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Tensile behavior of naturally and artificially corroded steel bars

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HIGHLIGHTS

- Presenting the tensile test results of naturally corroded steel bars.
- Presenting the tensile test results of artificially corroded A706 deformed steel bars.
- Examining the differences in the tensile behaviors between naturally and artificially corroded steel bars.

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ABSTRACT

The tensile behaviors of corroded steel bars are important in the capacity evaluation of corroded reinforced concrete structures. However, information on the tensile behaviors of naturally corroded steel bars is scarce. Moreover, differences in tensile behaviors between steel bars from natural and artificial corrosion are not well-understood. In this study, tensile testing was conducted on corroded steel bars from a residential building exposed to natural chloride attack, and from A706 corroded steel bars obtained from artificial corrosion using the impressed-current method. Based on the test results, reduction factors were proposed to relate the tensile behaviors with the corrosion mass loss for both the naturally and artificially corroded bars. Moreover, reduction factors from previous studies for both naturally and artificially corroded steel bars were collected. Comparison of reduction factors from this study and previous studies has shown that reductions factors for bars naturally corroded by chloride attack are generally larger than those by carbonation corrosion. Moreover, it is more appropriate to use the impressed-current method on bars embedded in concrete than on bare bars to simulate natural corrosion caused by chloride attack. On the other hand, reduction factors from the impressed-current method on bare bars are generally closer to those from natural carbonation corrosion than bars embedded in concrete.

1. Introduction

Corrosion of reinforcing steel bars is a common problem faced by many existing reinforced concrete structures. The two most common causes for corrosion of steel bars are chloride attack and concrete carbonation. The former is more common, and is typically caused by airborne salt, de-icing salt, and/or chloride contaminated aggregate. The latter is caused by carbon dioxide from the air and/or water. Corrosion affects the tensile behaviors of steel bars. It reduces the cross-sectional area, and hence the load-carrying capacity of the bars. Moreover, it induces non-uniform reduction in the cross-sectional area along the length of the bars (pitting corrosion), and hence decreases the deformation capacity of the bars [14,31]. These effects on the tensile behaviors of the bars could be significant. They should be properly considered in evaluating the capacity of existing structures with corroded reinforcement.

Due to the non-uniform nature of corrosion distribution, the tensile behaviors of corroded steel bars cannot be estimated simply by reducing the cross-sectional area in proportion to the corrosion mass loss. They are usually determined by tensile testing of bars with various corrosion. Ideally, testing should be conducted on corroded bars from natural corrosion (e.g. [35,27,23,31,32,36]). However, it takes time for natural corrosion to progress and removal of corroded bars from structures that are still in use is typically not possible. Therefore, many previous studies on tensile behaviors of corroded steel bars obtained the bars from artificial corrosion. The methods of artificial corrosion included the

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Notation

A_s	cross-sectional area of corroded steel bars
df	degree of freedom
E_{s0}	elastic modulus of un-corroded steel bars
E_{sc}	elastic modulus of corroded steel bars
f_s	stress of steel bars
f_{us}	ultimate stress of steel bars
f_{ys}	yield stress of steel bars
f_{us0}	ultimate stress of un-corroded steel bars
f_{usc}	ultimate stress of corroded steel bars
f_{ys0}	yield stress of un-corroded steel bars
f_{ysc}	yield stress of corroded steel bars
H_0	null hypothesis/the statement being tested in significance test
n	number of samples
R^2	coefficient of determination
t_{crit}	critical value from two-tailed Student's *t*-test
t_{test}	test statistic result from Student's *t*-test
$x(\%)$	degree of corrosion mass loss (%); i.e. $x = 10$ denotes 10% corrosion mass loss
β_E	reduction factor for elastic modulus
β_{fu}	reduction factor for ultimate stress
β_{fy}	reduction factor for yield stress
β_l	reduction factor for elongation
$\beta_{\varepsilon u}$	reduction factor for ultimate strain
$\beta_{\Delta sh}$	reduction factor for yield plateau length
Δ_{shs0}	yield plateau length of un-corroded steel bars
Δ_{shsc}	yield plateau length of corroded steel bars
ε_s	strain of steel bars
ε_{shsc}	strain of corroded steel bars at the onset of strain hardening
ε_{us0}	ultimate strain of un-corroded steel bars
ε_{usc}	ultimate strain of corroded steel bars
ε_{ysc}	yield strain of corroded steel bars
μ	sample mean
ρ	significance level
σ^2	sample variance

