PROJECT SUMMARY REPORT

UNIVERSITY of HOUSTON

Thomas T. C. Hsu Structural Research Laboratory

Project Summary Report 0-1854-S

Project 0-1854: New Method for Serviceability Design of Inverted "T" Bend Cap Ledges

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Crack Control for Ledges in Inverted "T" Bent Caps

Inverted "T" bent caps are used extensively on Texas bridges because they are aesthetically pleasing and offer a practical means to increase vertical clearance. As shown in Fig. 1, the cross-section of an inverted "T" bent cap consists of a "web" with short cantilever "ledges" at the bottom to support the bridge girders, thus minimizing the structural depth of bridges. The problem is that at service load unacceptable diagonal cracking frequently occurs between the cantilever ledges and the web as shown in Figs. 2. In addition to giving the appearance of structural distress, excessive crack widths can lead to the corrosion of reinforcement and the shortening of service life of bridges.

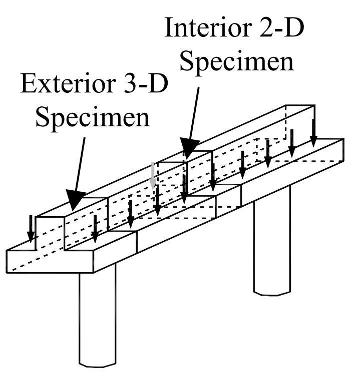

Figure 1 An inverted "T" bent cap showing an exterior 3-D specimen and an interior 2-D specimen

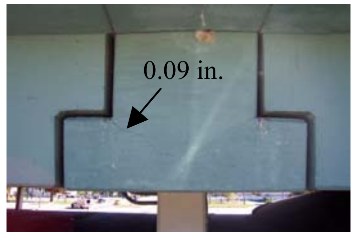

Figure 2 Crack width on end face of inverted "T" bent cap at Highway 59 over Laura Koppe Road, Houston, TX

What We Did…

The research described in this report seeks to develop a behavioral theory to support serviceability design for such bent caps. The research is divided into three phases: **Phase One** deals with two-dimensional (2-D) test specimens, Fig. 3, that represent the interior portions of inverted T bent caps and dapped ends of bridge girders. The stress flow and strain pattern in the 2-D specimens are simulated by a Compatibility-Aided Strut-and-Tie Model (CASTM). This model satisfies both the equilibrium of forces and the compatibility of deformations. Seven full-size 2-D test specimens were tested to calibrate the CASTM. This intelligible model served as a basis for development of a crack width prediction equation for the 2-D specimens.

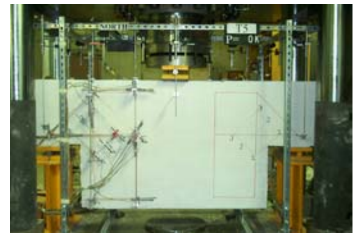

Figure 3 Tests of 2-D specimen (upside down)

Phase Two deals with three -dimensional (3-D) test specimens, Fig. 4, that represent the exterior portions of the bent cap where cracking is most visible. Ten 3-D test specimens were tested and were used to extend the applicability of CASTM from 2-D specimens to 3-D specimens. Since 3-D specimens tested in laboratory are limited in size to about 3/5-scale of full-size bridges used in practice, an equation for crack width prediction was developed for 3/5-size as well as for full-size bridges using the principle of similitude.

Figure 4 Tests of 3-D specimen (upside down)

Phase Three deals with the bent caps as a whole, Fig. 5, including both the interior span and the exterior cantilever portion. Two whole bent caps were tested in this phase of research. The interior span allow us to determine the distribution of hanger steel stress in the vicinity of the applied load on the ledge. This effective distribution width of hanger bars along the span defines the width of a 2-D specimen so that the CASTM model can be applied to determine the maximum crack width in the interior span. The exterior cantilever portions allowed us not only to check the equations for crack width prediction derived from 3-D specimens, but also to check the effect of the hanger bar spacing and the size of the bearing pad on the crack widths.

Figure 5 Tests of whole inverted T bent caps.

What We Found…

(1) At the interior spans of inverted T-beam, adding diagonal bars is an effective way to control cracks widths.

(2) At the end faces of cantilever spans, adding diagonal bars is not as effective as in the interior spans. The most effective variables to control crack width is the distance from end face to the most exterior load.

(3) To control diagonal crack widths at the end faces, it is very important to limit the service load to a "critical load" where crack widths begin to widen rapidly.

The Researchers Recommend…

In serviceability limit states design, using the notation in Fig. 6, the diagonal crack widths in the inverted T-beam shall be controlled as follows:

- **In the vicinity of interior applied load:**

The maximum crack width in the vicinity of an interior applied load should be limited to 0.013 in. (An interior applied load could act on the interior span or on an exterior portion). This crack width can be calculated from a 2-D specimen with an effective distribution width of W + 0.9d_e (in.). The CASTM formulation of crack width prediction is

$$w = L_{HF}\varepsilon_{HF} \le 0.013 \text{ in.}$$

where:

w = predicted diagonal crack width (in.)

L_{HF} = CASTM gauge length for calculated hanger and flexural steel strains $= 9500\,\varepsilon_{HF} - 3.0$ (in.)

