SECM/15/164

Investigation on Residual Cyclic Strength Capacity of Corroded Steel Bridge Members

W. K. N. I. Jayasundara[1*] and J.M.R.S Appuhamy[1]

[1]University of Ruhuna, Galle, Sri Lanka
*E-Mail: Nirmani.jayasundara@gmail.com, TP: +94783942140

Abstract: Steel bridges play a major role in road and railway infrastructures hence it directly influence on economy of any country. Traffic capacity reduction or even a temporary closure generates major inconveniences for the users and result in significant losses to the economy. Corrosion is one of the most significant causes of age related deterioration of steel girder bridges which affects their strength, long term mechanical performance, usability and durability. Numerous steel bridge structure collapses are associated with dynamic loadings like earthquakes and wind loading. Damaging vulnerability of steel structures due to dynamic excitations can be triggered with corrosion. Non availability of information and convenient methodology to determine the behavior of corroded steel members can lead to problematic situations for the civil engineers when evaluating the strength of deteriorated member. Therefore a comprehensive study in front of serviceability and ultimate limit states is necessary to develop efficient techniques to evaluate the structural integrity and safety. This is necessary to evaluate the feasibility of those steel structures for the current usage and to figure out the retrofitting requirement of corroded members. This research proposes a simple and reliable methodology to estimate remaining yield and ultimate cyclic strength capacities by measuring only the minimum thickness of a corroded surface based on the results of many experimental coupon tests and results of nonlinear FEM analysis of many actual corroded plates with different corrosion conditions, which can be used to make rational decisions about the maintenance management plan of steel infrastructures.

Keywords: Residual strength, cyclic loading, finite element analysis, corrosion, bridge structures.

1. Introduction

Among enormous structural edifices, bridges are a major component of any infrastructure, which facilitates day to day travel path for freights and passengers. The failure of a bridge will affect the economy of any country. When bridge structures expose to harsh environmental conditions result will be time-variant changes of their load-carrying capacity. Once the load carrying capacity reduced, the bridges' ability to safe service too violates (Appuhamy *et al,* 2009 [1]). In the future, it is evident that serious social problems will arise when the number of damaged bridges increases, as 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.

Benefits of regular and proper inspections of older bridges cannot be disregarded. They not only help in planning the necessary work but also help in discovering and monitoring any problems, thereby reducing expensive maintenance, reducing operating hazards, preventing structural failures and preventing emergencies. Therefore, no negligence in inspections should be permitted as they form the essential source of information to carry out a comprehensive evaluation of its current capacity. Some researchers have already done several experimental studies in terms of estimating the remaining strength capacities under monotonic loading, and developed some durability estimation techniques which were performed with detailed investigations on corroded surfaces (Matsumoto *et al,* 1989 [2]; Muranaka *et al*, 1998 [3]; Kariya *et al,* 2003 [4]; Appuhamy *et al,* 2009 [1]).

Recent severe earthquakes worldwide have shown that steel bridges can be vulnerable. In addition, there were many collapse, buckling, fracture and cracking occurred in many steel infrastructures due to earthquakes. It is evident that, even though most of the steel bridge structures perform well with their specific energy dissipation characteristics, the failure risk associated with severe corrosion under mega earthquake events could not be underestimated.

Therefore this paper investigate the effect of corrosion damage on remaining dynamic behaviour of existing steel bridge infrastructures and presents a simple, accurate and reliable methodology to estimate residual strength capacities of corroded steel plates using both experimental and numerical analysis with the results of coupon tests and finite element modelling technique. Further validation of use of corrosion condition modelling parameters (CCM) as a more reliable methodology to model the corrosion surface in FEM modelling software in cyclic strength estimation is also considered.

2. Methodology

2.1 Experimental Analysis

2.1.1 Corroded Test Specimens

The test specimens for this experimental study were cut out from a steel girder of the Koggala Bridge in Sri Lanka on the shoreline of the Indian Ocean, which had been used for about hundred years. This bridge was constructed as a railway bridge in 1900s and this bridge was dismantled due to serious corrosion damage in year 2012.

The specimens for cyclic loading tests were taken, cutting out from the corroded members of the bridge. Four corrosion-free specimens, cut down smoothly from both sides of corroded steel plate in order to clarify the material properties. Test specimens prepared according to the JIS No.5 as shown in Figure 1 and Figure 2.

