National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

DIGEST 65 - NOVEMBER 1974

Design of Bent Caps for Concrete Box Girder Bridges

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 12-10, "Analysis and Design of Bridge Bents," by J. E. Carpenter, J. M. Hanson, A. E. Fiorato, H. G. Russell, D. F. Meinheit, I. Rosenthal, W. G. Corley, and E. Hognestad, Portland Cement Association, Skokie, Illinois

THE PROBLEM AND ITS SOLUTION

The present strong emphasis on safe and aesthetic design of reinforced concrete highway bridges has resulted in substructure configurations that depart from the traditional footing-column-cap frame design. Whereas aesthetic considerations often dictate the concealment of massive concrete caps and reduction of the number of vertical columns, current design procedures are not applicable to these new configurations. At the time research was initiated there existed a general belief that current procedures resulted in overdesigned structures that contained much more steel than was necessary.

In 1970, the Portland Cement Association started work to develop more appropriate design procedures under NCHRP Project 12-10. Although the ultimate need is to establish valid procedures applicable to many configurations of bridge bent caps, this project was limited to investigation of integral bent caps concealed in straight, continuous, reinforced concrete box girder bridges. Because many similar bridges are being built, even a small reduction in the amount of reinforcing steel used in each bridge might result in substantial total savings. This project showed that reductions are possible.

The research was conducted in two phases -- analytical and experimental. Analytical studies of load distribution in bridge entireties and stress distribution in bent caps were conducted on two prototype bridges. The experimental phase included the construction of seven scale models. Two of the models, built to one-fifth scale of the prototype bridges, were representative of popular reinforced concrete box girder designs. Testing of these models provided information on the distribution of loads in the vicinity of integrated bent caps. The other five models represented transverse strips of bridge superstructures parallel to, and including, the bent caps and columns. Column flare and the amount and distribution of bent cap reinforcement varied in these models. These tests also provided information about critical sections and the effective width of bent caps.

Research has been completed and the final report is in the editorial and publication process and should be available early in 1975. The purpose of this Research Results Digest is to call immediate attention to the findings and recommendations.

FINDINGS

The objective of the project was to develop procedures for the design of bent caps. The design procedures were to include consideration of the following specific factors:

1. Location and distribution of critical AASHTO loading for a bent cap.
2. Effect of flaring a column.
3. Effective width of a bent cap.
4. Effect of spreading bent cap reinforcement into an adjacent box girder slab.
5. Location of critical cross sections.

Analytical Study

The analytical study consisted of a load distribution analysis and a bent cap analysis conducted on single-column and double-column prototype bridges.

Load Distribution Analysis - This part of the study was the analytical equivalent of the bridge model tests. The aim was to develop by elastic analysis a method of predicting the loads transmitted by the box girder superstructure to the bent cap, which would then be designed to carry those loads.

The load distribution analysis was carried out by Professor Alex C. Scordelis of the University of California at Berkeley. A specially developed computer program called MUPDI-3 was used. The program treats the box girder superstructure as an elastic folded plate system that is simply supported at the ends and propped at the center by a flexible bent of zero dimension spanwise to the bridge. Stiffnesses of the elastic bent were selected to approximate those of the actual bridge. The Goldberg-Leve solution is used for analysis of the folded plates.

Output from the program is in terms of shears, moments, and axial forces in the bent cap and girders. Other items of information can also be obtained. Thus, within the limits of the elastic analysis, the program gives the distribution of loads among the various girders.

The program was used to analyze the two prototype bridges developed for the bridge model test phase. Elevation of the bridges analyzed is shown in Figure 1. Cross sections of the single-column and the double-column prototype bridges are shown in Figures 2 and 3, respectively.

Bent Analysis - This part of the study was the analytical equivalent of the bent cap model tests. Its purpose was to develop a mathematical model of the bent cap portion of the bridge so that all details of behavior, including stresses in the concrete and reinforcement, could be predicted.

The bent cap analysis was carried out by Professor Paul P. Lynn of the University of Colorado. A finite element computer program was used to analyze the single-column bent cap model and its loading. The finite element used has provisions for nonlinear combined action of the reinforcement and concrete, including the effects of cracking and of slip between the reinforcement and concrete. Output includes stresses in the reinforcement.

Experimental Study

The experimental phase of this study included laboratory testing of seven structural scale models. Two models simulated complete bridges; each of the remaining five simulated a different configuration of bent cap and its surrounding region.

Model Bridge Tests - The testing program was conducted first on the one-fifth scale models of the two prototype bridges, shown in Figures 2 and 3, studied in the analytical phase. Both the single-column and the double-column bridge models were

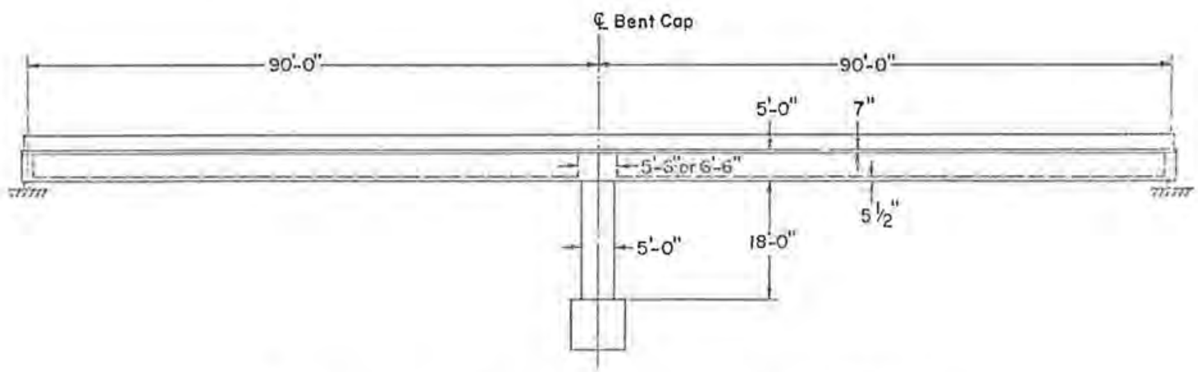

Figure 1. Elevation of prototype bridge.

