TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM

Project Summary Report 0-1851-S

Project 0-1851: Study of Flexural Cracking in Cantilever Standard Design Interior Bent Caps

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PROJECT SUMMARY REPORT

Cracking in Reinforced Concrete Bent Caps: Summary Report

Unexpected cracking in reinforced concrete (RC) bent caps at outside column locations (canti-levered regions) occurs occasionally in Texas bridges (see Figure 1). Smaller vertical flexural cracks exist in the bent over the supporting column and larger inclined flexure-shear cracks propagate from the girder loading region to the supporting column. This cracking typically occurs during service loading.

From engineering drawings of a sample bent cap constructed prior to 1989, several reinforcing details are noted with regard to their possible contribution to cracking:

(1) top longitudinal reinforcement without hooks or end plates at the bent cap end may have bond (or slip) problems due to insufficient embedment;

(2) shear span-to-depth ratio of about 1.5, which is close to the deep beam classification in the American Association of State Highway and Transportation Officials (AASHTO) and American Concrete Institute (ACI) 318 codes; and

(3) longitudinal skin reinforcement evenly distributed through the member depth or concentrated in the web tension region of the bent cap side faces per previous and current codes, respectively.

In addition to detailing issues, several previous and current design requirements may affect cracking. Code level serviceability requirements attempt to control flexural cracking by both limiting the level of tensile stress in the longitudinal reinforcement and the distribution of this reinforcement. AASHTO Standard Specifications, based on allowable stress design, limit the service stress in the longitudinal reinforcement (Grade 60) to 24 ksi. Alternatively, AASHTO Load Factor Design and Load and Resistance Factor Design limit the service load stress in the longitudinal reinforcement to 60 percent of the bar yield stress f_y, and a stress limit derived from the bent cap cross-section and distribution of the longitudinal reinforcement, plus a crack width parameter '*z*' (170 and 130 kips/in. for moderate and severe exposures, respectively).

Similarly, previous specifications in ACI 318-95 required that a quantity '*z*', based on the amount, arrangement, and tensile stress of the longitudinal reinforcement (limited to $0.60f_y$) at a critical bent cap section, be below the specified values for interior and exterior exposures (175 and 145 kips/in., respectively). These expressions indicate that an arrangement of several bars at moderate spacing are more

Figure 1. Cracking in TxDOT Bent Cap

effective in controlling surface crack widths than an equivalent amount of reinforcement made up of larger bars at larger spacing.

The most recent version of ACI 318-99 bases its only requirement for crack control on limiting the spacing between the longitudinal tension reinforcement. The service load stress in the longitudinal reinforcement (limited to $0.60f_y$) and the clear cover from the nearest concrete surface in tension to the surface of the longitudinal tension reinforcement determines the spacing limit.

What We Did ...

In an attempt to evaluate the causes of this unexpected cracking in RC bent caps, a total of 16 full-scale bent cap specimens were designed, constructed, and tested in the Testing, Machining, and Repair Facility at Texas A&M University. The experimental program consisted of three groups of specimens that subdivide these 16 specimens. Within each group, specific design and detailing characteristics were isolated and studied.

Figure 2 shows a sample bent cap subassembly specimen in the experimental test setup. The non-tapered end of the specimen represents the continuous span of the bent, where a portion of the longitudinal reinforcement was hooked at the ends to represent the bars that extend along the length of a multi-column bent cap. At the cantilevered (tapered) end, the top reinforcement extended 17 in. beyond the center of the applied load, which is typical of Texas Department of Transportation (TxDOT) practice. Transverse shear reinforcement, consisting of #5 closed stirrups at 6.25 in. spacing, was provided along the bent cap length. Other design details varied according to their association with one of the three specimen groups described below.

Group #1 – Existing Detail

- Horizontal side face (skin) reinforcement in two layers of #5 bars spaced evenly through the member depth and three layers of #4 bars concentrated within the web tension region.

