 7: Comparison of %errors in (a) yield and (b) tensile strength estimation of different special analytical models

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.

(4) The corrosion causes strength reduction of steel plates and minimum thickness ratio (μ) can be used as a measure of the level of corrosion and their strength degradation.

(5) 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.

(6) 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.

(7) Therefore, a regular coarse surface data measurement is sufficient for minor corroded members and a special analytical model with fewer corroded surface measuring points, concerning the severity of corrosion and stress concentration effect is necessary for moderate and severe corrosion members to estimate their remaining strength capacities.

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