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Prediction of Residual Buckling Strength in Corroded Steel Bridge Members

W.K.N. Sandamali1*, H.P. Wijesena[1] and J.M.R.S. Appuhamy[1]

[1]Faculty of Engineering, University of Ruhuna, Galle, Sri Lanka
*E-Mail: nirashakarunarathna@gmail.com, TP: +94717714086

Abstract: At present, degradation process of steel bridges has become major problem in all over the world. Steel bridges are exposed to numerous degradation processes during long year operation period, which causes various types of defects. Corrosion is one of major cause of deterioration process of steel bridge structures. Because of the corrosion, remaining load carrying capacities of steel bridge structures are gradually decreased. So it is very important to carefully evaluate the remaining strength of steel bridges in order to understand the feasibility of those steel structures for the current usage and to evaluate the necessity of retrofitting of selected corroded members to strengthen the existing structures. There are lots of researches have been conducted in order to find out remaining tensile strength of corroded steel bridge members. To find out remaining buckling strength of corroded steel, previously conducted tensile test results are not accurate. So evaluation of buckling strength is an essential source of information for carrying out a comprehensive evaluation of its current buckling strength capacity and also the parameters involve in the method should be easily measurable.

There is a need of more brisk and accurate assessment method which can be used to make reliable decisions affecting the cost and safety. This study proposes a new method to calculate the remaining buckling strengths by using minimum thickness ratio based on the results of many buckling strength tests conducted on specimens of corroded steel bridge plates with different corrosion conditions based on the results of many compression coupon tests of actual corroded plates. And also, it is an impossible task to predict remaining buckling strength capacities of each and every aged bridge structure by conducting experiments and so nowadays, the finite element analysis method has become the most common, powerful and flexible tool in 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 buckling behaviours, a simple and reliable analytical model is proposed by measuring only the maximum corroded depth (tc,max), in order to estimate the remaining strength capacities of actual corroded members more precisely.

Keywords: Corrosion, Remaining buckling strength, Steel bridges, Finite element analysis

1. Introduction

Use of steel in structures goes over 100 years. There are many advantages of use of steel in structures, such as steel exhibits a desirable physical property that makes it one of the most versatile structural materials in use and also due to its great strength, uniformity, light weight, ease of use, toughness, ductility, durability and many other desirable properties makes it the material of choice for numerous structures such as steel bridges, high rise buildings, towers, and other structures. Structural steel has a very high yield stress both in compression and tension. As a result of that, the amount of steel used in building to produce the equivalent performance is much less than that of using ordinary reinforced concrete. So as construction material steel was used during last few decades. And also steel is an efficient and economical material for bridge structures.

But major disadvantage of using steel for construction is the quick deterioration in steel with compare to other construction material. Due to the exposure to aggressive environmental conditions and inadequate maintenance, and often causes in reduction in their carrying capacities, Steel structures are prone to age related deterioration, such as corrosion wastage, fatigue cracking, or mechanical damage during their service life can give rise to significant issues in terms of safety, health, environment and financial costs. Corrosion is the most important causes of deterioration of steel bridges. It has been proven that the corrosion played a significant role in the catastrophic collapse of both the Silver Bridge (Point Pleasant, WV) in 1967 (Silver river bridge, 2014)[4] and the Mianus River Bridge (Connecticut) in 1983, USA (Mianus River Bridge, 2014)[3].

Due to the corrosion, remaining load-carrying capacities of steel bridge structures are gradually decreased. So it is essential to carefully evaluate the remaining strength of a steel bridge in order to understand the feasibility of the steel structure for the current usage and to evaluate the necessity of retrofitting of selected corroded members to strengthen the existing structure.

