A Crack Is Not a Crack: Shear Cracking

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As part of the ongoing *ASPIRE*® series on cracking, this article focuses on shear cracking that may occur in conventionally reinforced concrete members in service. To explore the topic of shear cracking in this article, we will set the context first, establish the guiding principle in engineering mechanics next, and finally provide useful tools from research projects on the subject of shear cracking.

Context

Shear strength of concrete members has been a topic of intense research, discussion, technical debate, and design code and specification development for quite some time. The large number of variables that influence the shear strength of concrete members formed the initial basis of research in the late 19th and early 20th centuries. Some explanations of load transfer from the points of application of loads into the supports involved early versions of strut-and-tie models for structural components.[1,2] As research and development efforts continued around the globe, reinforced and prestressed concrete member designs in the United States for most of the 20th century were based on developing shear force and bending moment diagrams, and designing all sections along the length of structural members by using the demands imposed. Even today, this approach—the sectional design of concrete components—forms the basis for a great majority of our designs in "B regions" (that is, beam regions or Bernoulli regions).

Sectional design of concrete components involves evaluating the demands imposed by a variety of load combinations on each section along the length of a structural component, determining the capacity, and confirming that the capacity of each section is greater than the demands. In this design approach, we use load factors and strength-reduction factors to achieve a target reliability factor that is consistent with the calibration of the applicable design provisions. For cases in which we do not have prestressing force to improve the shear resistance, the nominal shear capacity of a concrete component is the sum of the concrete contribution to shear strength and the stirrup (shear reinforcement) contribution to shear strength. When a prestressing force is present, we should account for the vertical component of the prestressing force, in accordance with design specifications. However, to simplify the discussion, only conventionally reinforced members are considered in this article.

At this point, it is useful to discuss the historical development of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[3] in general terms to further develop the context. Before the first edition of the AASHTO LRFD specifications was introduced in 1994, AASHTO's *Standard Specifications for Highway Bridges*[4] closely followed provisions for shear design that are still part of the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-25) and Commentary (ACI 318R-25)*.[5] With the introduction of the LRFD version of the bridge design specifications, AASHTO adopted a sectional shear design approach that is based on the modified compression field theory (MCFT) originally developed at the University of Toronto. Thus, the current inventory of bridges in the United States contains components that were designed using different approaches. This context serves as a backdrop as we discuss the mechanics of shear resistance in greater detail.

Structural Behavior

To discuss the shear cracking and shear resistance of a typical concrete component, let us consider a beam that is being loaded to levels that exceed typical service loads. More specifically, let us direct our attention to the beam depicted in **Fig. 1** as it is gradually loaded to failure. As the externally applied loads increase, we expect to see the formation of flexural cracks (cracks marked as "A" in Fig. 1). These cracks form when the longitudinal stresses reach the tensile strength of concrete. The typical flexure-shear crack (shown in Fig. 1 as crack "B") forms when a flexural crack that

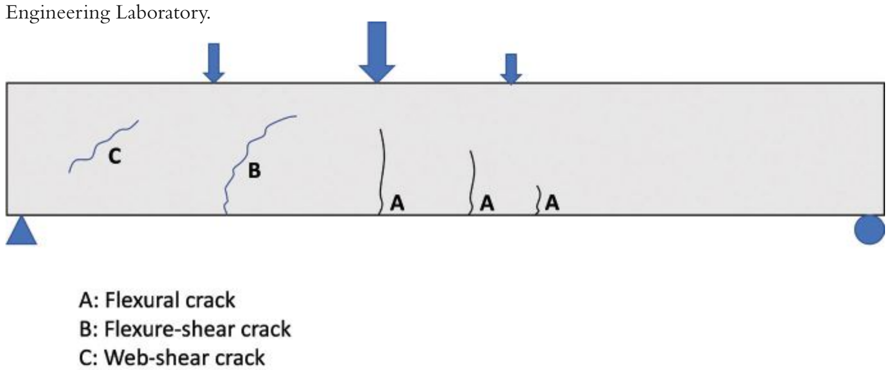

Figure 1. Cracks in a typical reinforced concrete beam. All Photos and Figures: Ferguson Structural Engineering Laboratory.

originally formed when longitudinal tensile stresses reached the tensile strength of concrete turns into a shear crack by changing its inclination due to the presence of shear stresses that change the direction of maximum principal tensile stress. It is important to note that for a flexure-shear crack to form, a flexural crack must form first. A web-shear crack (crack "C" in Fig. 1) forms when the diagonal tensile stress reaches the tensile strength of concrete without penetrating the flexural compression zone or the tensile side of the beam. Such cracks can form in members with thin webs or where large, concentrated forces are applied near the supports. In all cases, the formation of cracks relates to the tensile strength of concrete.

