A Crack Is Not a Crack: Mechanics of Reinforced Concrete

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There is a common misconception that all reinforced and prestressed concrete structures crack during their lifespans and all cracks are of equal significance. While some types of cracks are common and to be expected, others are not. A cracked concrete component is a structural feature that is trying to tell us its story. The significance, type, width, and the spacing of the cracks all contribute to the tale being told. The question is, can we understand this story?

This article is the first in a series on cracking in reinforced and prestressed concrete structures and why the conclusion that "a crack is a crack" can be greatly misleading. In this series, we will explore different types of cracks, and address why some cracking types and patterns are a cause for concern, why others require routine monitoring without any significant structural implications, and why some types of cracking require immediate action.

In the context of our aging infrastructure and the need to inspect and maintain our concrete bridges while maintaining the safety of the traveling public, this series will focus on the key aspects of structural behavior. To begin, let us start by focusing on the mechanics of reinforced and prestressed concrete before and immediately after cracking.

First, and as a simple example, let us direct our attention to a 6-in.-thick reinforced concrete component with no. 8 reinforcing bars spaced at 12 in. on center (**Fig. 1**). In other words, in this idealized example, we have about 1% reinforcement in the thin section. For context, it is important to note that this example is intended to facilitate discussion, rather than offer representations of best design practices.

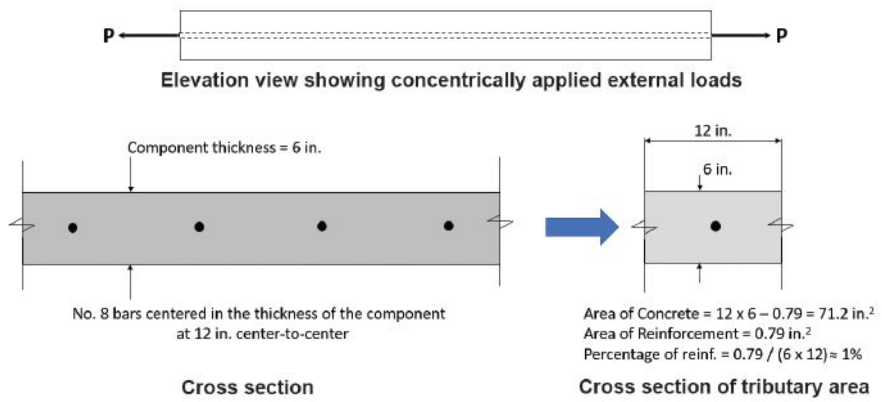


Figure 1. A 6-in.-thick concrete component reinforced with no. 8 bars at 12 in. center-to-center. All Figures and Photos, unless otherwise noted: University of Texas at Austin.

Let us assume that the compressive strength and modulus of elasticity of concrete are 5000 psi and 4000 ksi, respectively. To complete the context for this example problem, let us also assume that the tensile strength of the concrete is 400 psi. Dividing the tensile strength of the concrete by the modulus of elasticity, we can calculate the tensile strain at which cracking will occur: $\varepsilon_{cr} = 0.4$ ksi/4000 ksi = 0.0001 in./in. Assuming that this thin section is uniformly loaded in pure axial tension (Fig. 1), we can make the following observations:

1. Just before cracking, and assuming a perfect bond between the reinforcing bars and surrounding concrete, the strain in the reinforcing bars is equal to the strain in concrete. Multiplying this strain, 0.0001 in./in., by the modulus of elasticity of the steel reinforcement will give us the stress in the reinforcement: 0.0001 × 29,000 ksi = 2.9 ksi. For Grade 60 reinforcing bars, this stress is about 5% of the yield strength of the reinforcing bars. So, if the design criteria for this slab section include a desire to keep the section "crack free" under axial loads in service conditions, we can only use approximately 5% of the yield strength. Typical service-level stresses permitted by the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*,[1] or by any other North American structural concrete design code, is about 36 to 40 ksi. The ratio of the aforementioned numbers indicates that the desire to keep the component crack free could result in the use of impractical levels of reinforcement (that is, more than 10 times what is required). That is neither structurally feasible nor economical. Reinforcement quantities of that magnitude are not recommended in structural designs. Stated differently, before the concrete cracks, reinforcement does not significantly contribute to carrying the load in tension.
2. Upon cracking, concrete sheds the tensile force that it was carrying before cracking. In our example, this force is 71.2 $in.^2$ × 0.4 ksi = 28.5 kips for the tributary area of concrete reinforced by each of the no. 8 bars (Fig. 1). Let us make a reasonable assumption that this component is supporting gravity loads, and hence the load level is expected to stay constant after cracking. Therefore, the 28.5-kip force must be picked up by the reinforcement that is crossing the cracks. This will increase the stress in

the reinforcing bars by 28.5 kips/0.79 in.[2] = 36 ksi. This stress will add to the existing 2.9 ksi in the reinforcing bars. Stated differently, at the location of a crack, the reinforcement will do all the work in supporting the tensile load.