Many researchers have conducted tests on corroded steel based on tensile strength to find out strength reduction due to the corrosion. Although the tensile is most conservative method to evaluate strength reduction but it is not more accurate to calculate remaining strength when a member is subjected to a buckling load. This paper is mainly based on developing a methodology for remaining buckling strength of the corroded steel members with the relation of corroded condition parameters such as maximum corroded depth of corroded steel members. Experimental results can’t be used for all the structures practically. Because it is important to conduct numerical analysis due to the difficulty of measuring several thousands of points, to accurately reproduce the corroded surface by numerical methods and to predict their behaviours under compression load, a simple and reliable analytical model is proposed to estimate the remaining strength capacities of actual corroded members more precisely. Actual structures can be analysed based on the numerical analysis. By using experimental results, numerical method can be validated. Then those validated results can be used for the practical application very easily. If it is possible to derive an equation or any numerical analysis with parameters can be measured with respect to the initial thickness, like depth of corroded pit or remaining thickness of the elements then remaining strength can be easily calculated.

2. Methodology

2.1 Experimental Methodology

The specimens were collected from corroded steel bridges. Totally 14 numbers of specimens were prepared from corroded steel plates and two specimens from non-corroded places of each steel bridges were prepared to find out actual material properties of the steel. For that the specimens were tested under tension.

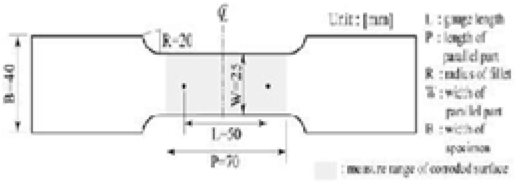

Figure 1: JIS 05 Standard Specimen size for tensile test

Figure 1 shows the JIS standard specimen size used for tensile test. For the compression test 200mm*80mm specimens were prepared.

Figure 2**:** Prepared specimen for the compression test

Figure 2 shows the specimen prepared for compression test. After preparation of specimens all the rust was carefully removed. The thickness of the corroded steel plates should be measured very accurately. The thicknesses of all specimens were measured by using 3D laser measurement system. From the data obtained from thickness measurements the specimens were categorized into three different corrosion conditions according to the minimum thickness ratio (μ). In here the tensile tests were conducted in order to clarify the material properties of test specimens, such as yield strength, modulus of elasticity, ultimate strength, and Poisson ratio can be calculated. Compression test is basically followed to achieve material parameter buckling strength of corroded steel specimens. Here 5mm/min loading speed is provided to the specimen. From the machine it can be obtained Load Vs Displacement graph.

2.2 Classification of Corrosion Levels

All specimens that obtained for the experiment are not being at same corrosion conditions. Hence it is very important to classify corrosion conditions to a 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 based on the numerical values that were obtained from the thickness measurements of each specimen. Three basic corrosion conditions were introduced during this study to be used for reliable remaining strength estimation of actual corroded steel structures They are,

1. Minor Corrosion
2. Moderate Corrosion
3. Severe Corrosion

Corrosion condition of the specimens categorized according to the μ value of each specimen. And μ value obtained from Appuhamy et al (2011) [1]. Table 1 shows the μ value with corrosion conditions.

Table 1: Categorization of corrosion conditions with μ value

μ Value	Corrosion condition
μ> 0.75	Minor
0.75 ≥μ ≥ 0.50	Moderate
μ<0.50	Severe

Where minimum thickness ratio,

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

tmin = minimum thickness
t0 = initial thickness

2.3 Numerical Methodology

Non-linear finite element method was performed for corroded specimens with different corrosion conditions. The three dimensional solid elements with hexahedral nodal points (HX8M) and updated Lagrangian method based on incremental theory was employed in this analysis. Von Mises yield criterions was assumed for material properties. Maximum corroded pit was modelled by using the representative diameter (D*) which could account for the stress concentration effect and the material loss due to corrosion was considered by using the representative avg. thickness parameter (t*avg) (Appuhamy et.al, 2011) [1].