In cases where an adequate quantity of shear reinforcement is present, the initial formation of shear cracks (types B and C) does not signal imminent shear failure of the member. Additional shear cracks are typically needed to push the beam in Fig. 1 toward failure.

As mentioned previously, early versions of shear design provisions in the AASHTO standard specifications mirrored the provisions in ACI 318. Those provisions were predicated on the fact that the shear strength of concrete V_c in a typical beam could be determined at the formation of the initial shear crack (either flexure-shear or web-shear). While the shear transfer mechanism changes after the formation of a shear crack, the design provisions were developed based on the assumption that V_c does not change in magnitude as loading increases. From a behavior standpoint, well after the formation of the initial shear crack, near the ultimate load-carrying capacity, the concrete contribution to shear strength involves the cumulative contributions of shear carried in the flexural compression zone, shear transferred across the diagonal cracks due to aggregate interlock, and flexural tension reinforcement serving as dowels to bridge the cracks. Collectively, these three mechanisms were considered the "concrete contribution to shear strength" and added to the stirrup contribution. However, we gained insight over the years from additional structural tests and came to understand that the tensile strength of concrete is influenced by the component size. Therefore, we realized that the simplified approach that has been used in shear design for decades could be unconservative in some cases because it did not account for the so-called size effect. In 1994, the AASHTO LRFD specifications adopted shear design provisions based on the MCFT, where V_c is attributed to the ability of cracked concrete to transfer shear stresses. With the adoption of MCFT, we no longer view the formation of the initial shear cracks as the "shear strength of concrete"—a perspective shift that represents an important and significant change in bridge design philosophy.

Field Performance of Substructure Components

The formation of shear cracks in the existing inventory of bridges is not uncommon. **Figure 2** shows a straddle bent cap with a rectangular cross section with shear cracks. **Figure 3** shows a variable-depth bent cap that is supported on multiple columns, and **Fig. 4** shows an inverted-tee straddle bent cap. The size of the cracks in Figs. 2–4 have been enhanced for visibility. Shear cracks that formed in service conditions such as those seen in Fig. 2, 3, and 4 served as the reasons for a series of research projects

Figure 2. Straddle bent with a rectangular cross-section and shear cracks. Cracks have been enhanced. Source: Adapted from Birrcher et al.[6]

Figure 3. Multicolumn bent with both shear and shear-flexure cracks. Cracks have been enhanced. Source: Adapted from Birrcher et al.[6]

Figure 4. Straddle bent with an inverted-tee cross section has shear cracks. Cracks have been enhanced. Source: Adapted from Larson et al.[7]

conducted at the Phil M. Ferguson Structural Engineering Laboratory.[6,7] While there are many aspects of these comprehensive research efforts that inform our understanding of the behavior of members subjected to shear-critical loads, I will focus here on the field evaluation component.

Rectangular Bent Caps

Because crack widths can be influenced by the specimen size, the investigators at Ferguson Laboratory conducted large-scale component tests and collected extensive data about the widths of diagonal cracks. Rigorous analysis of the data led to the development of a simple chart that can be used to evaluate the residual capacity in diagonally cracked, conventionally reinforced bent caps with rectangular cross sections; that chart is summarized in **Table 1**. It is important to note that the research team has also identified parameters of secondary nature that contribute to the inherent variability of the estimates summarized in the table.

An examination of Table 1 leads to the following observations:

1. Moving down vertically in the table, for a given diagonal crack width, we can see that a rectangular cap is closer to its design shear capacity if it contains a greater quantity of

Table 1. Diagonal crack width–to–capacity relationship for rectangular bent caps.[6]

Load on the Member, Quantified as a Percent of Ultimate Capacity on Average (± scatter)

Reinforcement \ w_{max} (in.)	0.01	0.02	0.03	0.04	0.05	0.06
$\rho_v = 0.002$ $\rho_h = 0.002$	20 (+10)	30 (±10)	40 (±10)	50 (±10)	60 (±15)	70 (±15)
$\rho_v = 0.003$ $\rho_h = 0.003$	25 (±10)	40 (±10)	55 (±10)	70 (±10)	80 (±10)	90 (±10)
$\rho_v > 0.003$ $\rho_h > 0.003$	30 (±10)	50 (±10)	70 (±10)	85 (±10)	~ Ultimate	~ Ultimate

Notation:
w_{max} = maximum measured diagonal crack width (in.)
ρ_v = reinforcement ratio in vertical direction ($\rho_v = A_v / bs_v$)
ρ_h = reinforcement ratio in horizontal direction ($\rho_h = A_h / bs_h$)
A_v & A_h = total area of stirrups or horizontal bars in one spacing (in.^{2})
s_v & s_h = spacing of stirrups or horizontal bars (in.)
b = width of web (in.)

