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STATISTICAL ANALYSIS OF TENSILE BEHAVIOR OF CORRODED STEEL BARS

HAIJUN ZHOU[1], XUEBING LIANG[1], YIFAN ZHOU[1], FENG XING[1]

[1]*Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University, Shenzhen, China.*

E-mail: haijun@szu.edu.cn

Abstract: A comprehensive mechanical behavior model of corroded rebar including an assessment of the variability and the correlation between the parameters is essential for assessing the residual loading capacity of corroded reinforced concrete structures. Twenty-nine samples of corroded steel bars from a demolished bridge located in the eastern part of Shenzhen were tested. The rebar was tensile loaded by MTS300. The nominal strength and actual strength of the corroded rebar were calculated to assess the effects of corrosion. The test data and reanalyzed published test results for naturally and artificially corroded steel bars were further evaluated by linear regression analysis. The variability and correlation coefficients were compared for two types of corrosion methods. It was confirmed that yield strength, ultimate strength, and dimensionless elongation decreased with an increase in the mass loss. A strong correlation was observed between yield strength and ultimate strength for the corroded rebar samples, while the correlation was moderate between strength, dimensionless elongation, and mass loss. A statistical analysis indicated no obvious difference between the results for the naturally and artificially corroded steel bars.

Keywords: rebar; corrosion; mechanical behavior; regression analysis; variation; correlation

1 Introduction

The corrosion of the reinforcement material has long been a serious deterioration issue for load-carrying aging reinforced concrete (RC) structures (Q. Feng 2015). The reasons of rebar corrosion may be contributed to aggressive ion (such as chloride) attack and concrete carbonation (Almusallam 2001), especially the aggressive ion attack. Studies have been conducted to evaluate the effects of reinforcement corrosion on the reliability of RC structures (Mark G. Stewart 2004 and 2009, Luisa Berto 2009, Melchers 2008 and Fabio Biondini 2009); however, most of these studies were highly dependent on empirical models of rebar mechanical deterioration derived from limited data in particular situations. This certainly limits the applicability of the results inferred from these models.

Due to this problem, many experimental studies have been conducted on the corrosion effects on the mechanical behavior of rebar. Test results shown that the tensile behavior of corroded rebar is seriously degraded. However, because the sample size for the tested specimens has been small, it is urgently required to re-analyze these types of data and analyze the corrosion effects on the mechanical behavior.

In this study, 29 rebar samples were obtained from a severely corroded bridge. The rebar samples underwent detailed tests to determine the corrosion effects on the tensile behavior. Subsequently, published test data were reanalyzed, and a linear regression analysis was performed to clarify the effects of the corrosion on the mechanical behaviors of the rebar, in addition, a comparison of the differences between natural corrosion and artificial corrosion was also performed.

2 Test program

The corroded steel bar samples used in this study were obtained from a demolished reinforced concrete bridge located in the eastern Shenzhen special economic zone, in the Guangdong Province of southern China. The bridge was demolished and the corroded steel bars were cut using a cutting machine. And 29 corroded steel bars were obtained.

In this study, the corrosion level of the steel bar samples were regarded as the ratio of the mass loss. Tensile tests were carried out using MTS300. The test was controlled by displacement with a loading velocity of 20mm/min.

3 Test results

3.1 *Fracture characteristics of corroded steel bars*

In this test, the corroded steel bars exhibit two forms of section fracture: normal section fracture (NF) and an inclined section fracture (IF) (Liao 2003). Figure 1(a) shows the NF of the 5th M-N-UZ; the fracture section is perpendicular to the longitudinal axis of the corroded rebar sample and the edge of the fracture section is jagged. Figure 1(b) shows the IF of the 3rd M-W-AZ2; the fracture is at an angle of about 45^{o} to the longitudinal axis of the corroded steel bar samples and its edge is smooth. It was found that most of the IF occurred for a high corrosion level with the pitting corrosion penetrating into the fracture area (Figure. 1(b)).

(a) Normal section fracture (5th M-N-UZ), (b) inclined section fracture (3rd M-W-AZ2)
Figure 1. Two different sectional fractures

3.2 *Stress-strain curves*

In this study, the original section area was used to calculate the stress of the corroded steel bar samples. Using the steel bars of the 3rd pier as an example, the stress-strain curves of the corroded steel bars with different corrosion levels are shown in Figure.2.

