Prediction of Hydrogen Embrittlement of Reinforcing Steel Bars in Concrete Poles

Takuya Kamisho, Ryuta Ishii, and Masayuki Tsuda

Abstract

Concrete poles are key components of the infrastructure facilities that support telecommunication services. Although the reinforcing steel bars in concrete poles rarely deteriorate under normal operating conditions, the combination of various adverse conditions may lead to hydrogen embrittlement. To enable safer and more economical maintenance of concrete poles, we have been investigating how to predict hydrogen embrittlement of reinforcing steel bars in concrete poles by means of accelerated tests to determine how tensile stress, hydrogen content on the surface of the reinforcing steel bars, and temperature affect the fracture probability and time to fracture. This article presents an overview of the technology for predicting hydrogen embrittlement, including the evaluation results of fracture probability, time to fracture, and their prediction accuracies.

Keywords: prediction of deterioration, concrete poles, hydrogen embrittlement

1. Introduction

Japan's social infrastructure was intensively constructed during the period of high economic growth in the 1960s and 70s, and as many of these structures are now aging, the cost of maintenance is increasing. The number of skilled maintenance personnel is also decreasing yearly due to the decline in the working-age population stemming from Japan's declining birthrate and aging population. These factors are poised to make the maintenance of social infrastructure quite difficult in the future. To solve this social problem, it is necessary to develop technologies to maintain infrastructure facilities safely and economically.

Concrete poles are key components of the infrastructure facilities that support telecommunication services in Japan. NTT owns about 7 million concrete poles throughout the country, and they are a familiar infrastructure in our daily lives. If an accident such as breakage of a concrete pole due to deterioration occurs, serious damage may result, so all concrete poles are meticulously maintained. The maintenance of concrete poles is currently very expensive, so a safer and more economical maintenance technology for concrete poles is required.

A concrete pole is a hollow reinforced concrete structure with a tensile strength guaranteed with the reinforcing steel bars in the concrete. Prestressed concrete, where compressive stress is applied by reinforcing steel bars to which tensile stress has been applied in advance, is used for concrete poles to suppress cracking. Although these reinforcing steel bars rarely deteriorate under normal operating conditions, the combination of various adverse conditions may lead to hydrogen embrittlement.

Hydrogen embrittlement is a phenomenon in which hydrogen penetrates a metal and reduces its strength under tensile stress, leading to cracking and fracture. The phenomenon known as "delayed fracture" occurs when hydrogen penetrates a metal under constant load and causes fracture to occur after a certain period. It is difficult to predict hydrogen embrittlement of reinforcing steel bars in concrete poles because the mechanism underlying it is not yet fully understood. Therefore, we have been investigating methods of

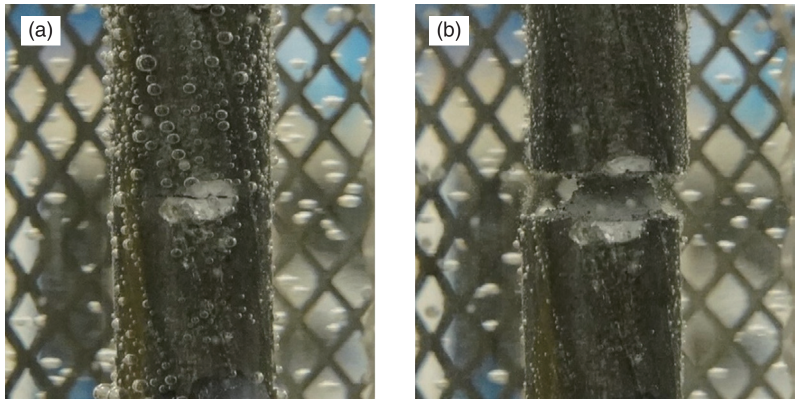


Fig. 1. Fracture of reinforcing steel bar from accelerated test of hydrogen embrittlement: (a) immediately before and (b) immediately after fracture.

predicting such hydrogen embrittlement to enable safer and more economical maintenance. This article presents an overview of the technology for such prediction.

2. Prediction of hydrogen embrittlement

Hydrogen embrittlement of reinforcing steel bars in concrete poles occurs when hydrogen is generated by corrosion of the bars and penetrates them with excessive tensile stress. Since concrete is usually an alkaline environment, corrosion of the bars does not occur in most cases. However, when concrete poles are deflected by excessive load, the concrete cracks and becomes neutralized, then the bars corrode. This deflection also applies excessive tensile stress to some of the reinforcing steel bars. The risk of hydrogen embrittlement increases when hydrogen is generated due to the corrosion of reinforcing steel bars with excessive tensile stress.