Directions:
1). Determine ρ_v and ρ_h for bent cap
2). Measure maximum diagonal crack width, w_{max}, in inches
3). Use chart with w_{max}, ρ_v, and ρ_h to estimate % of capacity

Important Notes:
In this chart, the maximum width of the primary diagonal crack in a shear-critical member is linked to the load on the member, quantified as a percent of its ultimate capacity. The intent of this chart is to aide field engineers in evaluating residual capacity in diagonally-cracked, reinforced-concrete bent caps subjected to concentrated loads at a/d ratios between 1.0 and 2.0. This chart was developed from crack width data from 21 tests of simply-supported reinforced concrete beams with overall heights between 42" and 75". The testing was conducted at an a/d ratio of 1.85. Data has shown that diagonal crack widths may slightly decrease with decreasing a/d ratio. The same crack width at a smaller a/d ratio indicates that a higher percentage of capacity from the above chart has already been reached.

This chart should be used in conjunction with sound engineering judgement with consideration of the following limitations:
-variability in crack widths in general (± scatter)
-members loaded at a/d < 1.85 may be at slightly higher % of capacity
-differences between field and laboratory conditions
-implications of an unconservative estimate of capacity

This chart is not intended to be used for inverted-tee bent caps.

crack-control reinforcement. For example, for a diagonal crack width of 0.03 in., 70% (±10%) of the cap's capacity would be exploited by the loads acting on the cap if both the crack-control reinforcement ratio in the horizontal direction ρ_h (skin reinforcement) and the crack-control reinforcement ratio in the vertical direction ρ_v (stirrups) were greater than 0.3%. The same crack width would signal a 40% (±10%) utilization of the ultimate capacity if the crack-control reinforcement were 0.2% in both the horizontal and vertical directions. This makes sense: the greater the amount of crack control reinforcement, the larger the load needed to open the crack.

2. For a given crack-control reinforcement ratio, as the diagonal crack widths increase, the rectangular bent cap comes closer to using its ultimate capacity. Let's take the 0.3% crack-control reinforcement ratio as an example. A diagonal crack of 0.010 in. points to a 25% (±10%) usage of the total capacity, whereas a diagonal crack width of 0.040 in. indicates that the component is loaded to 70% (±10%) of its ultimate shear capacity.

As we can see from the examples discussed, the chart presented in Table 1 is a useful decision-making tool for the inspection of a rectangular bent cap with diagonal cracks. Importantly, interpolation among various entries in the table is possible.

Inverted-Tee Bent Caps

The chart presented in Table 1 is intended for rectangular bent caps, and its application to inverted-tee bent caps is not advisable, as will be illustrated. To develop an understanding of the behavior of inverted-tee bent caps, the research team at Ferguson Laboratory tested a series of inverted-tee bent caps.[7]

At the conclusion of their comprehensive testing on inverted-tee caps, the team had a wealth of data about the formation and opening of shear cracks throughout the loading regimen to which the caps were subjected. The insights gained in the testing served a variety of objectives, and interested readers are advised to read the full research report.

In their investigation of the field performance of inverted-tee bent caps, the researchers followed a similar format to that used in the study of rectangular bent caps. **Table 2** summarizes the recommendations of the researchers. Importantly, the trends discussed previously regarding the observations on Table 1 for rectangular bent caps remain valid for inverted tees, although the percentage of the available capacity that is exploited differs. For example, for a diagonal crack width of 0.04 in. in an inverted-tee cap reinforced with a crack reinforcement ratio of 0.3% in each direction, we can see that the cap is loaded to 75% (±15%) of its capacity, as opposed to 70% (±10%) for a similar rectangular cap, as discussed earlier. This difference in the percentages can be attributed to tension-chord loading (inverted-tee section) being more "punishing" on a cap than compression-chord loading (rectangular section) would be. Conversely, we can see that the difference between 70% and 75% is small in relation to data scatter observed in the tests (±10% for rectangular caps and ±15% for inverted-tee caps). Interestingly, while the application of loads in the ledges of an inverted-tee cap adds a tension field as hanger reinforcement works to hang the load up to the compression chord, the ability of a diagonal crack to transfer stresses across the crack seems to be at a similar level of maturity for a given diagonal crack width.