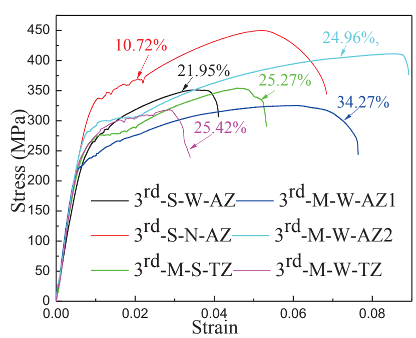


Figure 2. Nominal stress-strain curves of corroded steel bars

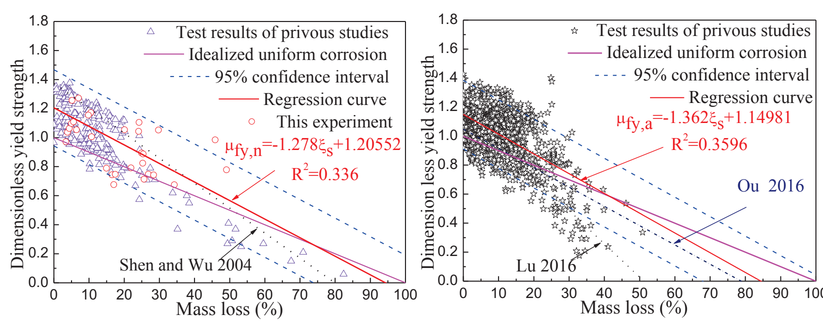
From Figure 2, it can be seen that the yield plateau of the stress-strain curves is greatly reduced for some of the corroded steel bar samples; this is actually related to the transformation of the tensile fracture to a brittle fracture. Both the strength and the deformation capacities of the corroded rebar samples tended to decrease with an increased corrosion level.

4 Data collection and statistical analysis

Because the number of samples was limited in the above-mentioned test, the published test results were reanalyzed statistically. Also, due to the different strengths of the steel bars in the collected dataset, the yield strength of the corroded bars was normalized with respect to the standard value of the yield strength of the rebar specimens. The dimensionless yield strength was defined as the yield strength of the corroded steel bar samples divided by the standard value of the yield strength. So is the ultimate strength and elongation.

4.1 *Dimensionless yield strength*

Figure 3(a) and (b) show the dimensionless yield strength of the naturally and artificially corroded rebar, respectively. Both types of corroded rebar showed clear decreasing trend of the dimensionless yield strength as the mass loss increased.



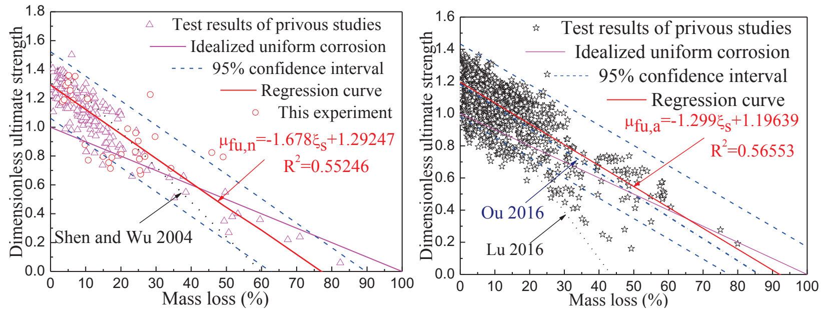
(a) Natural corrosion (b) Artificial corrosion

Figure 3. Dimensionless yield strength vs. mass loss

The linear equations proposed by Shen and Wu 2004 are also shown in Fig. 3(a); the data indicate that the two regression lines derived in this study and the regression line by Shen and Wu 2004 are not far from each other. However, the regression line of Shen and Wu 2004 over-predicts the yield strength when the mass loss is lower than 30%. An idealized uniform corrosion line ((0,1) to (1,0)) is plotted in Fig. 3(a) for comparison. It shows that an idealized uniform corrosion has safety margin at a lower corrosion level; however, this margin decreases as the corrosion level increases. Figure 3(b) shows nearly the same slope for the two regression lines of this study and of Ou 2016 for the dimensionless yield strength of the artificially corroded rebar samples. These lines are also close to the lines for the natural corrosion. However, the regression line from Lu 2016 exhibits a clear difference. It should be noted that the regression formula in Lu 2016 was based on test data of a corrosion level of less than 16%. Our comparison showed that large errors resulted when the regression line was extrapolated to the entire range of the corrosion level. Figure 3 also shows that there are only a few specimens scattered outside of the confidence interval; there are more outliers in Figure 3(b) than in Figure 3(a), which may be because there are more data in Figure 3(b), but it may be also attributed to the different artificial corrosion methods.

