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Probabilistic model for steel–concrete bond behavior in bridge columns affected by alkali silica reactions

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ABSTRACT

Past research has shown that in concrete bridges, cements with high alkali content combined with reactive siliceous aggregates can result in alkali silica reaction (ASR) in the presence of sufficient moisture. There is a concern that ASR may form at the steel–concrete interface and weaken the bond behavior in RC columns. This could result in a reduction of the structural capacity of columns and overall bridge reliability. Therefore, to accurately assess the column and bridge reliability over the service life of the structure, it is important to account for the possible effects of ASR on the steel–concrete bond behavior in the lap-splice region. This paper develops a probabilistic model of the steel–concrete bond behavior that considers the effects of ASR. The proposed model is formulated starting from a currently available bond–slip model suggested by CEB-FIP. Unknown parameters in the bond–slip model and their statistics are assessed through a Bayesian approach using available data from the load testing of eight large-scale bridge column specimens constructed to study the effect of ASR on the bond behavior in the lap-splice region. The experimental data do not directly show the bond behavior, but are in terms of the force–displacement response of the full specimens. Therefore, to assess the parameters in the bond–slip model, a finite element model is constructed to obtain the force–displacement responses as a function of the parameters in the bond–slip model. The results show that the bond stiffness and strength tend to increase for the specimens exhibiting moderate ASR deterioration, but decrease as ASR deterioration reaches a certain level.

1. Introduction

Knowing the current capacity of civil engineering infrastructure is crucial in the optimal allocation of resources for maintenance, repair, and/or rehabilitation of these systems. There are many deterioration mechanisms that can lead to weakening of the structural capacity. Such deterioration mechanisms can be either gradual with respect to time, with one example being the corrosion of the reinforcing steel [1–8] or sudden, in the case of, for example, an extreme loading condition (e.g., associated to a seismic event or a vehicle impact) that can damage a bridge [9–11]. Researchers have observed that cement with high alkali contents combined with reactive siliceous aggregates can result in alkali silica reactions (ASR) in the presence of sufficient moisture [12]. The alkalis and silica react to form a gel-like material that has a high propensity to absorb water. While absorbing water, the gel expands and creates an expansive pressure that can lead to cracking of the concrete. If this reaction occurs at the steel–concrete interface, ASR may weaken the bond and reduce structural capacity. Fig. 1 shows an example column with cracks induced by ASR. Cracks tend to propagate vertically along the length of the column due to Poisson's effect associated with the axial compression from the gravity load.

Non-seismically designed columns in reinforced concrete (RC) bridges commonly contain a lap splice of the longitudinal reinforcement near the base of the column. It is important to ensure that the integrity of the splice is sufficient to allow for the transfer of tensile forces from one bar to the other bar as it is disengaged, so that the column can resist the applied lateral loads. As the bond is critical to the development of reinforcing bars, any possible degradation of the bond behavior in the lap-splice region may directly affect the capacity of bridge columns and the reliability of the entire bridge. Therefore, it is critical to model the bond–slip behavior in columns affected by ASR.

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Fig. 1. Cracking in example columns due to ASR [13].

This paper develops a probabilistic bond–slip model for bridge columns considering different levels of ASR deterioration. Unknown parameters in the bond–slip model and their statistics are assessed through a Bayesian approach using available data from the load testing of eight large-scale bridge column specimens with levels of ASR deterioration. Because experimental bond data were not procured during the testing, to assess the parameters in the bond–slip model, a finite element model (FEM) is developed to obtain force–displacement responses as a function of the parameters in the bond–slip model. The FEM is developed using the commercial finite element program, Abaqus [19], using the same material properties and loading conditions as those in the experimental testing. Finally, the proposed probabilistic bond–slip model is used in a reliability formulation to estimate the conditional probability (or fragility) that the maximum bond stress demand exceeds the bond stress capacity for a given bond stress demand.

This paper first briefly reviews the design and testing information of the large-scale columns. Then the FEM is presented. Next the probabilistic bond–slip model is calibrated using a Bayesian approach. Finally, the two fragilities are estimated to gain further insight in the effects of ASR on the bond–slip behavior.

2. Experiment description

Bracci et al. [13] and Eck et al. [14,15] explored the effects of ASR on multiple large-scale column specimens. This paper includes a short description of the testing of the large-scale specimens and then offers a critical analysis and interpretation of the results. This paper focuses on the physical reasons that could explain the test results. Complete details about the construction materials and process can be found in Bracci et al. [13].

2.1. Specimen design

Bracci et al. [13] evaluated the behavior of large-scale bridge column specimens (0.61 m × 1.22 m cross section) subjected to different levels of ASR deterioration. The specimens contained six #35 M bars overlapped in the 2.74 m splice region. The details about the concrete mixture can be found in Bracci et al. [13]. Fig. 2 shows the dimensions and reinforcement layout. The splice length (2.74 m) was overdesigned by 54% based on the development length calculated using ACI-318 [16] and AASHTO LRFD Bridge Design Specifications [17]. The intention of the overdesign was to evaluate whether ASR deterioration could affect the bond in the splice region and whether this debonding would affect column performance. The axial compressive load typical of bridge columns was applied using a post-tensioning (PT) system, resulting in an initial compression load $N_0 = 2582.1$ kN on the specimens (approximately 10% of the column compressive capacity).

Internal strains caused by ASR expansion, applied load, and concrete creep were measured with strain gages installed in the columns. Fig. 3 shows the location of the 10 strain gages, denoted SG1 through SG10, that were placed on the longitudinal reinforcing bars in the splice region. No strain gages were installed on two control columns, specimens C1 and C2, as no ASR was expected in these two specimens.

2.2. Exposure program

Previous studies show that ASR progresses faster in moist and warm environments [12,18]. Exposure temperatures ranged from the low 10s °C in the winter to the mid $\sim$ 30s °C in the summer months. To accelerate the formation of ASR, the specimens were wet for 15 min, four times a day. The two control specimens, C1 and C2, were stored indoors and were maintained in the dry condition prior to testing. Only specimens C3 through C8 were subjected to wet-dry cycles. Different exposure times were used to develop different levels of ASR deterioration.

2.3. Damage qualification

Damage assessment of laboratory specimens is typically performed using expansion data – larger expansion indicates larger degrees of ASR, potentially more damage, and potentially lower performance. The challenge with field structures is that overall expansion is difficult to measure. Measurement of surface cracks is one approach used to assess damage. One method to process surface crack measurements is to measure cracks widths that intersect with a straight line drawn on the structure, sum these crack widths, and then divide the crack widths by the length of the drawn line. This provides a normalized measure of expansion and is referred to as the cracking index [20,21]. Smaoui et al. [22] assessed concrete blocks exhibiting ASR using this method and reported that surface cracking tends to increase globally with expansion and that the cracking index does provide an average estimate of expansion that is relatively close to actual measured