ε_{HF} = diagonal crack strain calculated by hanger and flexural strains $= \sqrt{\varepsilon_H^2 + \varepsilon_F^2}$

ε_H = hanger strain or strain in the vertical direction $= \dfrac{(1-B)V}{1.2E_S A_{SH}}$

ε_F = flexural strain or strain in the horizontal direction $= \dfrac{(1-B)V\cot\theta_V}{1.2E_S A_{SF}}$

V = applied service load at each loading pad (kips)

θ_V = angle between flexural steel bars and the diagonal strut at the point of load V

B = distribution factor for diagonal bars $= \dfrac{A_{SD}}{A_{SH} + 0.5A_{SF} + A_{SD}}$

A_{SD} = total cross-sectional area of diagonal reinforcement in the effective distribution width L_D (in.^{2})

A_{SH} = total cross-sectional area of hangar reinforcement in the effective distribution width L_D (in.^{2})

A_{SF} = total cross-sectional area of flexural reinforcement in the effective distribution width L_D (in.^{2})

L_D = $W + 0.9d_e$ (in.)

W = width of bearing pad (in.)

d_e = effective depth of ledge from extreme compression fiber to centroid of tensile force (in)

E_S = 29,000 ksi

- **For end face of exterior span**

Because cracks widen very rapidly at end faces after reaching a crack width of 0.006 in., service load shall be limited to a "critical load" corresponding to this crack width. The "critical load" can be calculated by a trial-and-error method (spread sheet program) using the crack width prediction equation:

$$w = \frac{2.6L_{HF}\varepsilon_{HF}}{(1+0.7L_E)^2} \le 0.006 \text{ in.}$$

where:

L_E = the distance from end face to the most exterior load V

Definitions of L_{HF} and ε_{HF} are given previously, except that B = distribution factor for diagonal bars =

$$\frac{A_{SD}}{A_{SH} + 0.5A_{SF} + A_{SD}} \left(\frac{0.44NS_D}{1 + L_E} \right)$$

A_{SD} = cross-sectional area of a diagonal steel bar at end face of Inverted 'T' bent cap (in.^{2})

A_{SH} = cross-sectional area of a hangar steel bar at end face of inverted 'T' bent cap (in.^{2})

A_{SF} = cross-sectional area of a flexural steel bar at end face of inverted 'T' bent cap (in.^{2})

N = number of diagonal bars from the end face to the center of first bearing.

S_D = center-to-center spacing of diagonal bars, same as spacing of hangar bars.

At the end faces of cantilever span, the most effective means to reduce crack width is to increase L_E, the distance from the end face to the most exterior load. Adding diagonal bars is not an efficient way to control crack width.

The proposed equations have been applied to predict the crack width on the end face of the bent cap at Highway 59 over Laura Koppe Road, Fig. 2. It was satisfying to find that the measured crack width of 0.090 in. matched the predicted crack width of 0.083 in. very well.

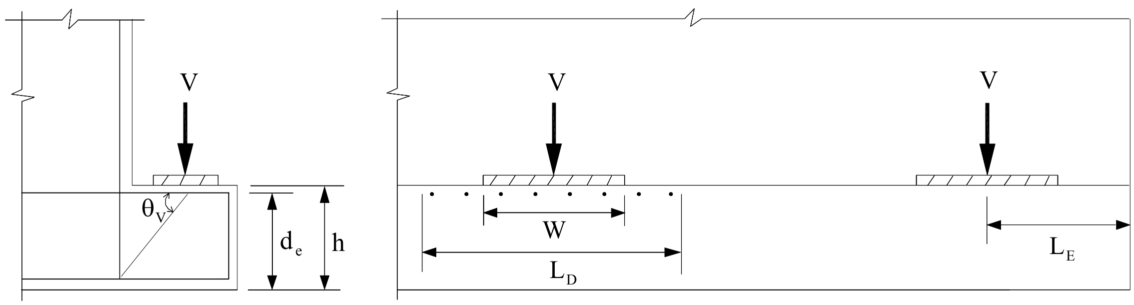

Figure 6 Notation for inverted "T" beam

For More Details…

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The research is documented in a journal paper and the following reports:

Zhu, R. H., Wanichakorn, W., Hsu, T. T. C., and Vogel, J. (2003). "Crack Width Prediction Using Compatibility-Aided Strut-and-Tie Model," ACI Structural Journal, V. 100, No. 4, July-Aug., pp. 413-424.

Research Report 1854-3, Zhu, R. H., Wanichakorn, W. and Hsu, T. T. C. (2001). "Crack Width Prediction for Interior Portion of Inverted 'T' Bent Caps," Department of Civil and Environmental Engineering, University of Houston, Houston, Texas.

Research Report 1854-4, Zhu, R. H., and Thomas T. C. Hsu (2003). "Crack Width Prediction for Exterior Portion of Inverted 'T' Bent Caps," Department of Civil and Environmental Engineering, University of Houston, Houston, Texas.

Research Report 1854-5, Zhu, R. H., Dhonde, H., and Thomas T. C. Hsu (2003). "Diagonal Crack Control for Ledges in Inverted 'T' Bent Caps," Department of Civil and Environmental Engineering, University of Houston, Houston, Texas.

To obtain copies of reports please contact the research supervisor.

TxDOT Implementation Status
January 2004

The recommended Compatibility Aided Strut and Tie Model (CASTM) is being incorporated into the design of dapped-end prestressed concrete girders by the Bridge Division. These same CASTM methods will be used in the development of repair/retrofit strategies of existing reinforced concrete bent caps using fiber-reinforced polymer (FRP) materials in the Houston District. A paper has been published in the American Concrete Institute Structural Journal describing how to control cracking using the CASTM Model.

For additional information, contact Tom Yarbrough, P.E., RTI Research engineer, at (512) 465-7403 or email at tyarbro@dot.state.tx.us.

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