These two parameters called CCM parameters. To classify members according to the corrosion level based on minimum thickness ratio (μ) (Appuhamyet.al 2011) [1]. For modeling of the specimens ANSYS software was used. First the model is created based on the CCM parameters. Material properties assign to the model from properties obtain from non-corroded test specimen. Then one end of the specimen was fixed and incremental load was applied to the specimen. The applied load varies from 0kN to 200kN. The analyses were conducted until they reach their pre-defined termination limits and the load-displacement behavior for model was obtained. The values obtained from the numerical analysis were compared with experimental results and obtained relationship between numerical results and experimental results.

3. Results and Discussion

3.1 Experimental Analysis

From tensile test results the material properties were calculated. Actual material properties are similar to the JIS standards property value. So, tested material is in the standard quality of steel. Table 2 shows the tensile test results and table 3 shows standard for JIS No.05 specimens obtained from Appuhamy *et.al* (2010) [2].

Table 2: Tensile test results

Specimen No.	Elastic modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Elongation at braking (%)
1	185.2	269	427	24.8
2	183.6	275	435	26.39
Average 1 &2	184.4	272	431	25.59
3	179	243	426	18.24
4	181.2	249	411	20.01
Average 3& 4	180.1	246	418.5	19.12

Table 3: JIS standard tensile test results

Elastic modulus (GPa)	Yield stress (MPa)	Tensile strength (Mpa)
200	245	400-500

Totally 14 no. of specimens were tested including, 6 severe corrode members and 4 members for both moderate and minor corrode members. For non-corroded specimen buckling load is obtained as 173.08kN. Figure 3 shows the relationship between minimum thickness ratio (μ) and the buckling load with all specimens in experiment. Here having a coefficient of correlation of R^2= 0.9575 indicates the high accuracy of the experimental results.

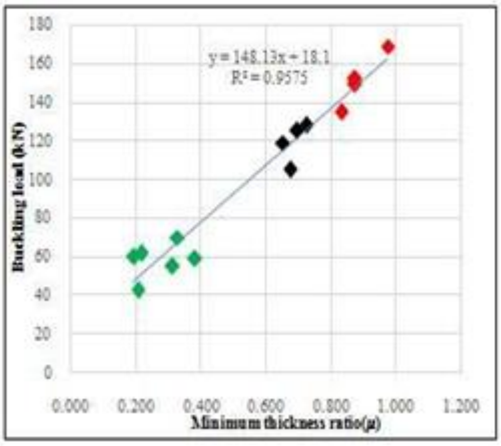

Figure 3: The graph of Minimum thickness ratio Vs Buckling load

From Figure 3,

$$P = 148\mu + 18 \quad (2)$$

Where,

P= Buckling load

μ= Minimum thickness ratio

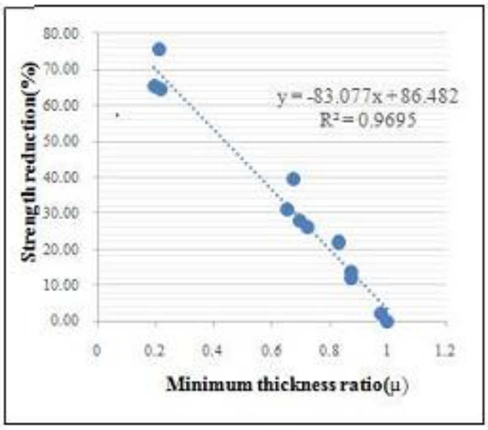

Figure 4: The graph of strength reduction Vs minimum thickness ratio

Figure4 shows the relationship between minimum thickness ratio (μ) and the strength reduction as a percentage with all specimens in experiment. Here having a coefficient of correlation of R^2 = 0.9695. From Figure4,

$$E = -83\frac{t_{min}}{t_0} + 86.5 \quad (3)$$

Where, E = Strength reduction as a percentage, t_{min}= Minimum thickness ratio and t_0 = Initial thickness.

By this equation strength reduction can be calculated with using easily measurable parameters through a quick and careful site investigation.