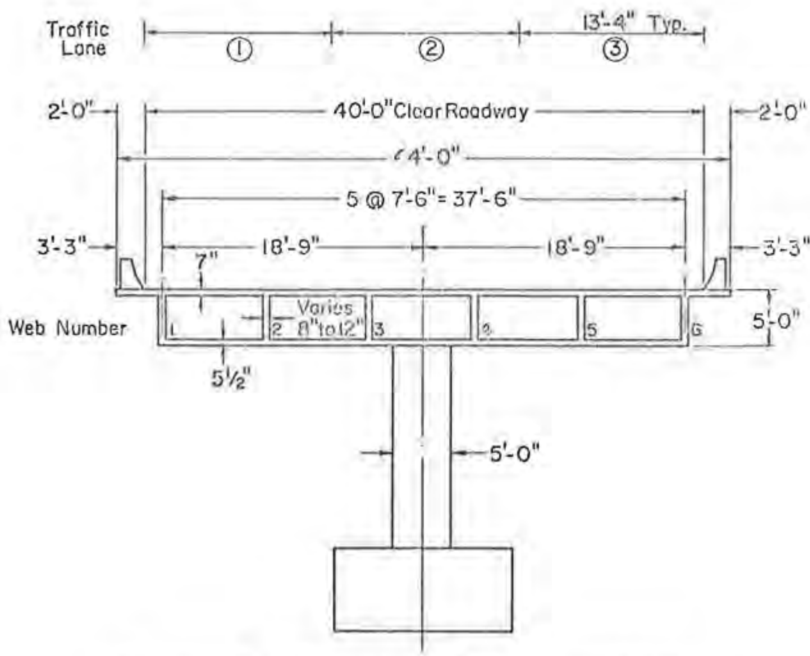

Figure 2. Prototype bridge section showing single-column bent cap.

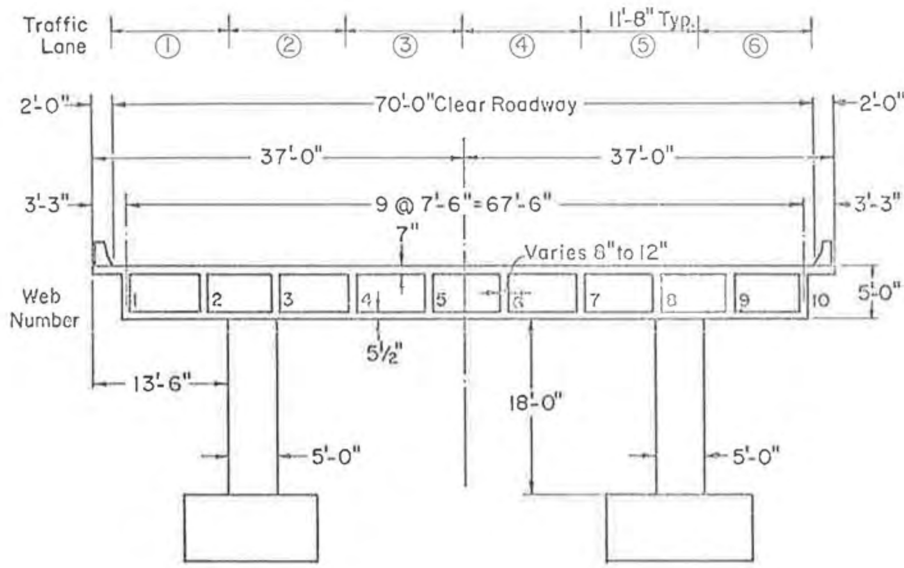

Figure 3. Prototype bridge section showing double-column bent cap.