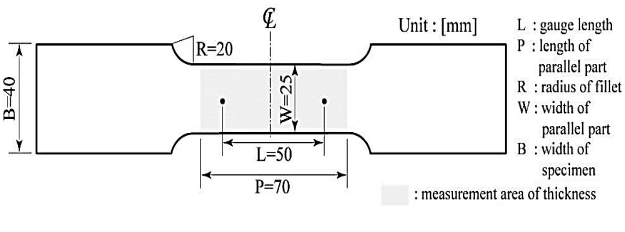

Figure 1: JIS No.5 specimen for cyclic loading test

Figure 2: Prepared test specimens according to standard shape

2.1.2 Corroded Surface Measurements and Material Properties

The rust and paint on the surface were removed by using a steel wire brush and then applying high pressure water carefully in order to not change the condition of the corrosion irregularity. Then the thicknesses of all scratched specimens were measured by using a 3D scanning of surface before the cyclic loading test and the intervals of measurement data are 2mm in X and Y directions respectively. The statistical thickness parameters such as average thickness (t_{avg}), minimum thickness (t_{min}), were calculated from the measurement results.

Table 1: Material Properties

Non Corroded Specimen no.	Elastic Modulus (GPa)	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation at Breaking (%)
Sample set 1	184.4	272	431	25.59
Sample set 2	180.1	246	418.5	20.01
SS400 JIS	200	245~	400~510	-

Tensile testing was performed for the four corrosion-free specimens. The fundamental mechanical properties of the material were obtained and compared with the standard values by JIS as shown in Table 1. The material properties of actual specimens were lied within the property ranges of SS400 (JIS).

2.1.3 Cyclic Strength Determination by Cyclic Loading Test

Each specimen was tested under predetermined cyclic displacement as shown in Figure 3. It is obvious that the bridges are more vulnerable to random loading. The main focus of this research was to figure out the strength reduction percentage for a cyclic loading. Loading pattern can be random or monotonic. Particularly the loading should not be fatigue, and in addition, incremental load was selected in order to facilitate breaking point rapidly.

Applied load and the stroke displacement was recorded as shown in the Figure 4. Displacement histories were analysed to identify actual yield and ultimate cyclic strength of each specimen; shown in Table 2.

Yield point was figured out at the point where the hysteretic deviates from linear behavior and the maximum load of the hysteresis was noted as the ultimate load.

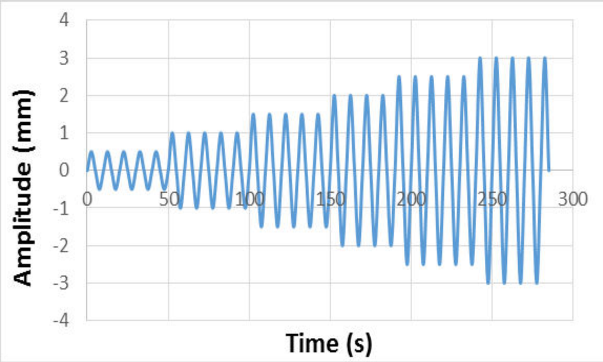

Figure 3: Graph of amplitude vs. time of applied cyclic displacement pattern

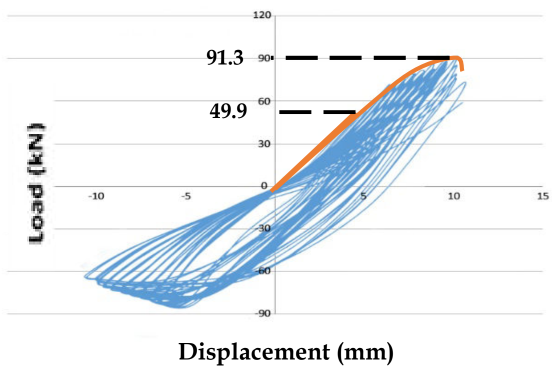

Figure 4: Load vs. displacement curve of specimen (μ = 0.359) obtained by experimental analysis