The occurrence of hydrogen embrittlement is determined by the tensile stress on and hydrogen content and temperature of the reinforcing steel bars. We can estimate the magnitude of the tensile stress on the bars by measuring the amount of deformation of the concrete pole, and the temperature can be determined from meteorological data. If the hydrogen content in a reinforcing steel bar is known, it should be possible to predict the hydrogen embrittlement of that bar from the deformation data of the concrete pole and meteorological data. In this study, we predicted the hydrogen embrittlement of reinforcing steel bars in concrete poles by deriving the relational expressions of the fracture probability and time to fracture obtained from an accelerated test. We can use these values in place of those in the actual environment.

2.1 Accelerated test of hydrogen embrittlement

Hydrogen embrittlement of reinforcing steel bars is expected to take ten years or more to occur in an actual environment. Since this length of time is impractical for an actual experiment, we conducted an accelerated test to generate hydrogen embrittlement fractures in a shorter time by increasing the hydrogen content in the reinforcing steel bars (**Fig. 1**). We then evaluated the relationship between hydrogen embrittlement and each variable.

The accelerated test was carried out by applying a predetermined tensile stress to a reinforcing steel bar using a tensile testing machine and charging hydrogen into the reinforcing steel bar. The bar was immersed in a test solution using a test cell, and the hydrogen was charged using a cathode charging method in which hydrogen was generated by electrolysis through the current flow. We used a test solution of 1 mol/L $NaHCO_3$ with a predetermined amount of NH_4SCN, which increased the amount of hydrogen penetration. The hydrogen content in the reinforcing steel bar was controlled by the amount of NH_4SCN added. The temperature was controlled by circulating water at a predetermined temperature in the outer layer of the test cell.

2.2 Prediction of fracture probability

Hydrogen embrittlement of reinforcing steel bars may or may not occur under the same environmental conditions, so we express whether a reinforcing steel bar will fracture in the future as the fracture probability.

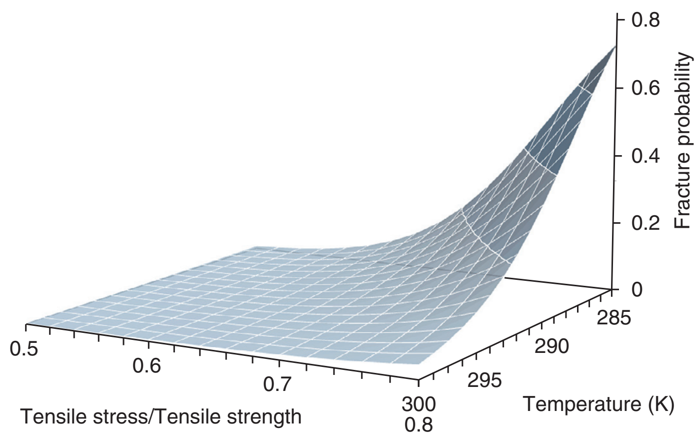


Fig. 2. Relationships between fracture probability, tensile stress, and temperature.

The fracture probability increases when both the tensile stress applied to a bar and the hydrogen content in the bar increase. The fracture probability becomes almost zero when the tensile stress and hydrogen content are low enough. In addition, we assume that the fracture probability is affected by temperature since the mechanical properties of reinforcing steel bars and the diffusion behavior of hydrogen change as temperature changes.

We used logistic regression analysis to quantitatively evaluate the relationship between the fracture probability and each variable. This type of analysis is typically conducted to evaluate the probability when the objective variable is binary (e.g., fracture or not fracture). We can determine how the fracture probability changes depending on each variable of hydrogen embrittlement by defining the fracture of a reinforcing steel bar from the accelerated test as 1 and the non-fracture as 0 then conducting logistic regression analysis.

The relationships between the fracture probability, tensile stress, and temperature at a certain hydrogen content on the surface of a reinforcing steel bar after repeated accelerated tests under various conditions are shown in **Fig. 2**. We can see that the fracture probability increased with increased tensile stress and decreased temperature, and the risk of hydrogen embrittlement increased at high tensile stress and low temperature. In the future, it should be possible to predict the fracture probability in an actual environment by substituting the values of each variable in the environment with the relational expression of the fracture probability obtained from the accelerated tests.

2.3 Prediction of time to fracture

When a reinforcing steel bar fractures due to hydrogen embrittlement, the time to fracture changes depending on the environmental conditions. It is clear that the time to fracture decreases with increasing tensile stress and hydrogen content, and that the time to fracture is affected by temperature as well as the fracture probability, but the interactions among the variables, including temperature, are not yet clear.

Regression analysis using a simple linear model cannot be used to effectively evaluate the relationship between the time to fracture and each variable because of the complex interactions among variables. Therefore, we evaluated this relationship by applying variable transformation analysis and maximum likelihood estimation to the time-to-fracture data obtained from the accelerated test.