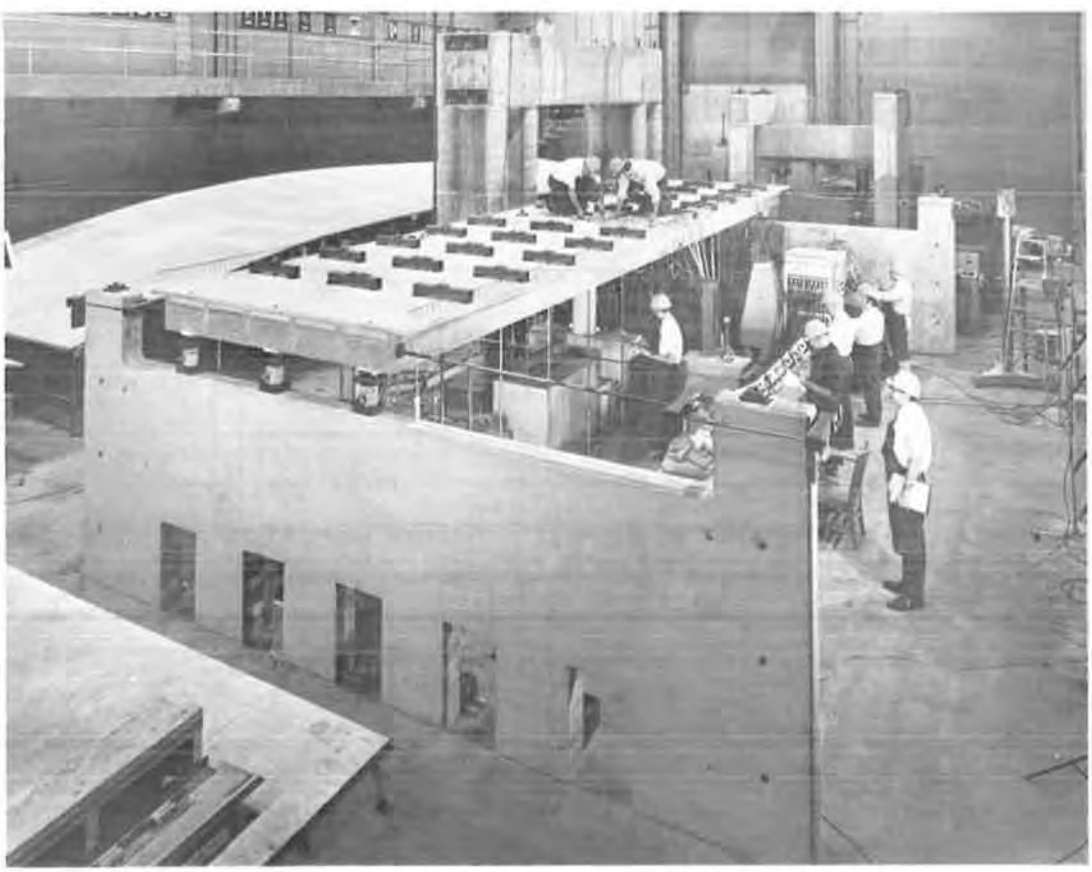

Figure 4. Testing of single-column bridge model.

designed according to working stress methods. Figure 4 shows the single-column bridge model undergoing testing. The main purpose of the bridge tests was to determine experimentally the location and distribution of the critical AASHTO loading for a bent cap. The bent cap portions of the model bridges were instrumented to obtain information on behavior. Both bridges were subjected to various loading combinations culminating in a test to destruction.

Model Bent Cap Tests - The experimental investigation of items 2 through 5 of the aforementioned factors was carried out by means of tests on the following five bent cap models:

1. Single-Column Bent SC-3;
2. Single-Column Bent: Flared Column SF-4;
3. Single-Column Bent: Flared Column SF-5;
4. Single-Column Bent: Spread Reinforcement ST-6; and
5. Double-Column Bent DC-9.

Model elevation and cross-section drawings are shown in Figures 5 through 10. Figure 11 shows a single-column bent cap model undergoing testing.

Data from all five models were used to determine the effective width of a bent cap and the location of the critical design section. The effect of flaring the column was evaluated by comparing the results of tests on models SC-3, SF-4, and SF-5, the latter two of which had flared columns. The effect of spreading bent cap reinforcement was studied by comparing the results of the tests on models SC-3 and ST-6.

Each bent cap model represented the central portion of a two-span continuous bridge, including the bent cap and column or columns, between the lines of inflection in the two spans. The single-column models were constructed at two-fifths scale, and the double-column model at one-fifth scale. The load factor method was used to design the models to resist a single pattern of loads representing dead load plus a uniformly distributed live load.

Recommended Design Procedure

On the basis of this investigation, the following provisions are recommended for design of bent caps. Where appropriate, suggested wording for incorporation in the AASHTO Specifications is given.

Determination of Design Loading on Bent Cap - Recommendation: *Use present AASHTO design methods.*

Experimental results in this project indicated only a small amount of lateral distribution of loads when applied loadings approached the capacity of the bridge. On the other hand, the elastic analysis predicted a considerable amount of lateral distribution. For the design of the bent cap, the smaller the amount of lateral distribution assumed, the more conservative the design. Consequently, no changes were recommended in the current design method because it assumes no lateral distribution of loads within the structure.

This study concerned only the strength, serviceability, and load distribution characteristics of box girder bridges. The use of more refined design methods makes it more important that the design loadings correspond to the actual loadings; however, determination of whether or not the magnitude of the design loading is representative of actual loadings on the bridges was beyond the scope of this program.

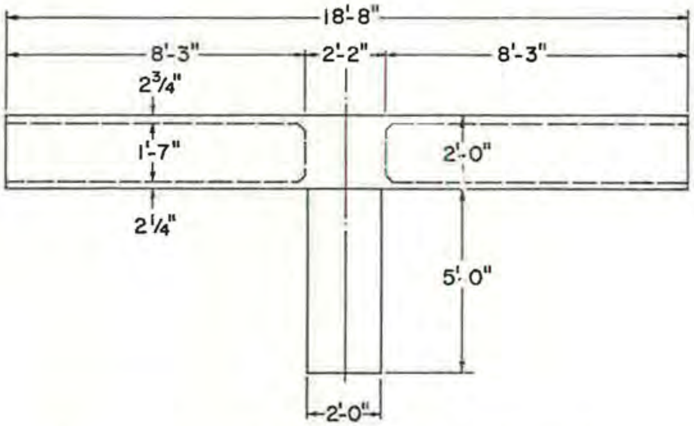

Figure 5. Elevation of single-column bents SC-3, SF-4, and SF-5.