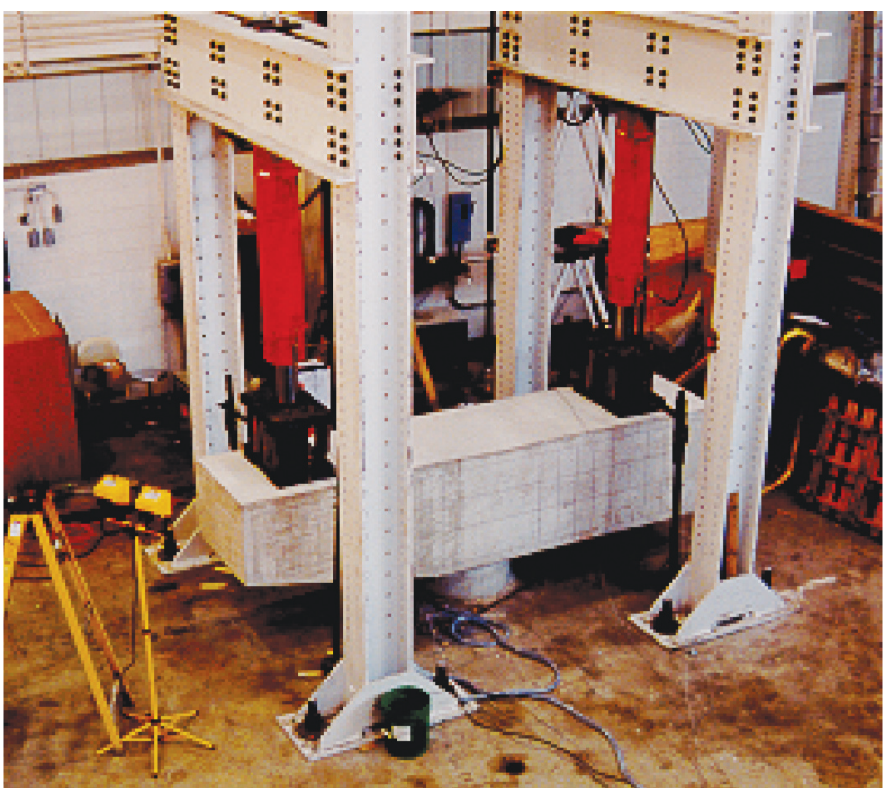

Figure 2. Experimental Test Set-Up

Group #2 – Modified Details

- Bent cap critical section for flexure design at the equivalent column face versus column center. Specimen geometry under consideration indicates that if a linear strain gradient exists from the applied load to the support center, then demands at the column face are underestimated by about 20 percent.
- Amount and arrangement of the longitudinal reinforcement to vary the ACI 318 '*z*' factor calculated at the column face for crack control during service loading.

Group #3 – More Modified Details

- Enhanced shear strength and core concrete confinement using overlapping (double) stirrups for transverse reinforcement at the same 6.25 in. spacing.
- Amount and arrangement of the longitudinal reinforcement to vary the '*z*' factor and satisfy the spacing requirements of the current ACI 318-99 code.

Quasi-static monotonic loading was applied to the specimens using two 600 kips actuators, symmetrically located at a distance of 4.5 ft. from the column center (see Figure 2). Beneath each actuator, a wide flange steel section and a pair of neoprene bearing pads were used to distribute the common actuator load to the specimen. This loading configuration reflects the location of longitudinal bridge girders at 9 ft. centers seated upon a transverse bent cap supporting two adjacent spans.

Specimens were loaded in 40 kips increments to failure. After each increment, the load was temporarily held constant and cracks were visually identified, measured using crack width identification cards, and recorded on the specimen along with the corresponding actuator load. As load increased and cracks widened to 0.013 and 0.016 in. (benchmark maximum crack widths corresponding to the crack width parameter '*z*' in AASHTO and ACI 318-95), the corresponding loads were again recorded on the specimen adjacent to the cracks.

Strain gauges were placed on the reinforcement at various locations in each specimen. Several displacement transducers monitored deformations at critical locations, such as near the applied loading. Measured data from the instrumentation were acquired and stored using a PC-based data acquisition system.

Non-linear finite element modeling (FEM) analyses of several bent cap specimens were also conducted to complement the experimental program. Two parameters used in the modeling, namely the concrete tensile strength and the shear retention factors, were varied in an effort to best correlate with the experimental results. Concrete and reinforcing steel strength parameters were taken from compression cylinder tests and mill records, respectively. The effect of concrete confinement from the closed stirrups was accounted for by a modified constitutive relationship.

What We Found ...