4.2 *Dimensionless ultimate strength*

Figure 4 shows that the dimensionless ultimate strength decreased considerably with increases in the corrosion level.



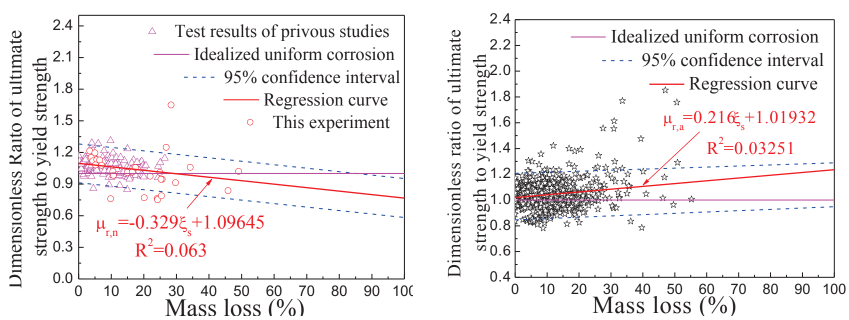
(a) Natural corrosion (b) Artificial corrosion

Figure 4. Dimensionless ultimate strength vs. mass loss

Figure 4(a) shows that there is a considerable difference in the regression lines of this study and of Shen and Wu 2004 for the natural corrosion; the line based on Shen and Wu 2004 exhibits a faster decrease. Another obvious difference was that the safety margin of the idealized uniform corrosion line was smaller when compared to the dimensionless yield strength. This might suggest that the ultimate strength was more sensitive to and correlated with the corrosion compared to the yield strength. Figure 4(b) shows that the regression line of Ou 2016 is nearly parallel to the lines derived in this study. It should be noted that the linear regression line of Shen and Wu 2004 had a significantly greater slope than the lines derived in this study for yield and ultimate strength; this suggests that the variability in strength was much higher for the corroded rebar than for the intact rebar.

4.3 *Dimensionless ratio of ultimate strength to yield strength*

Figure 5 shows the dimensionless ratio of the ultimate strength to the yield strength for naturally and artificially corroded rebar samples.



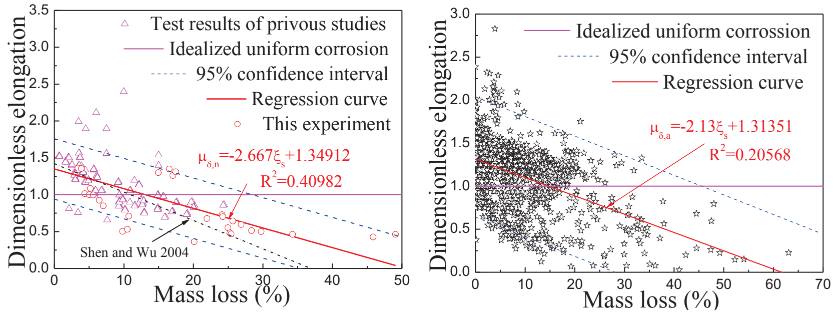
(a) Natural corrosion (b) Artificial corrosion

Figure 5. Dimensionless ratio of ultimate strength to yield strength vs. mass loss

Corrosion is almost no effects on the dimensionless ratio of the ultimate strength to the yield strength because the coefficients of determination were close to 0 for the naturally and artificially corroded specimens. This phenomenon was also observed in Ou 2016, but the mechanisms require further investigation.

4.4 *Dimensionless elongation*

Figure 6 shows that the dimensionless elongation decreases with increases in the corrosion level for the naturally and artificially corroded steel bars. It should be noted that the slope of the dimensionless elongation was almost twice the value of the slopes for the dimensionless yield strength and the dimensionless ultimate strength; this indicates that the ductility decreased much faster than the strength of the corroded rebar.