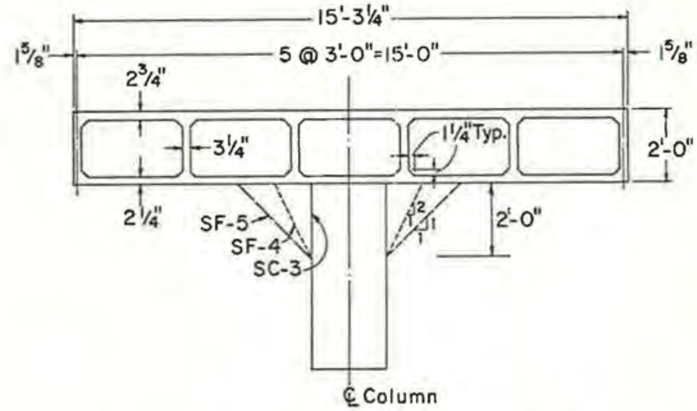

Figure 6. Cross sections of single-column bents SC-3, SF-4, and SF-5.

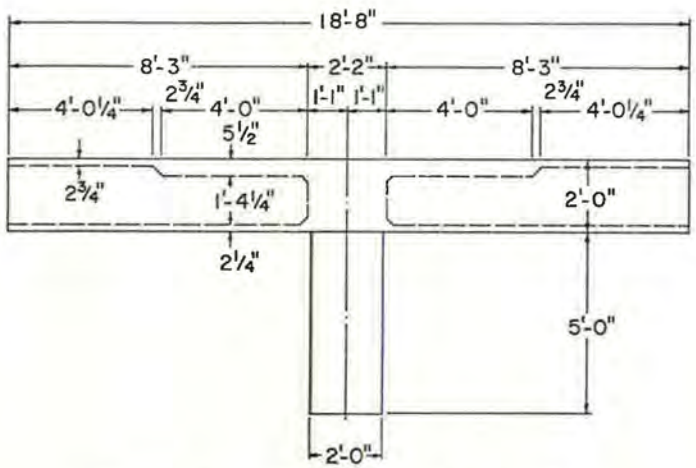

Figure 7. Elevation of single-column bent ST-6.

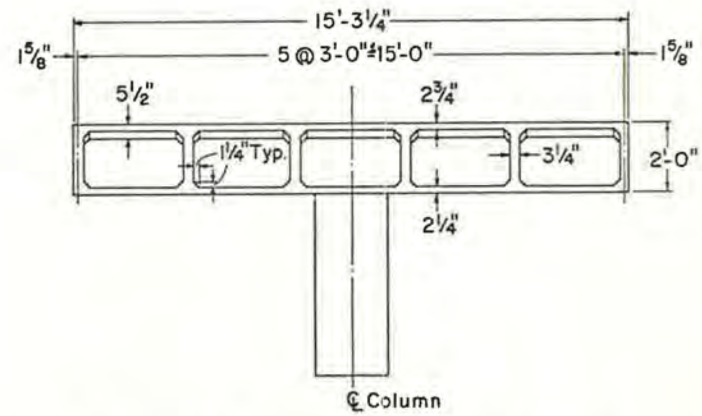

Figure 8. Cross section of single-column bent ST-6.

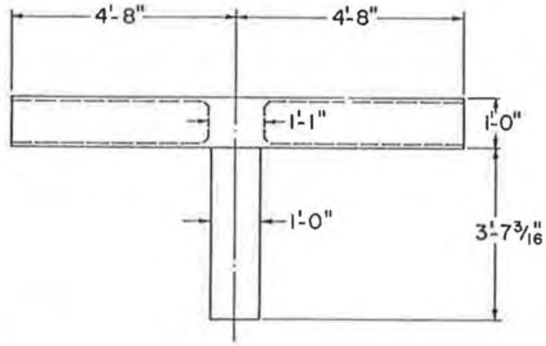

Figure 9. Elevation of double-column bent DC-9.

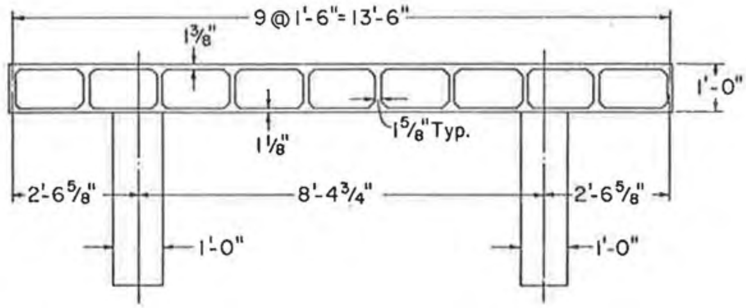

Figure 10. Cross section of double-column bent DC-9.