Table 2: Yield and Ultimate cyclic strength values of test specimens

Minimum Thickness Ratio ($t_{min}/ t_{initial}$)	Yielding Load - P_b (kN)	Ultimate Load - P_y (kN)
1.000	51.25	95.10
1.000	38.70	61.92
0.375	42.90	71.90
0.378	31.45	47.99
0.456	33.73	54.02
0.743	37.06	58.89
0.691	48.45	87.8
0.359	49.89	91.30
0.871	50.38	92.67
0.689	34.67	57.07
0.785	49.00	90.53

2.2 Numerical Analysis

Numerical analysis was conducted based on finite element modelling to have more reliable strength data easily. Usually, accurate predictions are based on how accurately statistical parameters are estimated and therefore mainly depend on experimental and field data. 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 use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry.

2.2.1 Numerical Procedure

In order to clarify yield and tensile strengths, non-linear finite element analyses were performed using LUSAS finite element analysis software for all specimens with different corrosion conditions. 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 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 70 mm×25 mm (Figure 05) 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 predetermined displacement was applied to the loading edge. Actual material properties obtained were assigned and non-linear elasticplastic material properties obtained from the non-corroded specimen's tensile test results were assigned to all analytical models, respectively the model was compiled by assigning the same loading condition given to actual experimental specimens at the experimental analysis. Obtained results for yield and ultimate strength capacities were compared with the actually obtained strength. Models were adjusted till the results of ultimate strength of analytical models lies within close proximity with experimental results. Hence the numerical model was validated.

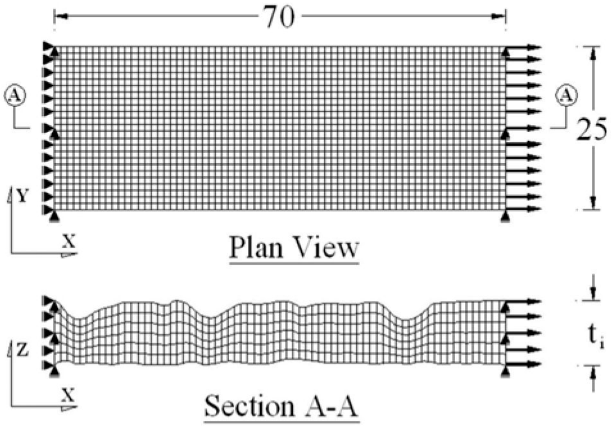

Figure 5: Analytical Model of Corroded specimen

2.2.2 Modelling of Corrosion Condition

Two corrosion condition modelling (CCM) parameters were defined to model a corroded surface considering the material loss due to corrosion and stress concentration effect (Ohga *et al,* 2011 [5]) and Appuhamy *et al,* 2011 [6]).

$D^* = 5.2\ t_{c,max}$ (1)

$t^*_{avg} = t_0 - 0.2t_{c,max}$ (2)

Where D^* and t^*_{avg} are the representative diameter of maximum corroded pit and representative average thickness respectively. ($t_{c,max}$ = maximum corroded depth, t_0 = initial thickness)

Actual specimens were modelled using CCM parameters and analysed using validated FEM modeller and cyclic strength values were obtained. Effective stress distributions of several analytical models using CCM parameters at ultimate loads are shown in Figure 6 and Figure 7.

Comparison of experimental results with analytical results shows that there is a close relationship between strength results as shown in Table 3. The percentage error varies within negative four and positive six, which can be considered as a considerably small value. Therefore obviously the corrosion condition modelling parameters derived for tension can be effectively utilized under cyclic or seismic loading conditions.

Table 3: Ultimate cyclic strength values of test specimens under numerical analysis

Minimum Thickness Ratio ($t_{min}/t_{initial}$)	Experimental ultimate load (kN)	Numerical ultimate load (kN)	Percentage Error (%)
1.000	95.10	94.50	0.63
1.000	61.92	63.01	-1.76
0.375	71.9	70.00	2.64
0.378	47.99	45.01	6.23
0.456	54.02	55.25	-2.27
0.743	58.89	56.97	3.26
0.691	87.80	84.00	4.32
0.359	91.30	94.70	-3.72
0.871	92.67	87.08	6.032
0.689	57.07	55.54	2.68
0.785	90.53	90.53	-0.58

