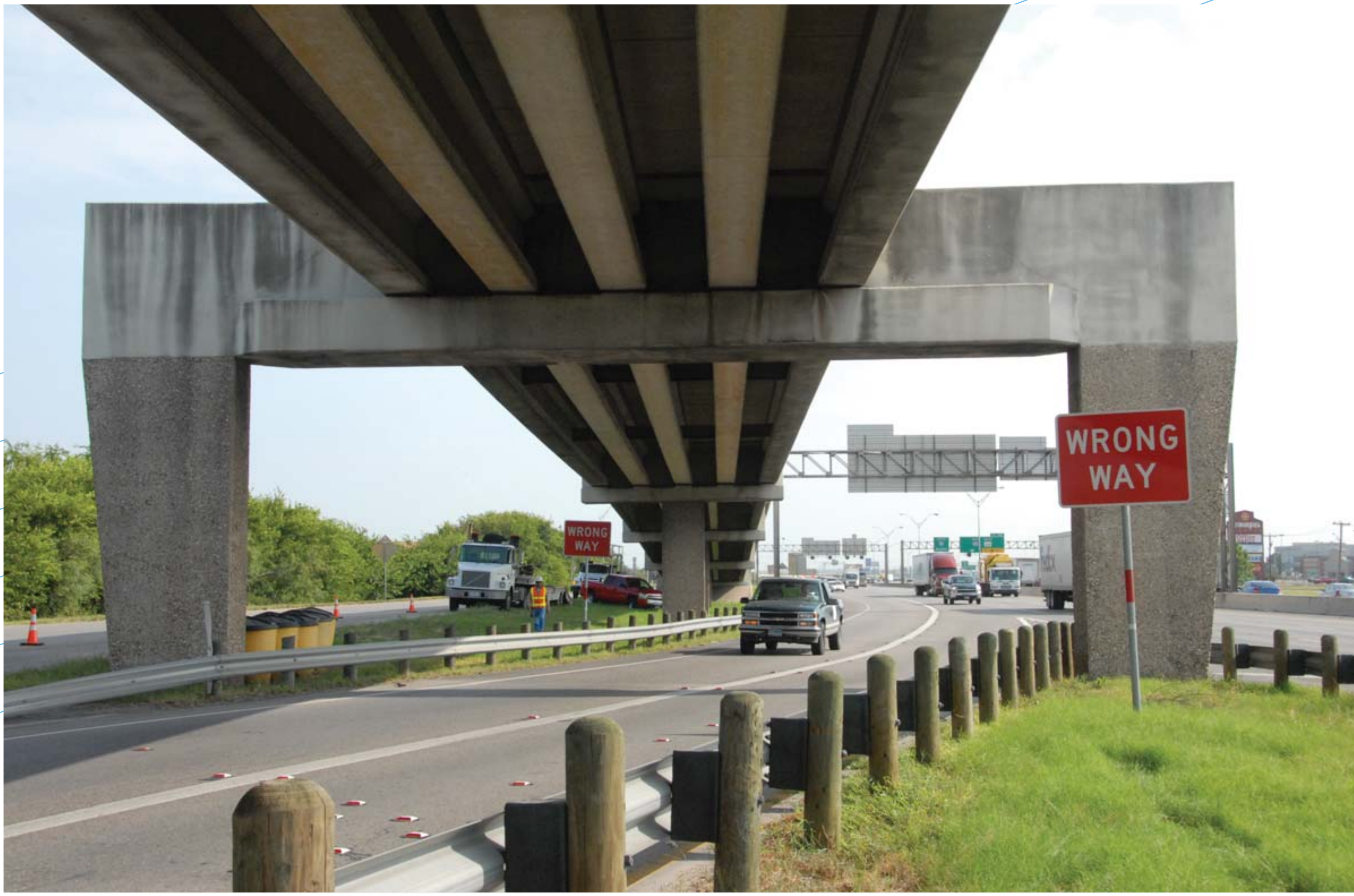

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Diagonal move

Crew studies cracks on inverted-T straddle bent caps

Reports of diagonal cracking of reinforced concrete inverted-T straddle bent caps raised concerns about the strength and serviceability of the recently constructed bridge structures.

These bridge elements are common throughout the U.S., and many of the diagonal shear cracks are large enough to be visible to passing motorists. The goal of this article was to assess the condition of the in-service bent caps and evaluate improvements to current design practices to limit cracking in future structures.

Inverted-T straddle bent caps are beam-type elements with ledges at the bottom of the section that support bridge girders. This ledge-support system decreases the overall structure depth as compared with typical rectangular bent caps and is typically used for bridges constructed directly above other roads or obstacles.