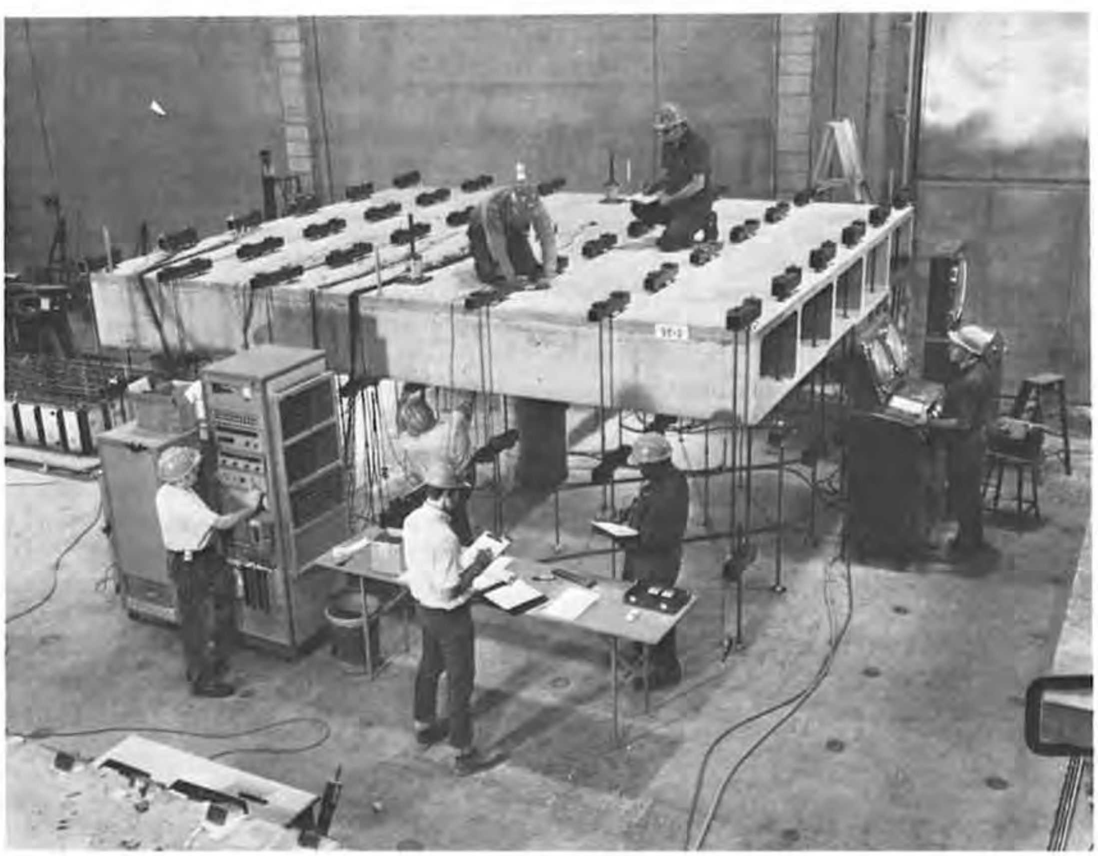

Figure 11. Testing of single-column bent model.

No evidence was gathered in this project on the local distribution to the adjacent girder webs of live loads applied to the deck. Present design methods commonly place the entire live load lane reaction directly on the bent cap at the lane centerline. If the lane centerline happens to be at or near a box centerline, it is physically impossible for the lane load to be applied to the bent cap at that point. A more logical approach would be to consider some distribution of the live loads to the girders, which would then be assumed to carry the loads to the bent cap. Minor local changes in the moment diagram would result from assuming the live load to be applied through the girder webs. Changes would also occur in the location and magnitude of the steps in the shear diagram for the bent cap. The present specifications are silent on this point, and no formal changes are proposed.

It is believed that application of the recommended design methods, along with the load factor method, will yield structures more closely exhibiting the intended behavior than has any previous method.

<u>Effect of Column Flare</u> - Recommendation: *For an integral support to be considered effective, the angle of greatest slope of the surface of the support shall not exceed 45 degrees from the vertical.*

Models having columns flared in the plane of the bent caps were tested to determine whether flared columns provide effective supports for bent caps.

Models SF-4 and SF-5 had single columns with two-to-one and one-to-one flares, respectively, as shown in Figure 6. The test results for these two models were compared with the results for SC-3, a model having a circular cylindrical column. Except for the flare detail, all three models had the same nominal dimensions. The main flexural reinforcement in the bent caps consisted of 12 bars each of No. 7 bars for model SC-3, No. 6 bars for SF-4, and No. 5 bars for SF-5.

The effectiveness of the flares was evaluated by comparing the longitudinal tensile and compressive stresses in the bent caps as well as the stresses in the concrete of the flare for the models described above. A comparison of the distributions of stresses in the main flexural reinforcement and in the concrete at the bottom of the bent cap is shown in Figure 12. To facilitate comparisons among the three models, the distance between the face of support and the center of the exterior web has been drawn as though it was constant. The face of support is the intersection of the surface of the straight or flared column with the bottom surface of the bent cap at the longitudinal centerline of the bent cap.

In Figure 12, and subsequent figures, the load is given as the ratio, $\underline{K}$, of the total applied load to the design ultimate load. Thus, $\underline{K} = 1.0$ represents the load corresponding to $1.8\ \underline{D} + 3.0\ (\underline{L+I})$. The stresses, plotted at the design ultimate load, were determined from the measured strains using stress vs. strain relationships obtained from control tests.

Figure 12 shows that the distributions of reinforcement stresses are similar for the three specimens, particularly in the vicinity of the face of support. Compressive stresses in the concrete also match well for the straight and flared column models.