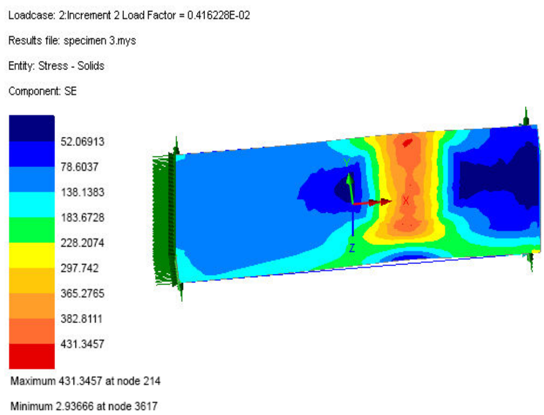

Figure 6: Stress distributions of analytical model (μ = 0.375) using CCM parameters at ultimate load

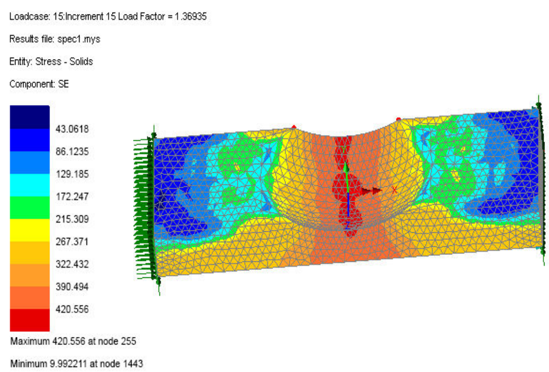

Figure 7: Stress distributions of analytical model (μ = 0.456) using CCM parameters at ultimate load

3. Results and Discussion

The percentage yield and ultimate strength reductions (%SR) were obtained by comparing the strength results of corroded specimens with non-corrosion specimen from same source according to the Equation 3. And the percentage strength reduction was plot against minimum thickness ratio of each specimen as shown in Figure 8 and Figure 9.

$$\%SR_{Yield/ultimate} = \left| \frac{P_{Y(Non-corroded\ specimen)} - P_{Y(Model\ with\ specimen)}}{P_{Y(Non-corroded\ specimen)}} \right| \times 100 \quad (3)$$

Considering the complexity and acceptable accuracy using minimum thickness ratio, two quadratic equations were obtained as relationships, between yield and ultimate percentage strength reduction values with minimum thickness ratio of corroded specimens.

Thus $\%SR_{yield} = 25\ (1-\mu)\ (1.4-\mu)$, $\%SR_{ultimate} = 25\ (1-\mu)\ (1.7-\mu)$, can be used as a tool to estimate the residual strength of prevailing corroded bridge parts by only measuring minimum thickness.

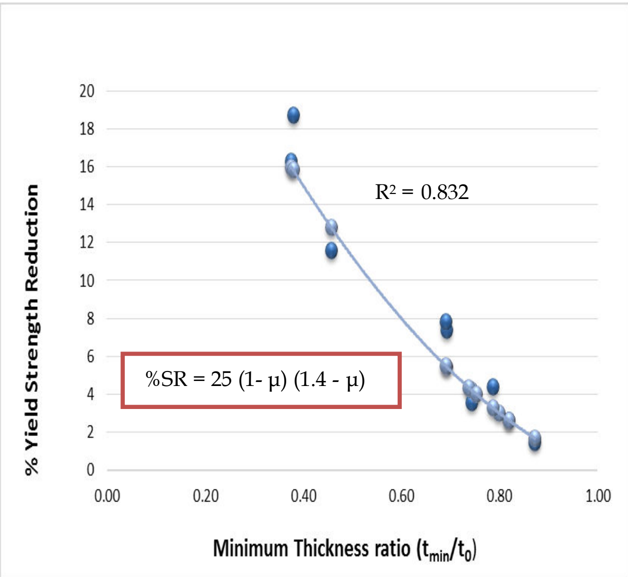

Figure 8: Relationship of percentage yield strength reduction vs. minimum thickness ratio (μ)

