Fatigue Behavior of Reinforced and Prestressed Concrete

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This article explores fatigue behavior of reinforced and prestressed concrete components and explains the reasons behind a variety of different exemptions made in Article 5.5.3 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] Let's first explore the behavior of axially loaded components and then extend the discussion to flexural components.

Axially Loaded Prism

To understand the fatigue behavior of reinforced concrete, let us start with the behavior of a steel reinforcing bar cast in a concrete prism with a square cross section and then placed under tensile loads. To facilitate the discussion, let us focus on a typical reinforcing bar tensile test (that is, a "Bar" test) and a test of a reinforcing bar that is embedded at the centroid of a concrete prism with ends protruding (that is, a "Bar + Concrete" test). Refer to **Fig. 1** for illustrations of these tests.

Figure 1. Schematic of axial tensile tests. The specimen on the far left (Bar test) is a steel reinforcing bar, and the specimen at the center of the figure is a reinforcing bar that is embedded at the centroid of a concrete prism with ends protruding (Bar + Concrete test). The right side of the figure shows that upon cracking of the concrete, the stresses along the length of the bar encased in concrete vary. At the location of the cracks, the stress in the reinforcing bar is equal to applied load *P* divided by the area of the bar A_b. The stress between the cracks, in the concrete-encased portion, is lower. All Figures: University of Texas at Austin.

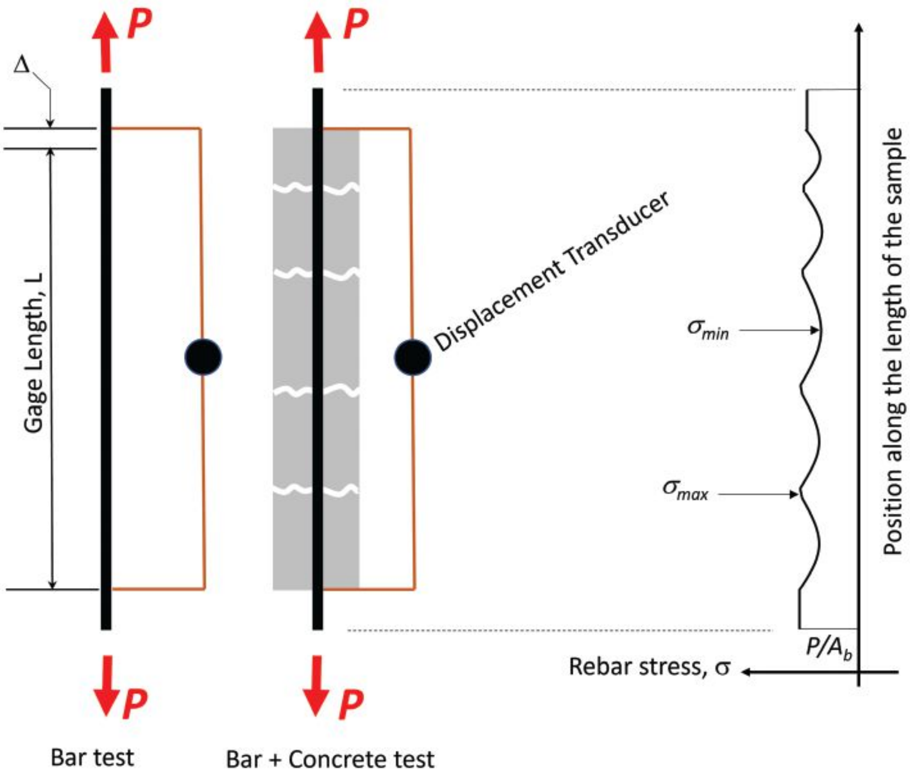

Figure 2 shows the stress-strain relationships from the two tensile tests for ASTM A615[2] reinforcing bars. The reinforcing bar will display a linear-elastic behavior with a modulus of elasticity of about 29,000 ksi up to the yield point, and the yield plateau of this mild reinforcing steel will take place at a stress that is typically slightly greater than 60 ksi. The behavior of the reinforcing bar after the yield plateau—within the strain hardening region—is noted, but that behavior is beyond the scope of our discussion herein.

The behavior of the same reinforcing bar encased in a concrete prism is quite different at low levels of axial strain, before the reinforcement yields. First, note the difference in axial stiffness. The presence of uncracked concrete substantially stiffens the overall response because the axial stiffness of concrete *AE*/*L* is significant even though the modulus of elasticity of typical concrete can be 5 to 7 times less than that of reinforcing bars. The significant increase in stiffness is because the axial prism under consideration has a cross-sectional area that may be 50 to 100 times more than the area of the bar encased in it (for example, a no. 9 bar in a 9 in. × 9 in. cross section). For our example, let us assume that the concrete cracks at 400 psi, as determined in a direct tension test (the cracking strength would be about 750 psi as determined by a modulus of rupture test), and its modulus of elasticity is 6000 ksi. This provides a modular ratio of steel to concrete (29,000/6000 = 4.83). At the point concrete cracks, the stress in the reinforcing bar would be about 2 ksi (1.93 ksi to be exact).