Table 2. Relationship between diagonal crack width and capacity for inverted-tee bent caps.[7]

Load on the Member, Quantified as a Percent of Ultimate Capacity on Average (± scatter)

Reinforcement \ w_{max} (in.)	0.01	0.02	0.03	0.04	0.05	0.06
$\rho_v = 0.003$ $\rho_h = 0.003$	30 (± 10)	50 (± 15)	65 (± 15)	75 (± 15)	80 (± 15)	90 (± 10)
$\rho_v = 0.006$ $\rho_h = 0.006$	40 (± 10)	65 (± 10)	85 (± 10)	~ Ultimate	~ Ultimate	~ Ultimate

Notation:

w_{max} = maximum measured diagonal crack width (in.)
ρ_v = reinforcement ratio in vertical direction ($\rho_v = A_v / bs_v$)
ρ_h = reinforcement ratio in horizontal direction ($\rho_h = A_v / bs_h$)
A_v & A_h = total area of stirrups or horizontal bars in one spacing (in.^{2})
s_v & s_h = spacing of stirrups or horizontal (skin reinf.) bars (in.)
b = width of web (in.)

Directions:

1). Determine ρ_v and ρ_h for bent cap
2). Measure maximum diagonal crack width, w_{max}, in inches
3). Use chart with w_{max}, ρ_v, and ρ_h to estimate % of capacity. Interpolate for intermediate values ρ_v and ρ_h. For unequal ρ_v and ρ_h use the average of the two when reading off the chart.

Important Notes:

In this chart, the maximum width of the primary diagonal crack in a shear-critical member is linked to the load on the member, quantified as a percent of its ultimate capacity. The intent of this chart is to aid field engineers in evaluating residual capacity in diagonally-cracked, reinforced-concrete bent caps subject to concentrated loads at a/d ratios between 1.0 and 2.5. This chart was developed from crack width data from 33 tests of simply supported reinforced concrete inverted-T beams with overall heights between 42" and 75". The testing was conducted at a/d ratios of 1.85 and 2.5.

This chart should be used in conjunction with sound engineering judgment with consideration of the following limitations:

-variability in crack widths in general (± scatter)
-members loaded at a/d < 1.85 may be at slightly higher % of capacity
-differences between field and laboratory conditions
-implications of an unconservative estimate of capacity

This chart is intended to be used for inverted-T bent caps. Not applicable with reinforcement ratios above 0.6%

Informed Decision-Making

In all cases, engineering judgment and analysis are necessary to determine the appropriateness of structural retrofit and/or load posting for a bridge that is supported by a cap with diagonal cracks. Tables 1 and 2 can be viewed as additional tools in the toolbox to inform decision-making about reinforced concrete bridge substructure members with diagonal shear cracks.

To the best of my knowledge, such information does not readily exist for prestressed concrete (both pretensioned and post-tensioned concrete) superstructures. With that said, the MCFT-based shear design provisions in the AASHTO LRFD specifications may also come in handy in evaluating the capacity of bridge components in service when tools such as those presented in Tables 1 and 2 do not apply. Thoughts and research to consider for shear capacity evaluation include the following:

- The AASHTO LRFD specifications adopted MCFT, at least in part, because of the theory's accuracy in predicting the shear behavior of reinforced and prestressed concrete members. MCFT-based predictions offered the consistency needed to calibrate the shear design provisions in the AASHTO LRFD specifications.

- After the AASHTO LRFD specifications adopted MCFT-based shear design provisions in 1994, many research teams investigated the provisions' accuracy and conservativeness. For example, Nakamura et al.[8] examined an extensive database of shear design provisions from around the globe and concluded that the MCFT-based provisions were the most accurate.

- Zaborac et al.[9] and Holt et al.[10,11] offer detailed approaches that can be used in evaluating the inventory of prestressed concrete beams. The approaches described in these publications have a strong theoretical basis and therefore serve as great tools to use when evaluating prestressed concrete superstructures. Importantly, the approaches outlined in these documents to aid in the load-rating process employ MCFT in an inverse manner compared to that used in design. (Design starts with loads and designs or details a member, whereas inverse analysis starts with a crack pattern and/or structural details and then estimates the load acting on the member.)

Concluding Remarks

Structural behavior of shear-critical components has been a topic of significant interest to many researchers and funding agencies since the end of 19th century and the beginning of the 20th century. Significant insights gained around the globe have helped in the code and specification development processes. Research and development efforts for the AASHTO LRFD specifications and AASHTO's *Manual for Bridge Evaluation*[12] have helped advance state-of-the-art procedures used to evaluate structural components that show signs of distress. The evaluation of the existing inventory of structures, part of the stewardship efforts that are underway, remains a topic of interest in the research community. In the future, I fully expect that the toolbox for bridge evaluation will be further populated by useful tools and techniques developed in the United States and around the globe. As the bridges in the current U.S. inventory age and the traffic loads continue to increase, we will need to extend the service lives of our bridges and participate in the responsible renewal or retrofit of those bridges that require such actions.

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