The relationships between the time to fracture, tensile stress, and temperature at a certain hydrogen content on the surface of a reinforcing steel bar after repeated accelerated tests under various test conditions are shown in **Fig. 3**. We can see that the time to fracture decreased with increased tensile stress and decreased temperature. This indicates that there is a risk of fracture in a short time at high tensile stress and low temperature. In the future, it should be possible to predict the time to fracture in an actual environment by substituting the values of each variable in the environment with the relational expression of the time to fracture obtained from the accelerated tests.

2.4 Evaluation of prediction accuracy

To apply the relationship between the fracture probability and time to fracture to the maintenance of

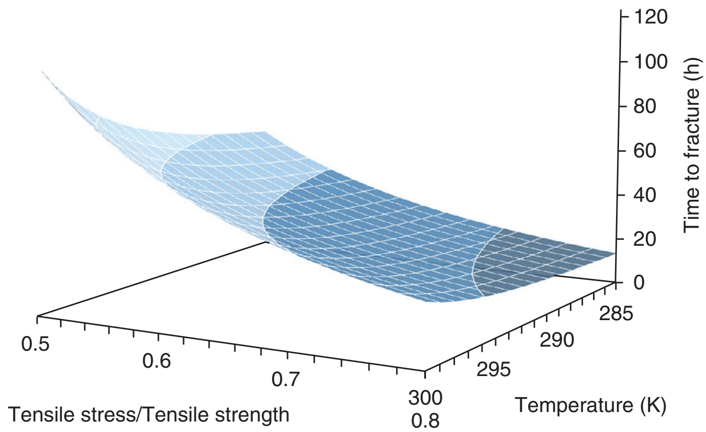


Fig. 3. Relationships between time to fracture, tensile stress, and temperature.

concrete poles, we need to know the prediction accuracy.

We evaluated the accuracy of the fracture probability as determined from the percentage of correct predictions, defining the predicted fracture probability ≥ 0.5 as fracture and < 0.5 as no fracture. The evaluation results indicate that the prediction accuracy of the fracture probability was 0.87, which demonstrates that sufficient prediction accuracy was obtained.

Next, we checked the accuracy of the time to fracture by examining the predicted vs. measured plot of the time to fracture. This plot is a graph in which the predicted value is plotted on the horizontal axis and the measured value on the vertical axis. The closer the plot is to the diagonal line, the better the prediction accuracy. The results are shown in **Fig. 4**, where the plots of the measured values represent the mean of the measured values and the error bars represent ± standard deviation. We can see that the plots were gathered around the diagonal line, which indicates that sufficient prediction accuracy was obtained. We also examined another quantitative measure of accuracy, the mean absolute percent error (MAPE), and found that the MAPE of the mean value of the time to fracture was 14%, which confirms that sufficient prediction accuracy was obtained.

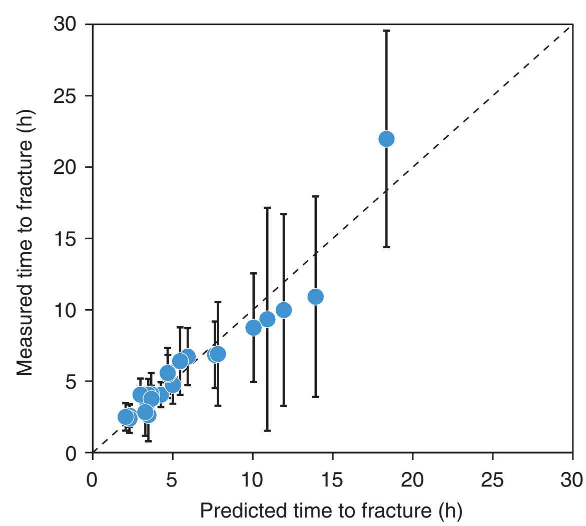
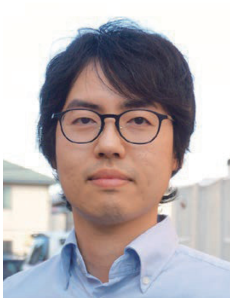


Fig. 4. Predicted vs. measured plot of time to fracture (plots represent mean of measured values, and error bars represent ± standard deviation).

3. Conclusion

To enable safer and more economical maintenance of concrete poles, we examined how to predict hydrogen embrittlement of reinforcing steel bars in concrete poles by means of accelerated tests to determine how tensile stress, hydrogen content on the surface of the bars, and temperature affect the fracture probability and time to fracture. We derived the relational expression of the fracture probability and time to fracture of these reinforcing steel bars and found that sufficient prediction accuracy was obtained. In the future, it should be possible to predict the fracture probability and time to fracture in an actual environment by substituting the values of each variable in the environment with the relational expressions of the fracture probability and time to fracture obtained from the accelerated tests.



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