To determine whether the concrete in the most highly stressed region of the flare showed any signs of distress, strains were measured for SF-4 and SF-5 on the face of the flared column 3 in. below the bottom of the bent cap. The concrete strain in model SF-5, which had the widest flare, was slightly greater than the corresponding strain in model SF-4 at all load levels. In neither model, however, did the strain at the design ultimate load indicate that the concrete in the flare was overstressed. At the design ultimate load, the maximum measured strain in the concrete of the flare was 1420 millionths for SF-4 and 1550 millionths for SF-5. At service load, the maximum strains were 390 millionths for SF-4 and 460 millionths for SF-5.

For both the straight and flared column models, strains measured in the bent cap stirrups located above the column were insignificant, even at higher load levels. As would be expected, flaring the column decreased the deflection of the bent cap.

Based on measured strains in the bent cap and on the face of the flared column, it can be concluded that the flared columns are as efficient as equivalent cylindrical columns in supporting the bent cap.

The surface of the widest flare tested had a maximum angle of 45 degrees with the vertical along the longitudinal centerline of the bent cap, as shown in Figure 6. Because no information was obtained for surfaces with larger angles, this angle is recommended as a limit for column flares. The 45-deg limit is consistent with that used in the ACI Building Code and the British Standard Code of Practice for flat slab supports.

The proposed provisions were developed from tests on flared columns in which the shape of the support at the bottom of the bent cap has parallel sides and rounded (elliptical) ends. The provisions should not be applied to supports of less compact cross section than those tested. For example, they should not be applied to a section with pointed ends.

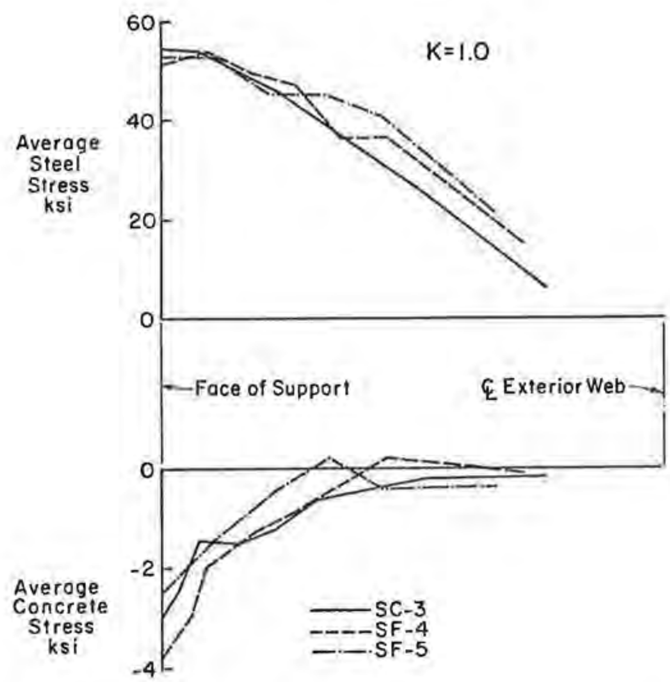

Figure 12. Distribution of stresses in bent cap of specimens SC-3, SF-4, and SF-5.

Effective Flange Width in Compression - Recommendation: *The effective width of an overhanging compression flange on either side of the web of an integral bent cap shall not exceed any of the following:*

1. *One-half the clear distance to the next bent cap.*
2. *Six times the least thickness of the slab.*
3. *One-tenth the span length of the bent cap. For cantilevers, the span used shall be twice the length of overhang.*

The bent cap models were used to determine the extent of participation of the soffit and deck slabs in resisting the bending moment applied to the bent cap. In single-column bent caps, and in the negative moment regions of double-column bent caps, the deck and soffit slabs serve as the tension and the compression flanges, respectively. In the positive moment region of double-column bent caps, the roles of the deck and soffit slabs are reversed. The effectiveness of both tension and compression flanges was investigated.

Transverse distributions of strains parallel to the longitudinal centerline of the bent cap were used to obtain a measure of the participation of the deck and soffit slabs. Based on measured strains in the main tensile reinforcement for the bent cap and the top reinforcement in the deck slab as well as those in the concrete on the bottom surface of the soffit slab, the representative distributions shown in Figure 13 were constructed for the single-column bent cap models. Results similar to those shown in Figure 13 were obtained in the negative moment regions of the double-column bent cap.

In Figure 13, the strains are plotted as a percentage of the strain at the bent cap centerline. Strains decreased in magnitude with increasing distance from the bent cap. This decrease is indicative of shear lag in the slabs. As can be seen, effectiveness of the slab portions farther away from the bent cap is reduced.

The negative moment compressive strains, shown in Figure 13, indicate the participation of the soffit slab. Because of high strain concentrations at the intersection of the bent cap with the support, the drop-off in the concrete compressive strain distribution is accentuated at the section along the support face. Therefore, a representative distribution along a section 6 in. outside the face of support is also plotted in Figure 13.

The strain distributions indicate that the soffit slab acted as a compression flange in resisting the applied bent cap moment. The effectiveness of the soffit slab decreased in portions of the slab farther from the bent cap in a manner similar to that in T-beam flanges observed by others.

An adequate estimate of the effective flange width of the bent cap in compression was found to be suggested by the spirit of existing specifications for the width of compression flanges in box girders and T-beams. The provisions recommended here are a restatement in terms of overhanging flanges of current provisions. The test results and calculations both indicate the strength of the bent cap is insensitive to the compression flange width. Consequently, the present provisions are satisfactory.