Due to the loading condition on the ledges, the flow of forces through inverted-T beams is more complex than in rectangular bent caps. The bridge girder loads applied to the ledge flow in the transverse direction to the bottom of the web, then vertically to the top (compression) chord and finally along the length of the beam to the supports on either end. These three-dimensional forces generate regions of stress discontinuities that are typically designed using empirical equations.

Strut and tie

Given the observed cracking in the inverted-T bent caps, coupled with the fact that these beams commonly have complex stress states associated with disturbed regions, an alternative design procedure was investigated. In other words, for such bent caps, Bernoulli's beam theory can no longer be assumed, as plane sections no longer remain plane, and thus sectional design provisions should not be used to design these structures. As a result, in recent years, many engineers are turning to strut-and-tie modeling (STM), already present in structural design codes as an option for the design of deep beams and other structures with discontinuities like those present in the inverted-T bent caps.

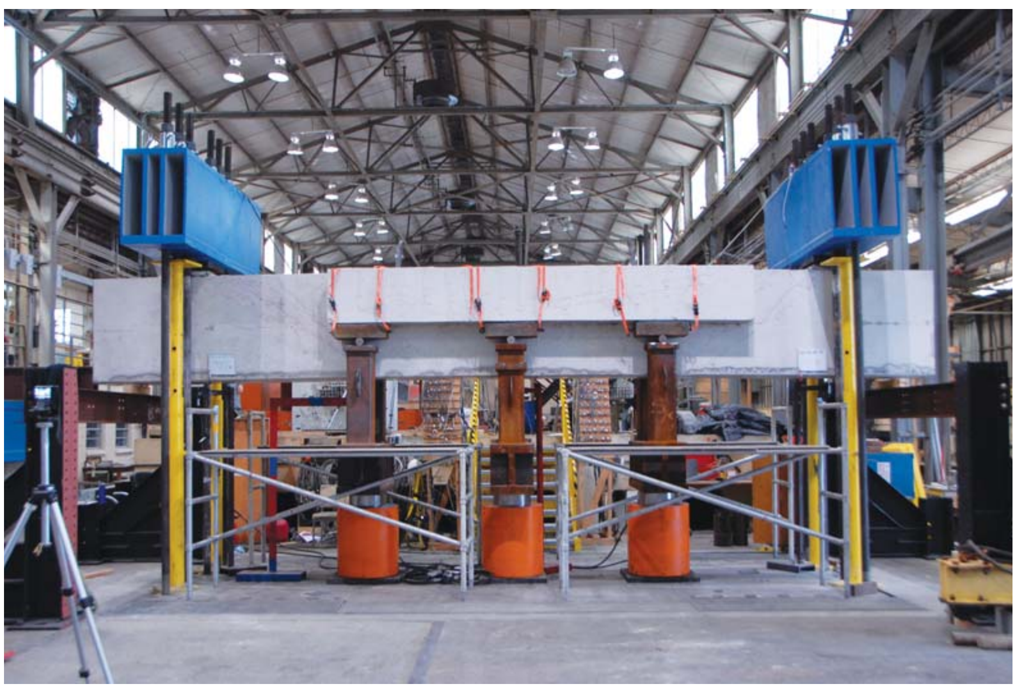
STMs allow designers to idealize complex states of strain in reinforced concrete structures as a truss, simplifying the forces into uniaxial elements. Ties consisting of tensile-steel reinforcement and struts consisting of concrete and compressive reinforcement intersect at nodes. These nodes are often the most critical element of STMs, as they are subjected to the highest concentrated stresses. STM is a lower-bound approach and will yield a conservative design if the resulting truss model is in equilibrium with the external forces and the elements have the strength and ductility to carry the internal forces.

STM was originally developed for two-dimensional applications, such as deep beams or walls, and limited studies on three-dimensional states of stress are available. Research on inverted-T beams comparable to the diagonally cracked bent caps also is scarce. Thus, a comprehensive large-scale experimental program was necessary to properly examine the behavior of such structural elements and assess the accuracy and validity of implementing STM design.

The state of eight

The first step in assessing the diagonal cracking problem involved field inspections of eight in-service inverted-T straddle bent caps with various levels of distress. Along with the crack widths and locations, variables such as the ledge height, ledge length, shear span-to-depth ratio, number of bridge girders supported by the bent cap, and the shear and horizontal skin-reinforcement ratio were recorded. The inverted-T bent caps had maximum inclined cracks ranging from 0.01 to 0.04 in. wide. The experimental program incorporated these variables with the goal of assessing the effects on both the strength and serviceability of these structures.