3.2 Experimental Analysis

First, analytical modeling of th e non-corroded specimen was done with above des cribed modeling and analytical features to understa nd the accuracy of the adopted procedure. The variation of bucking load vs. displacement is shown in Figure 5. From numerical analysis conducted for non-corroded specimen it was found that the analytical model results were almost same as the experimental results with having a negligible percentage error of 0.05% in buckling strength. So it can be concluded that the conducted numeral analysis is accurate and the developed analytical model is validated.

Then, all other experimentally successful specimens were modelled to find out variation of specimen compare to numerical values. Numerical and experimental buckling load variation of the specimens is shown in Figure 6 and the percentage difference between experimental and numerical buckling strength is almost less than the 5%. So it was revealed that a very good comparison of the strength variation can be obtained for all corrosion specimens for the proposed analytical model. Having a coefficient of correlation of R^2 = 0.99 indicate the accuracy and the possibility of numerical investigation method to predict the buckling strength of actual corroded specimens.

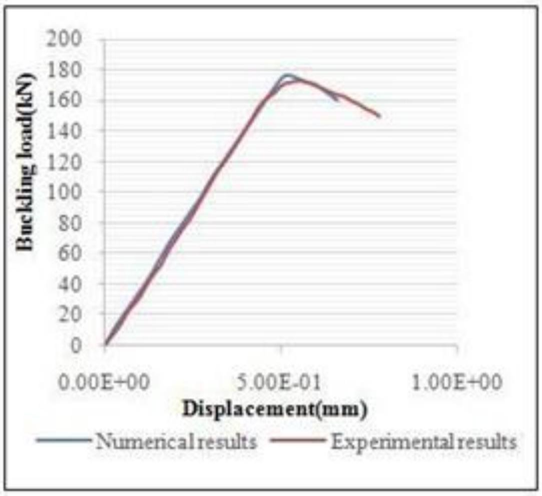

Figure 5: Load displacement variation of non corroded specimen

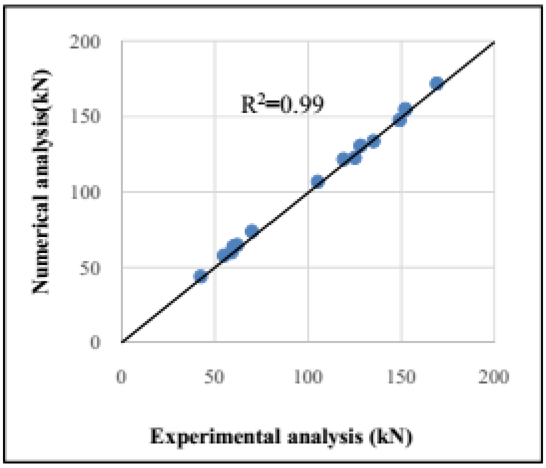

Figure 6: The graph of buckling load vs. Displacement for numerical and experimental

4. Results and Discussion

The residual strengths are decreased with the severity of corrosion and minimum thickness ratio (μ) can be used to for a quick estimation of their strength degradation. Equation obtained for strength reduction due to corrosion,

$$E = -83\frac{t_{min}}{t_0} + 86.5 \qquad (4)$$

Where, E = Strength reduction as a percentage, t_{min}= Minimum thickness and t_0= Initial thickness.

Involved parameters of proposed equation are easily measurable and it will reduce the contribution of the errors occurred during the practical investigation of a corroded member. Further this method is simple and hence can be used for the maintenance management of steel bridge infrastructures with better accuracy. Strength reduction can be obtained as a percentage by substituting the minimum thickness of the corroded members in the structure to the above equation. So it will give clear idea about the stability of the member with compression. If the strength reduction percentage is not much higher value, then it can be used as a simple method to strengthen the structure. If the strength reduction of structures is higher, then structure cannot withstand for the load longer time.

Non-linear FEM Analytical results indicated a very good comparison of the experimental and the analytical load-elongation behaviours for all three classified corrosion types. So, it can be concluded that the adopted numerical modeling technique can be used to predict the remaining buckling strength capacities of actual corroded members accurately. So, it is evident that this numerical modelling procedure can be extended to establish 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 in future studies.

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