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Bond life degradation of steel strand and concrete under combined corrosion and fatigue

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ABSTRACT

The destruction of the bond between steel bar and concrete induced by corrosion–fatigue damage is important in concrete-structure research, but related works are few. This study aimed to investigate the corrosion–fatigue damage behavior of the bond in pre-tensioning prestressed concrete structures. We conducted a series of combined actions of corrosion and fatigue (i.e., three levels of corrosion and eight levels of fatigue) chronically for 20 bond specimens of steel strand and concrete. Results showed that the corrosion–fatigue failure of the bond occurred mainly in split mode. The corrosion–fatigue life of the bond decreased with increased fatigue stress range under a constant action of corrosion. Similarly, the corrosion–fatigue life of the bond decreased with increased corrosion current density under constant fatigue action. An empirical model of the corrosion–fatigue bond life was established by regressing and extending the experimental results. From the model, the correlation equation of corrosion and fatigue for the constant life of two million was derived.

1. Introduction

The corrosion of prestressing steel bars of prestressed concrete (PC) structures subjected to severe environmental conditions often results in structural failure [1–4]. When prestressing steel bars are corroded, their tensile performance and bond performance with concrete degrade. However, relevant research has focused mainly on static performance [5–9], which is evidently insufficient because buildings with PC members are particularly susceptible to the combined action of corrosion–fatigue. Many PC structures are required to bear the action of fatigue resulting from road vehicles, trains, and industrial cranes. Solely applying the action of fatigue is not detrimental because the failure would be avoided by controlling the fatigue stress range below the fatigue limit of the material or bond. However, if the eroding action induced by corrosion is applied simultaneously with fatigue, then corrosion would promote the nucleation and extension of fatigue damage and the fatigue limit would be disregarded. The consequence is nonconvergent corrosion–fatigue damage and final failure even when the fatigue stress range is small [10,11].

The present study focuses on the corrosion–fatigue damage of the bond between steel strand and concrete. The bond between steel strand and concrete significantly influences structural performance in terms of the serviceability and load-carrying capacity of PC structures, particularly for pre-tensioning PC structures, because of the anchoring requirement.

Steel bar corrosion has two major effects on the bond. First, corrosion products (loose oxide) envelop the steel bar surface and weaken the adhesion action. Second, the corrosion products expand in volume and form a corrosion expansion force, which may

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result in cover-concrete cracking, thereby weakening the friction and interlock actions. These two results lead to bond-resistance deterioration [12–14], and then members bearing capacity and service performance deterioration [15–17].

The damage of the bond interface induced by fatigue is mainly reflected by the weakening of adhesion and friction during most of the fatigue life (i.e., the initiation stage of fatigue failure). When adhesion and friction are significantly damaged, the bond slip rapidly enlarges and the damage induced by fatigue weakens the interlock actions, which correspond to the stable propagation stage of fatigue failure [18–20].

When corrosion and fatigue occur together, damage to the bond interface induced by corrosion may lead to a decrease in fatigue resistance and accelerate fatigue damage. Al-Hammoud et al. [21] conducted an experiment involving two separate processes, i.e., the accelerated action of corrosion applied initially in isolation to achieve the needed extent and the accelerated action of fatigue applied subsequently in isolation. They aimed to investigate the acceleration effect of steel bar corrosion on the fatigue damage of the bond interface. These processes are conventional methods for investigating the corrosion–fatigue issues in civil engineering [22–26]. However, the two separate processes cannot sufficiently simulate the actual combined simultaneous action of corrosion and fatigue. The corrosion damage of such combined process needs some time to accumulate and reach the corrosion damage degree of the separate process. Thus, the acceleration effect on the fatigue damage of the combined process is less than that of the separate process.

In view of rare related works that investigated the corrosion–fatigue issues based on the combined action of corrosion and fatigue, the combined action was adopted in the present study to analyze the coupled corrosion–fatigue failure of the bond between steel strand and concrete. A series of combined actions was applied chronically for 20 specimens of steel strand and concrete by combining three levels of corrosion and eight levels of fatigue. Accordingly, the corrosion–fatigue failure mode of the bond was observed, the influence of the actions of corrosion and fatigue intensities on the corrosion–fatigue life of the bond was investigated, and the predicted model of the corrosion–fatigue life of the bond was established. Our results can serve as a reference for learning the coupled corrosion–fatigue damage behavior of PC structures.

2. Research significance

The degradation of the performance of materials and structures under the combined action of corrosion and fatigue is a well-established issue. The adverse effect of corrosion and fatigue and particularly their combination on the performance of materials and structures is fundamentally understood. However, comprehension is mainly confined to cases of a single material (e.g., the corrosion–fatigue damage of steel) [27,28], as well as to a qualitative level. The degradation of the bond between steel and concrete under the combined action of corrosion and fatigue differs from that in a single material, which is mainly reflected in the corrosion effect. Degradation worsens monotonously for the single material but non-monotonously for the bond, such that the combined process of damage also differs. In this work, a quantitative study on the bond issue under the combined action of corrosion and fatigue was conducted. Results may elucidate the influence of the action intensity of corrosion and fatigue on bond life. The proposed model of bond life may further serve as a reference for quantitative study. The achievement in this paper may enrich the knowledge on bonds under a combined action of corrosion and fatigue.

An experimental study is necessary for the complex issue of combined corrosion and fatigue. However, previous experimental-simulation studies consist of two separate processes of foregoing accelerated corrosion and succeeding accelerated fatigue. The two separate processes cannot simulate the actual combined simultaneous action of corrosion and fatigue. Accordingly, a combined simultaneous action was conducted in this work, where a more rational result was obtained. Moreover, we provided a realistic experimental method of applying a long-term combined simultaneous action of corrosion and fatigue for several specimens, as well as an effective method of applying fatigue load with an assistant spring system for a bond specimen with high rigidity. These methods may serve as a good reference for future related research.

3. Experimental program

3.1. Designing and fabricating specimens

The design of the specimens is shown in Fig. 1. One steel strand of $\phi^{S}15.2$ (1 × 7) 1860 (with ultimate tensile strength $f_{ptk} = 1860$ MPa) was placed bias in the concrete block as bond bar. The tested diameters for the central and outer wires were 5.19 and 5.00 mm, respectively. For convenience, three holes were set for loading the basic bond force.

Concrete with grade C30 (i.e., having a compressive strength of 30 MPa) was used in the experiment. The mixture proportions of water/cement/stone/sand = 0.53:1:1.84:3. The cement used in concrete was Type 42.5 Portland cement, and the aggregates were fine river sand and crushed stone with particle size of 10 mm to 20 mm. Tap water was used to mix the concrete. The average of the compressive strength of the tested concrete tube cured for 28 days was 32.6 MPa. The average bond strength of the aforementioned designed specimens was 4.36 MPa under the condition without action of corrosion and fatigue.

3.2. Corrosion program

The galvanostatic method was used to accelerate the action of corrosion for steel strands. The casted specimens were initially cured for 21 days, and then the casted specimens were immersed in 5% NaCl solution for 7 days to form an essential electrolyte solution in the concrete to apply current conveniently. Afterwards, the specimens were fixed on the experimental setup to apply the action of fatigue synchronously and the action of corrosion by the galvanostatic method with DPS-305CF Type DC stabilized power