(a) Natural corrosion (b) Artificial corrosion

Figure 6. Dimensionless elongation vs. mass loss

4.5 *Variation and correlation coefficients*

In this paper, the coefficients of variation for the strength and elongation parameters were analyzed. It was found that the variations in the dimensionless yield strength and dimensionless ultimate strength were both larger than 15%. However, a significantly larger variation of greater than 36% was observed for the dimensionless elongation. The coefficient of variation of these parameters is relatively large for engineering applications. And the correlation coefficient for the parameters was further discussed, indicating very weak to very strong correlations. The mass loss, the dimensionless yield strength, and the dimensionless ultimate strength for artificially and naturally corroded steel bars show strong correlations (55%-88.63%). The correlation coefficient for the dimensionless ratio of ultimate strength to yield strength and mass loss is very low. In conjunction, with the linear regression results, these data suggest that corrosion has no effects on the ratio of ultimate strength to yield strength.

There was an interesting difference between natural corrosion and artificial corrosion with regard to the correlation coefficients related to dimensionless elongation. For artificial corrosion, the correlation coefficient (45.44%) for the dimensionless elongation and mass loss was lower than the value for natural corrosion (64.29%). However, the correlation coefficients for the dimensionless elongation with dimensionless yield strength and ultimate strength were larger than the values for natural corrosion (41.92% and 54.6%). These differences in the correlation coefficients between naturally corroded and artificially corroded rebar may suggest a slight difference between the artificial and natural corrosion that results in changes in the mechanical behavior and requires further investigation.

5 Conclusions

This study evaluated the mechanical behaviors of corroded rebar based on experimental tests and statistical analysis of samples from previously reported test data; the following conclusions can be drawn:

- The parameters of the mechanical behavior based on the nominal intact rebar area, including the nominal yield strength, ultimate strength and dimensionless elongation decreased with increases in the mass loss of the rebar. But corrosion was almost no effects on the dimensionless ratio of ultimate strength to yield strength.

- A linear regression analysis of the data showed a significant reduction in the dimensionless yield strength, dimensionless ultimate strength and dimensionless elongation as the mass loss increased. The dimensionless elongation decreased faster than the other two parameters, which indicated that the ductility decreased faster than the strength for the corroded rebar;
- The coefficients of variation for the dimensionless yield and ultimate strength were greater than 15% for the corroded rebar; and the coefficient of variation for the dimensionless elongation was greater than 30%. These values are relatively large for engineering applications when compared with non-corroded rebar. There were moderate correlations between the strength, mass loss, and elongation.
- There was significant difference between the results for the naturally and artificially corroded steel bars based on the statistical analysis. However, further investigations are required because our conclusions are based on a large number of re-analyzed samples and large differences were observed for certain groups of samples.

Acknowledgments

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References

Q. Feng, P. Visintin and D.J. Oehlers, Deterioration of bond-slip due to corrosion of steel reinforcement in reinforced concrete. Magazine of Concrete Research, 68(15), 68-781, April,2016.

A.A. Almusallam, Effect of degree of corrosion on the properties of reinforcing steel bars, Construction and Building Materials. 15 (8), 361–368, December,2001.

Mark G. Stewart, Spatial variability of pitting corrosion and its influence on structural fragility and reliability of RC beams in flexure, Structural Safety, 26, 453–470, October,2004.

Mark G. Stewart, Mechanical behavior of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams, Structural Safety, 31,19–30, January,2009.

Luisa Berto, Renato Vitaliani, Anna Saetta, Paola Simioni, Seismic assessment of existing RC structures affected by degradation phenomena, Structural Safety, 31,284–297, July,2009.

R.E. Melchers, C.Q. Li, W. Lawanwisut, Probabilistic modeling of structural deterioration of reinforced concrete beams under saline environment corrosion, Structural Safety, 30, 447–460, September,2008.

Fabio Biondini, Dan M. Frangopol, Lifetime reliability-based optimization of reinforced concrete cross-sections under corrosion, Structural Safety, 31, 483–489, November,2009.

Yu-Chen Ou, Yudas Tadeus Teddy Susanto, Hwasung Roh, Tensile behavior of naturally and artificially corroded steel bars, Construction and Building Materials, 103,93–104, December,2015.

D.J. Shen, S.X. Wu, Experimental Study on Mechanical Properties and the Corrosion Model of Steel Bar in Concrete under Atmosphere Condition, China concrete and cement products, 3,46-50, July, 2004. (In Chinese).

C.H. Lu, S.Q. Yuan, P. Cheng, R.G. Liu, Mechanical properties of corroded steel bars in pre-cracked concrete suffering from chloride attack, Construction and Building Materials. 123, 649–660, July, 2016.

J.Y. Liao, Analysis of effectiveness of metal components (M), Chemical Industry Press, Beijing, 2003. (In Chinese)