Effective Flange Width in Tension - Recommendation: *The effective width of an overhanging tension flange on either side of the web of an integral bent cap shall not exceed either of the following:*

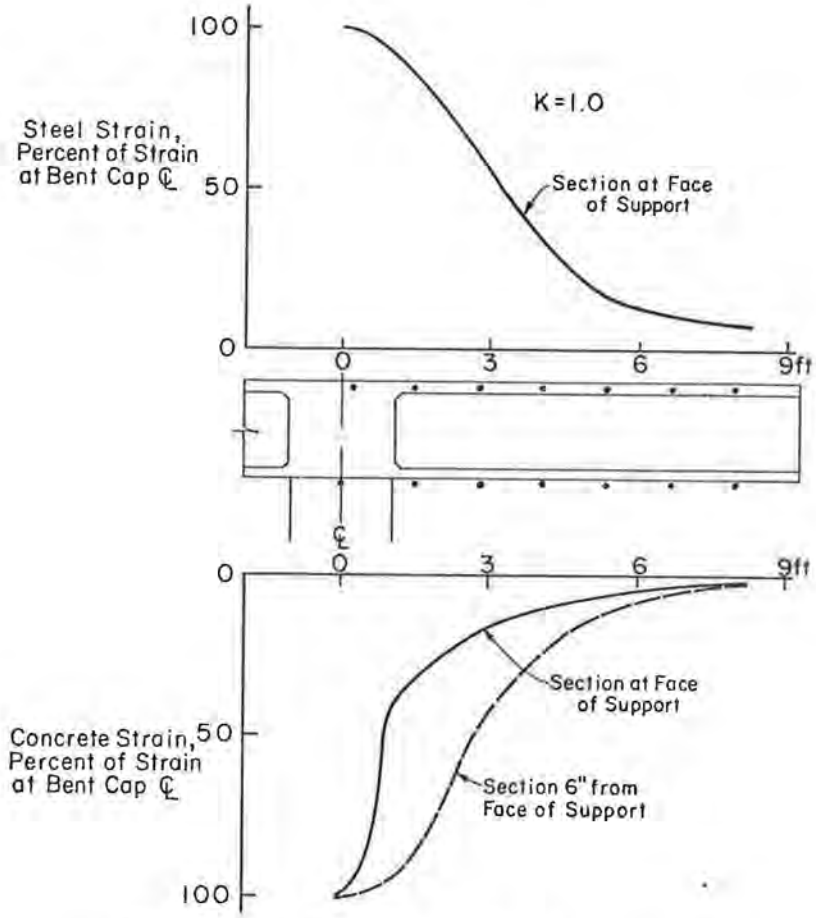

Figure 13. Representative transverse distributions of strains parallel to longitudinal centerline of bent cap.

1. *The effective width defined for compression.*
2. *One-fourth the average spacing of the intersecting box girder webs.*

All longitudinal reinforcement located within the specified flange widths may be considered fully effective.

The effectiveness of reinforcement was found to decrease rapidly with distance from the bent cap web. Reduced effectiveness was attributed primarily to shear lag. In a prototype bridge subjected to traffic, bars outside the bent cap web would also be stressed by concentrated loads on the deck. To take into account the reduced effectiveness and the stresses due to loadings not included in this test program, restrictions were placed on the assumed flange width for tension.

All properly oriented reinforcement within the specified flange width can be considered effective. The proximity to the bent cap web minimizes secondary stresses resulting from concentrated loads and shear distortion of the box girder cells.

Design Section for Negative Moment - Recommendation: *Moments at the face of support may be used for design of the bent cap. The face of support is defined as the limit of the effective support along the centerline of the bent cap.*

The most significant requirement for determining a critical design section is that it be located where maximum stresses occur.

The distributions of the average longitudinal tensile stresses in the single-column bent caps are shown in Figure 14. These curves show that the stresses are maximum at or near the face of support. For any particular curve, the stress gradient tends to be relatively flat in the vicinity of the face of support. At the center of the support, the reinforcement stresses tend to be smaller than at the face of support. This is presumably because the support serves to increase the effective depth of the bent cap.

The data shown in Figure 14 confirm the location of the critical design section at or near the face of the column.

Effect of Spreading Reinforcement - Recommendation: *Use the provisions specified for the effective flange width in tension.*

As shown in Figure 7, model ST-6 had a thickened deck in order to accommodate a portion of the bent cap tensile reinforcement. Spread bent cap reinforcement might be used when the width of the bent cap stem is not large enough to accommodate the required flexural reinforcement.

Figure 15 shows the effect on steel stresses within the bent cap when the tensile reinforcement is spread. To construct the figure, the strains measured on the longitudinal reinforcement within the bent cap were averaged and converted to stresses using stress-strain relationships determined by test. In comparison, models