3. In a new loading scenario, let us now assume that the axial tension is introduced by an imposed deformation, as opposed to an externally applied load. That is, let us assume a boundary condition that introduces 0.0001 in./in. of strain due to thermal effects that are present elsewhere on the structure. With that context, we can reasonably assume that the previously described boundary conditions will be maintained and the strain level will remain at 0.0001 in./in. In this case, the loads that will be applied on the remaining portion of the structure by this 6-in.-thick slab component will decrease from (28.5 kips + 2.9 kips) = 31.4 kips to 2.9 kips. In effect, the structural cracking will relieve the restraint forces on the component by about 90%.
4. The width of the crack in the loading scenario described in item 2 would be different (and much wider) than the crack width that would be observed in the scenario described in item 3. Stated differently, the ability of the same percentage of reinforcement to control cracks will vary depending on the boundary condition (load maintained in item 2 and displacement or strain maintained in item 3). In other words, depending on the boundary conditions (imposed load versus imposed displacement), the widths of the observed cracks will be different.

Next, let us consider a scenario in which the actual compressive (and therefore tensile) strength of concrete ends up being much higher than what was specified. With additional tensile strength, the load at which the component will crack increases. That can be an advantage if the component does not crack. However, when the concrete cracks, the observed cracks will be wider than those covered in item 2. In this context, more is not necessarily better. That is, for a given percentage of reinforcement, an increase in concrete material strength that was not accounted for in the original design may lead to wider cracks. If the wider cracking takes place under service loads, that could be a concern.

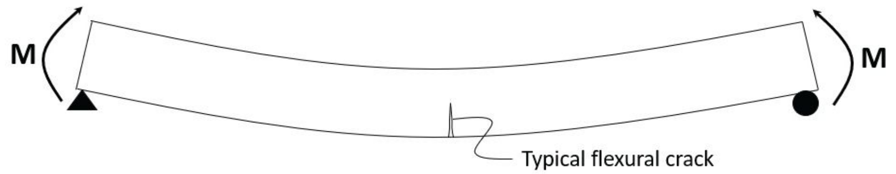


Figure 2. Elevation of a beam under external loads creating a pure-bending condition at midspan.

Next, let us consider beam bending, with the same intent of looking at the strain and stress states just before and at cracking. **Figure 2** illustrates an idealized beam-bending example that we will use to further our discussion. Let us assume the depth of the flexural tension zone in the case of pure bending is about the same as the entire thickness of the component we considered in Fig. 1, approximately 6 in., and the mild reinforcement is placed as shown. **Figure 3** shows that the concrete stress varies linearly through the depth just before flexural cracking, which implies that the force that will be released upon flexural cracking is about half of the force (due to the triangular distribution) considered in Fig. 1, if all else remains the same or comparable. With that setup for comparison established, if we use 1% flexural reinforcement in our beam, we expect the force to be picked up by the flexural tension reinforcement to be approximately half of the tension force we previously determined in the axial load case. Given that the percentage of reinforcement is the same in both examples, we expect the additional stresses that will be picked up by the flexural tension reinforcement to be less than (about half) the 36 ksi we previously calculated. Comparatively speaking, we then expect the "average" crack width to be smaller. The challenge in making this comparison relates to the fact that the flexural crack is widest at the bottom face of the beam. It is somewhat narrower at the location of the flexural tension reinforcement, and as we approach the neutral axis, the crack closes. We see no crack near the neutral axis (point of zero stress) as we move up toward the flexural compression side of the beam.

Let us now take the next step and look into the behavior of a typical pretensioned concrete beam. When typical strands are tensioned in a precast concrete plant, the

Figure 3. Strain and stress states at midspan of the reinforced concrete beam depicted in Fig. 2 just before cracking.