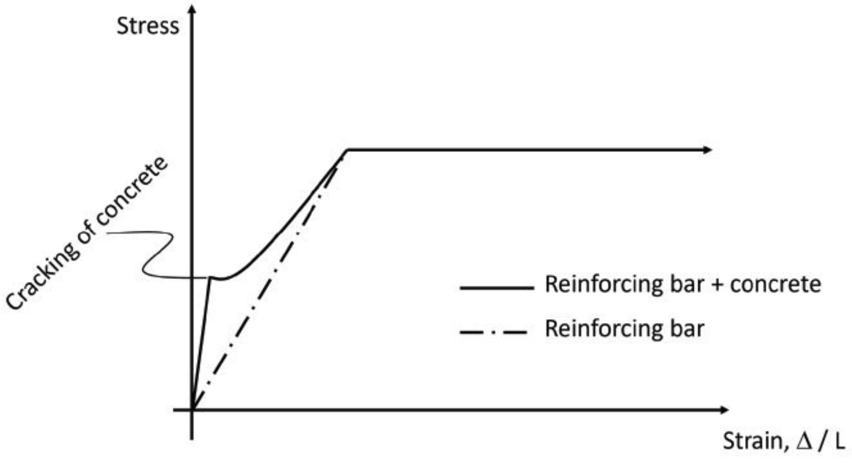

Figure 2. Stress-strain behavior for a tensile test of a reinforcing bar alone and for a reinforcing bar encased in a concrete prism.

Before discussing the post-cracking behavior of the bar encased in the concrete specimen, let us first discuss reinforcing bar fatigue. Fatigue in steel is a function of the mean stress and the cyclic stress applied to the bar. If the stress is low and below a stress level called the "endurance limit," the bar has an infinite fatigue life. As long as the concrete remains uncracked, it is difficult to envision tensile stresses developing a stress range that can lead to finite fatigue life under typical loading scenarios for typical reinforced concrete components. A good example of this type of tensile stress could be a reinforced concrete deck supported on several beams that experiences primary load effects due to "axial" effects that can be attributed to volume changes that the deck concrete experiences, as opposed to live loads supported on the decks.

Upon cracking, the stresses along the length of the bar encased in cracked concrete vary (Fig. 1). At the location of the cracks, the stress in the reinforcing bar is equal to applied load P divided by the area of the bar A_b because concrete does not contribute to the load-carrying capacity at those locations. The actual stress in the reinforcing bar between the cracks drops as the concrete "takes a bite" out of the stresses in the reinforcing bars. That is to say, the bond between the reinforcing bar and surrounding concrete will lead to load transfer from the bar to concrete. Conversely, the presence of concrete between the cracks will stiffen the response, an effect known as "tension stiffening." Importantly, the crack spacing and cross-sectional area of concrete that is stiffening the response of the bar both influence the drop in stress between the cracks. Those subtleties stated, at this stage of the cracked-concrete response, it is possible to envision theoretical scenarios in which the stress range can enter the territory of finite fatigue life and may surpass the endurance limit. At this point, I emphasize "theoretical" because fatigue failures are exceedingly uncommon in concrete bridges. To complete the discussion on the axially loaded component, the stress in both the bare reinforcing bar and the one encased in concrete will top out at the yield strength, and the capacity of the bar encased in concrete will be realized at the location of a crack.

Reinforced Concrete Beam

A natural extension of the preceding discussion is to consider, "How do we go from axially loaded components to flexural elements?" With that as the primary objective, let us look at the behavior of reinforced concrete beams before and after flexural cracking. For simplicity, consider the reinforced concrete beam depicted in **Fig. 3.** Before the flexural cracks form, the stress profile in the reinforcing bars on the flexural tension side of a typical Bernoulli beam follows the overall shape of the bending moment diagram. In our case, this is the bending moment diagram of a simply supported beam with uniform loads. Upon the formation of flexural cracks, and afterward, the stresses in the reinforcing bars will spike at the location of flexural cracks, as shown in Fig. 3. In this condition, the stress range experienced by the reinforcing bars under permanent loads and cyclical application of transient loads may produce stress ranges that may produce finite fatigue lives, at least hypothetically.