impressed-current method on bare bars [14,34] and on bars embedded in concrete [13,26,1,14,24,25,36,19], salt spray on bare bars [8–11,7] and bars embedded in concrete [11,7], cyclic wetting and drying on bars embedded in concrete [24,25], and cyclic wetting and drying with impressed current on bars embedded in concrete [12,34]. The impressed-current method is the most common method of artificial corrosion because corrosion process can be completed in a shorter time than the others. The corrosion current density in the impressed-current method used in the studies stated previously ranged from 0.01 to 2.4 mA/cm^2, whereas in natural corrosion, the density typically ranges from 0.001 to 0.003 mA/cm^2 [34]. The influence of such differences in the corrosion current density on the tensile behaviors of corroded steel bars is still not clear. Apostolopoulos et al. [11] and Xia et al. [34] showed that corrosion patterns from artificial corrosion with bars embedded in concrete had more pitting than those from artificial corrosion with bare bars. Du et al. [15,16] observed that for the same corrosion mass loss, corrosion had a more significant effect on the tensile behaviors of plain round bars than deformed (ribbed) bars, and had a more pronounced effect on the smaller bars than larger bars. The reason for the former observation is that reduction in the rib area of deformed bars due to corrosion hardly affects the loading capacity of the bars. On the other hand, reduction in cross-sectional area due to corrosion in plain round bars occurs entirely in the sectional area that carries the external load. The reason for the latter observation is that for a given ratio of maximum local corrosion penetration to the average corrosion penetration, the maximum local corrosion penetration in a smaller bar has a greater effect on the load-carrying capacity of the residual cross sectional area. However, their effects are not significant enough to necessitate different tensile behavior models between plain round and deformed bars, or between smaller and larger bars [14–16].

Simulation of the tensile behaviors of corroded steel bars in evaluating the capacity of a corroded structure requires the information on the yield point, yield plateau (if present), and ultimate point of the corroded bars. However, most of the studies stated previously do not provide all the information, particularly for the modulus of elasticity and ultimate strain. And, as stated previously, data on the tensile behaviors of corroded steel bars from natural corrosion are few and lack information on the modulus of elasticity and ultimate strain. This prevents the comparison between naturally and artificially corroded steel bars in such tensile behaviors. Therefore, the first objective of this study was to provide more experimental information on the tensile behaviors of naturally corroded deformed steel bars. Data on the modulus of elasticity and ultimate strain were measured. The second objective was to test the tensile behaviors of artificially corroded A706 [5] deformed steel bars, which have not been tested in the literature. Corrosion was induced by the impressed-current technique. With the test data from this research and from the literature, the third objective was to examine the differences on the tensile behaviors between naturally and artificially corroded steel bars.

2. Experimental program

2.1. Process to obtain naturally corroded steel bars

Naturally corroded deformed steel bars in this study were obtained from a corroded residential building complex located close to the coastline of northern Taiwan (Fig. 1). The building was constructed in the 1970s. Because of the close proximity to the coastline, this building was directly exposed to sea wind. At several locations of the building, concrete and corroded steel bars samples were taken. The process started by removing the concrete cover of the region suspected of steel bar corrosion using an electric jackhammer. Some of the concrete cover blocks were brought back to the laboratory to examine their chloride-ion content. After removing the cover concrete, the corroded steel bars were cut using an electric grinding machine. In some cases, the concrete cover had already spalled due to severe corrosion of steel bars. Corroded steel bar samples were removed from columns, beams, and walls from the first, second, and third floors. Only a small number of corroded steel bars were cut from each location so that the structural capacity of the building was not significantly affected. Fig. 2(a) and (b) show a corroded beam before and after removing the cover concrete. It can be seen that although no rust was seen on the surface of the beam (Fig. 2a), the bars had suffered severe corrosion (Fig. 2b). The corrosion mass loss for the piece of the longitudinal steel bar sample removed from the beam was 28.7% (Fig. 2c). The corroded steel bar samples were brought back to the laboratory to examine their corrosion mass loss and tensile behaviors. The corroded steel bars contained D13, D16, and D19 deformed steel bars. A total of 18 corroded steel bars were obtained.