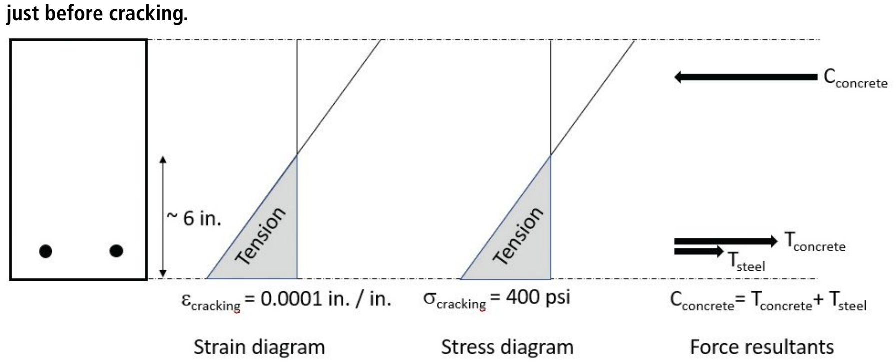
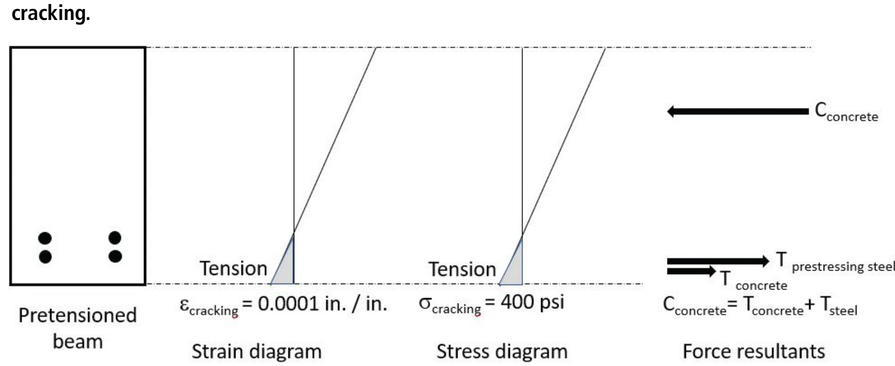


Figure 4. The strain and stress states at midspan of a pretensioned concrete beam just before cracking.



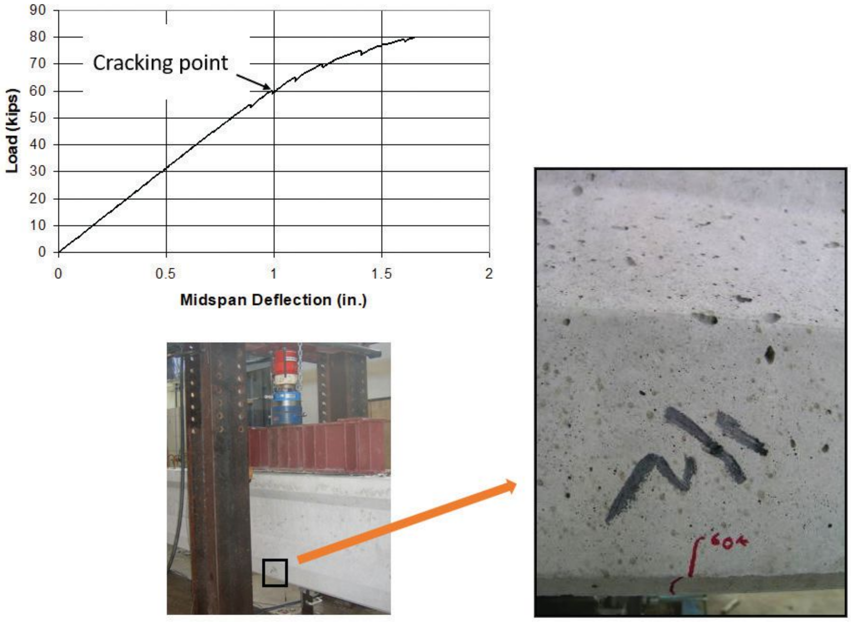


Figure 5. Cracking in a pretensioned concrete I-beam.[2]

stress in those strands is initially slightly over 200 ksi. Let us assume that after the prestress is transferred, the stress in the strands drops to 165 ksi due to elastic shortening of the beam, relaxation of the strands, and creep and shrinkage of concrete. Due to the effects of prestressing, just before flexural cracking under externally applied loads (such as those shown in Fig. 2), the neutral axis would be near the bottom face of the beam, as necessitated by the sectional equilibrium (**Fig. 4**). At cracking, the stress in the strands would be approximately 170 to 180 ksi, and as such, the incremental stress increase in the strands would be a small fraction of the initial prestress.

Figure 5 shows a load-deflection plot from laboratory testing of a pretensioned concrete beam that exhibits the gradual change of the flexural stiffness (that is, the effective EI) when cracking occurs.[2] In this setting, both the formation and propagation of flexural cracks are quite different from those observed in comparable reinforced concrete beams. A key advantage of pretensioned concrete relates to this behavioral attribute. As a consequence, the percentage change in the stress in the strands crossing the flexural cracks is much smaller in magnitude in relation to the percentage change seen in reinforced concrete beams. Naturally, this observation is coupled with smaller crack widths (Fig. 5).

As discussed, cracks differ among axially loaded components, ordinary reinforced concrete beams, and pretensioned concrete beams. A thorough understanding of loading conditions, boundary conditions, material properties, and structural behavior is a prerequisite to our analysis of cracked concrete components. In forthcoming articles, we will look at various other types of cracking.

References

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2. Birrcher, D. B., and O. Bayrak. 2007. *Effects of Increasing the Allowable Compressive Stress at Release of Prestressed Concrete Girders.* FHWA/TX-07/0-5197-1. Austin, TX: Center for Transportation Research, University of Texas at Austin. https://library.ctr.utexas.edu/ctr-publications/0-5197-1.pdf.