Prestressed Concrete Beams

Let us next discuss prestressed concrete girders, focusing our attention on pretensioned concrete beams. By precompressing the flexural tension side of pretensioned beams, we effectively control cracking. Under typical application of live loads, tension flange cracking is not expected in pretensioned components of bridges that are designed in accordance with the AASHTO LRFD specifications. In an effort to improve the expected service life of their bridges, some owners go even further in their bridge design manuals and use zero-tension designs. As a result, they do not expect to see flexural cracking under normal permanent and transient loads. However, under permit loads and superheavy loads, cracking is not only possible but anticipated in some cases. It is important to note that upon removal of such loads from pretensioned concrete girders, the flexural cracks that may form should close. The number of cycles associated with the application of such extreme loads (that is, very few load cycles) in the service life of any given pretensioned concrete bridge is in orders of magnitude less than any finite life (the number of cycles associated with fatigue concerns) we may calculate. We should also recognize that the stress ranges that can be supported by smooth wires in a seven-wire strand can be higher than those that can be tolerated by reinforcing bars, due to the stress concentrations at the locations where deformations (ribs) meet the shaft of the bar. That is to say, for infinite fatigue life, we have a higher stress range for strands than we do for reinforcing bars.

Compressive Stresses in Concrete

In reinforced or prestressed concrete designs, we rely on strands or reinforcing bars to carry tension while we count on concrete on the compression side. What about the fatigue life of concrete under cyclic compressive stresses? According to Article 5.5.3.1 of the AASHTO LRFD specifications, "for prestressed components in other than segmentally constructed bridges, the compressive stress due to the Fatigue I load combination and one-half the sum of the unfactored effective prestress and permanent loads shall not exceed $0.40f'_c$ after losses." This

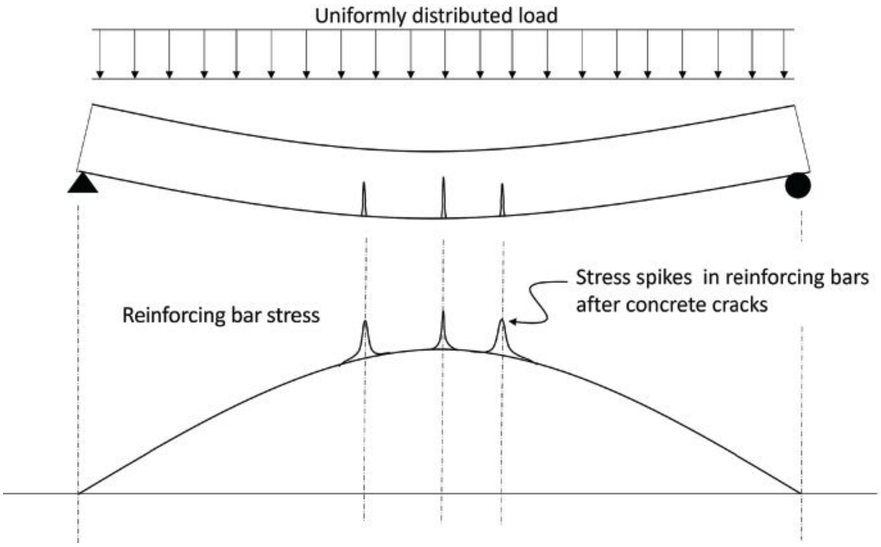

Figure 3. Stress-strain behavior for a tensile test of a reinforcing bar alone and for a reinforcing bar encased in a concrete prism.

stress limitation is intended to virtually eliminate the possibility of microcracking in concrete under repeated application of compressive stresses—a requirement that is easily met in a great majority of cases. This aspect of concrete behavior has not received wide-ranging attention in the research arena over the years, and there is a good reason for that: subjecting concrete to millions of cycles of compressive load with the maximum stress not to exceed 40% of its compressive strength has not produced any ill effects.

Because of the aforementioned material behavior, the AASHTO LRFD specifications offers many exemptions for explicit fatigue considerations, and, again, there is a good reason for these exemptions. Prestressed concrete components that meet Service III stress limit requirements, concrete decks supported on multiple beams, and box culverts are exempt from the checks. Why? We do not know of field problems or calculations that would raise a cause for concern. Even in cases where we check stress ranges in reinforced concrete components, typical stress ranges are very low. After all, fatigue-related failures in concrete components are exceedingly rare to the point of being almost nonexistent. Consideration of the behavioral aspects covered in this article may prove to be useful as context when one reviews the Article 5.5.3 requirements of AASHTO LRFD specifications, as discussed by Dr. Francesco Russo in a Concrete Bridge Technology article in the Winter 2024 issue of *ASPIRE*®.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
2. ASTM International. 2022. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. ASTM A615/A616M-22. West Conshohocken, PA: ASTM International. A