For RC bent caps at outside column locations with a shear span-to-depth ratio of about 1.5:

- Flexural cracking initiated when longitudinal reinforcement stresses were about 4 to 7 ksi, well below service stress limits in current codes. Therefore, some degree of cracking can be expected when using established RC design procedures.
- At low serviceability load levels, concentrating the side face reinforcement within the web tension region, as specified in current codes, more effectively controlled vertical flexural cracking than evenly distributed horizontal reinforcement placed through the member depth.
- Slip of the longitudinal reinforcement in the cantilever region due to bond failure was not a contributing factor to cracking in the specimens.
- Tensile stress in the longitudinal reinforcement was the primary factor influencing flexural cracks in the bent cap specimens. Other factors which appear in code serviceability expressions for crack control were shown to have little influence on cracking. Test results showed that limiting the service load longitudinal reinforcement stress to about 30 and 24 ksi at the equivalent column face corresponded to maximum expected crack widths of 0.016 and 0.013 in., respectively.
- Although the specimen flexural capacity was adequately predicted using standard beam bending theory, standard beam theory did not accurately predict the actual strain profile in the bent cap specimens. Reinforcement strains at and near the support were typically larger along the side face of the bent caps when compared with reinforcement strains at the bent cap center for the same transverse plane. In addition, the longitudinal strains were generally higher at some distance below the longitudinal reinforcement level due to significant shear demands.
- Following initial cracking of the specimens, the longitudinal reinforcement strains near the column center were consistently higher than the reinforcement strains near the equivalent column face. Therefore, the location of the critical section for flexural design based on ultimate load conditions existed within the column support region, not at the equivalent column face.
- Field investigations of in-service bent caps with similar shear span-to-depth ratios showed that inclined flexure-shear cracks were generally larger than flexural cracks. Bent cap specimens with nominal transverse reinforcement displayed a similar cracking behavior during service loads and failed in a brittle shear manner along about a 45 degree plane between the loading point and the column face. Specimens with enhanced shear strength using overlapping transverse reinforcement had reduced inclined flexure-shear cracking throughout the entire load history, and developed a more desirable (ductile) flexural failure mechanism at ultimate loading. Increasing the shear resistance and concrete core confinement effectively reduced the shear transfer demands on the main compression strut from the applied load to the support by increasing the participation of the compression fan region.

The Researchers Recommend...

For RC bent caps at outside column locations with a shear span-to-depth ratio of about 1.5:

- Bent cap flexure design should use the column center as the critical section. Inevitably, this will require additional longitudinal reinforcement and provide flexural overstrength at the equivalent column face. This increased strength, in turn, effectively reduces bar stresses during service loads. Longitudinal reinforcement stresses at the column center during service loading should be limited to 36 and 30 ksi for moderate and severe exposures, respectively. This requirement will essentially limit the service bar stress at the equivalent column face to about 30 and 24 ksi, respectively, for similar shear spans and column support widths.
- The nominal shear resistance of bent caps, computed using standard code procedures, should exceed: (1) the factored shear demands at the equivalent column face from normal bridge loading; and (2) the shear demand required to develop flexural overstrength of the bent at the equivalent column face. Flexural overstrength should be calculated using standard beam theory with a reinforcement stress of 1.25 f_y.

For More Details . . .

The research is documented in:

Cracking in Reinforced Concrete Bent Caps, TxDOT Report 1851-1, August 2000

Cracking in Reinforced Concrete Bent Caps by Bradley S. Young, Texas A&M University, Master of Science thesis, August 2000

"Cracking in Reinforced Concrete Bent Caps" by B.S. Young, J.M. Bracci, P.B. Keating, and M.B. Hueste, *ACI Structural Journal,* Vol. 99. No. 4, Jul-Aug, 2002, 488-498

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TxDOT Implementation Status
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The recommendations for flexure and shear design of reinforced concrete bent caps with span-depth ratios of approximately 1.5 were reviewed by the TxDOT Bridge Division and determined to be both reasonable and conservative; however, the phased implementation of the AASHTO LRFD Bridge Design Specifications has now superseded some of these recommendations. As the Bridge Division develops design guidelines for LRFD Bridge Design Specifications, it will review and include all applicable and warranted research recommendations from this project.

For more information, contact Tom Yarbrough, P.E., RTI Research Engineer, at (512) 465-7403, or e-mail tyarbro@dot.state.tx.us.

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