A total of 33 tests on full-scale inverted-T specimens were performed. The large number of specimens was required to allow for the variables discussed above to be varied in order to fully capture the bent-cap dimensions observed in the field. The web height was either 42 in. or 75 in., while the width of the web was a constant 21 in., and ledge widths were 10.5 in. on each side. The length of the ledges varied from lengths cut off at the edge of the bridge girder to continuous ledges running from support to support and lengths in between. Two ledge depths also were investigated: a "shallow" depth equal to one-third the beam height and a "deep" ledge of one-half the beam height. Both the vertical shear and horizontal web reinforcement were varied from 0.3% to 0.6% to assess their effects on strength and diagonal crack widths. The specimens also were loaded at either one or three points, with loads applied directly to the ledges. The load points were located at two specified distances



Given the observed cracking in the inverted-T bent caps, coupled with the fact that these beams commonly have complex stress states associated with disturbed regions, an alternative design procedure was investigated. Eight specimens were observed in the field.

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from the support in order to investigate both deep-beam and sectional-shear behavior with two shear span-to-depth ratios.

The specimens were fabricated in the laboratory using grade 60 reinforcement and concrete with compressive strengths, f'c, ranging from 3 to 6 ksi. After a curing period of 28 days, the specimens were tested in a simply supported, upside-down testing frame. The load was applied equally to the ledge at one to three points on each side of the web via U-shaped frame(s) attached to hydraulic ram(s). The specimens were monotonically loaded in 100-kip increments, between which crack widths were measured and their locations and extensions documented. During testing the deflection along the beam (measured with linear potentiometers) and the reinforcement strain at various locations (measured with strain gauges) also were recorded.

The diagonal crack widths were measured and compared with applied load to help field engineers evaluate the residual capacity of a diagonally cracked inverted-T bent cap. Compiling results from all 33 tests, a simple chart was developed to correlate the maximum diagonal crack width in an inverted-T beam to the load acting on the member, quantified as a percentage of its ultimate capacity, plus or minus a degree of scatter. The chart also considered variables found to affect this relationship, including the shear reinforcement ratio and shear span-to-depth ratio. It was interesting to note that when compared with rectangular reinforced-concrete bent caps, an inverted-T beam with the same crack width was found to be loaded closer to its failure load.

The crack width chart provides a straightforward means to make an informed decision regarding the amount of distress when a more sophisticated means of evaluation is unavailable. When the crack widths from the eight bent caps were compared to the chart, it was concluded that several of the existing structures had been subjected to loads up to 70-85% of their ultimate capacity.

More accurate description

Concerning the design of future inverted-T bent caps, STMs using both ACI 318-11 provisions and UT-STM provisions were found to yield reasonably conservative results. Primarily based on the STM provisions of the International Concrete Federation (i.e., fib) and as a result of 12-year-long research efforts, UT-STM provisions were developed at the University of Texas. (http://www.utexas.edu/research/ctr/pdf_reports/0_5253_1.pdf). These provisions were found to be more accurate and slightly more conservative than the ACI-318's STM provisions. Guidelines to the application of UT-STM provisions to inverted-T beams and the supporting experimental research discussed herein also were developed at the University of Texas (http://library.ctr.utexas.edu/ctr-publications/0-6416-1.pdf).

Furthermore, the STMs provided more accurate results than those given by the current empirical design method, which was based on beam theory, both in terms of failure mode (shear, flexure, local ledge failure, etc.) and ultimate capacity. The complex geometry of inverted-T beams required the use of a three-dimensional STM model or two complementary two-dimensional models for design purposes. By simplifying the design into a visual model, each element and failure mode can be more easily understood and addressed in the design process. The STMs also were used to identify potential areas of high stresses, such as cutoff ledges, which were not adequately accounted for in the previous design methods. The use of STM provisions is recommended for structures with complex three-dimensional states of stress such as inverted-T beams.

Fact Finder

A total of 33 tests on full-scale inverted-T specimens were performed. The web height was either 42 in. or 75 in., while the width of the web was a constant 21 in., and ledge widths were 10.5 in. on each side.

Along with strength-design provisions, a service-load shear check was provided to limit diagonal cracking. The simple and conservative equation considers the concrete tensile strength—expressed as a function of the compressive strength—along with the cross-sectional area of the beam to estimate the diagonal cracking load of inverted-T beams. Designers are encouraged to size the inverted-T beams such that the service-level shear is less than this estimate to prevent or limit diagonal cracking. Furthermore, a recommended minimum web-reinforcement ratio was found to limit crack widths to acceptable levels at service-level loads.

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