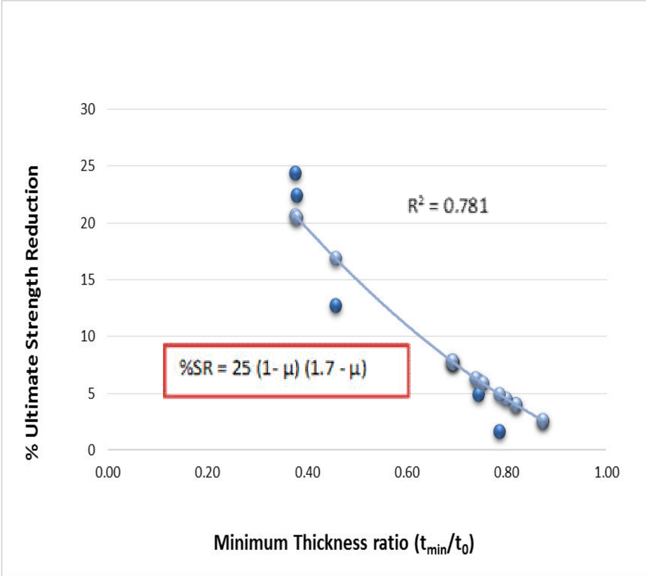

Figure 9: Relationship of percentage ultimate strength reduction vs. minimum thickness ratio (μ)

5. Conclusions and Future Directions

The yield, ultimate behaviors of steel bridge members with different corrosion conditions under cyclic loading were studied in this research. The main conclusions of this study can be summarized as follows.

It was revealed that the corrosion has a significant effect on the dynamic behavior of steel bridge infrastructures. As a reliable and efficient methodology to estimate the percentage reduction of yield/ultimate strengths due to corrosion under cyclic loading can be obtained using following Equation (4) and Equation (5).

$$\%SR_{Yield} = 25 \times (1-\mu) \times (1.4-\mu) \quad (4)$$

$$\%SR_{Ultimate} = 25 \times (1-\mu) \times (1.7-\mu) \quad (5)$$

As the proposed strength and energy reduction equations only requires the measurement of minimum thickness ratio μ, which is an easily measurable parameter through a quick and careful site investigation, this method can be used as a simple and reliable method to predict the cyclic, seismic behaviors of corroded steel members more easily and precisely. Furthermore, as the %SR charts give a good indication about the percentage strength reduction according to the severity of corrosion, bridge engineers would be able to decide whether the infrastructure requires any initial corrosion prevention precautions such as painting etc., retrofitting of some selected members or replacement of some critical members in order to assure the adequate safety of the existing structure.

In addition a very good agreement between experimental and nonlinear FEM results can be seen for all three classified corrosion types. Thus the adopted modelling technique can be used to predict the remaining strength capacities of actual corroded members accurately.

Usually, the accurate predictions are based on how accurately statistical parameters are estimated and therefore mainly depend on experimental and field data. 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 use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry.

Therefore adopted numerical modelling technique can be precisely used as a more reliable method to model run and retrieve the residual strength data of modelled actual bridge members.

Finally it can be concluded that this research findings have immense importance in bridge maintenance and management industry as well as the ultimate goal of this findings may safeguard human lives and property from accidental collapses in bridges all around the world.

References

[1] Appuhamy J.M.R.S, Kaita T, Ohga M & Dissanayake P.B.R (2009), *A simple and Comprehensive Estimating Method of Remaining Tensile Strength of Corroded Steel Bridge Plates*, Annual Research Journal of SLSAJ, no. 9 , pp. 6-10.

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

[3] Muranaka A, Minata O & Fujii K (1998), *Estimation of residual strength and surface irregularity of the corroded steel plates,* Journal of Structural Engineering, vol. 4A, pp. 1063-1071.

[4] Kariya A, Tagaya K, Kaita T & Fujii K (2003), Basic study on effective thickness of corroded steel plate and material property, Annual Conference of JSCE, Tokushima, Japan, pp. 967–968.

[5] Ohga M, Appuhamy J.M.R.S, Kaita T, Chun P, and Dissanayake, P.B.R (2011), *Degradation of tensile strength with the severity of corrosion condition,* World Congress on Advances in Structural Engineering and Mechanics (ASEM11plus), Seoul, Korea, pp. 5280–5297.

[6] Appuhamy J.M.R.S, Kaita T, Ohga M & Fujii K (2011), *Prediction of residual strength of corroded tensile steel plates*, International Journal of Steel Structures, vol. 11, no. 1, pp. 65–79