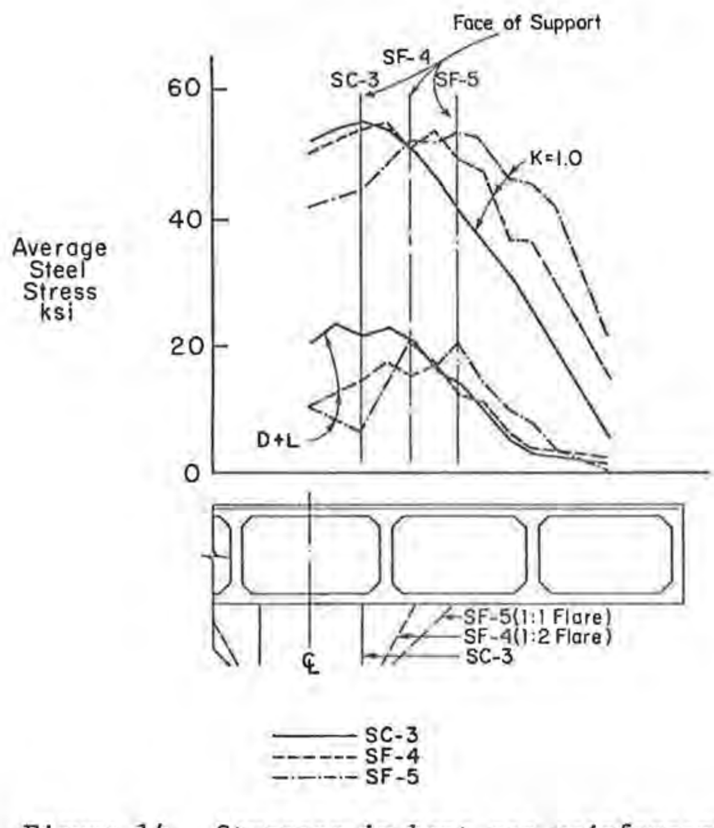

Figure 14. Stresses in bent cap reinforcement of single-column bents.

SC-3 and ST-6 had the same total amount of reinforcement. Model SC-3, with no spread reinforcement, contained 12 No. 7 bars within the bent cap. Model ST-6, with spread reinforcement, contained 36 No. 4 bars. However, only eight of these bars were placed within the width of the bent cap stem.

As shown in Figure 15, the maximum stresses were higher in model ST-6 than in model SC-3. In addition to higher bent cap reinforcement stresses, model ST-6 had greater bent cap deflections than model SC-3. For example, at the service load level, the deflection measured at the end of the bent cap in ST-6 was 7 percent greater than that in SC-3. At the design ultimate load the deflection of ST-6 was 45 percent greater than that of SC-3.

Because the model having the spread reinforcement had higher maximum stresses and greater deflections, it would appear that wide spreading of the main bent cap reinforcement is not a desirable design practice.

The reduced amount of reinforcement that meets the requirements of the load factor method of design will probably eliminate the need for spreading reinforcement outside the limits of the bent cap stem width. However, if spreading is required, the test results indicate that reinforcement placed anywhere within the specified tension flange may be considered effective.

APPLICATIONS

One of the primary aims of the project was to determine whether current design methods resulted in more reinforcement than needed in the bent cap. Because of the wide variety of proportions possible within the specified geometry, no exact reductions can be calculated, but a range of values can be determined.

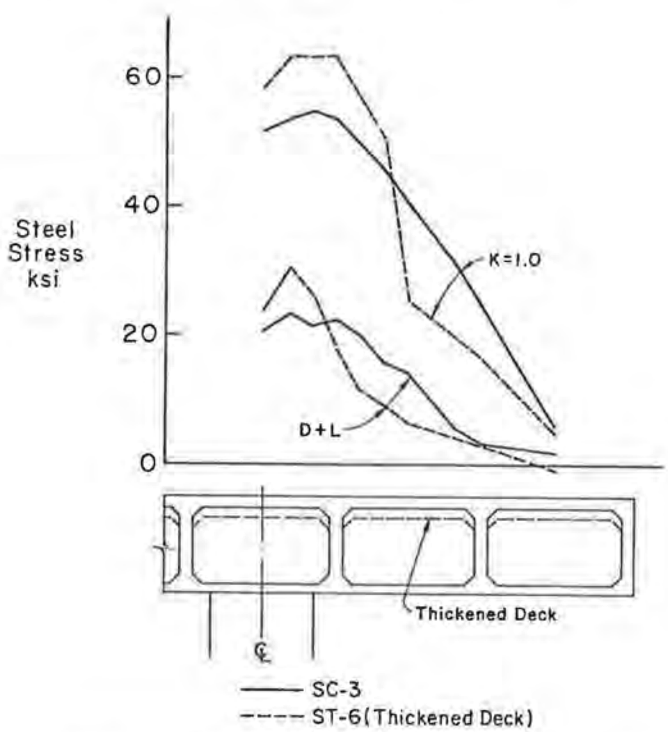

Figure 15. Effect of spreading bent cap tensile reinforcement on steel stresses within the bent cap.

The major factor determining the amount of flexural reinforcement is the design method used. For box girder bridges of the proportions specified, the use of load factor design rather than working stress design results in a reduction of roughly 30 to 35 percent in bent cap flexural reinforcement. This reduction is evidence that an indirect effect of the current specifications requires a bridge designed by the working stress method to have more load carrying capacity than one designed by the load factor method.

The degree of column flare can have a substantial effect on the amount of flexural reinforcement required. In the series tested, the bent cap having the column with the widest flare required approximately 30 percent less reinforcement at the critical design section than the similar bent cap having a nonflared column.

Choice of critical design section can also influence the amount of flexural reinforcement required, particularly for wide column flares or for regions of steep moment gradients such as those encountered in the negative moment regions of multiple column bents. Reinforcement savings can amount to 10 to 20 percent when the design section is considered to be at the face of support rather than a point one-sixth the support diameter from the column centerline, the assumption often used.

The effective flange width chosen has little effect on the amount of flexural reinforcement required.

The amount of shear reinforcement required is not significantly different for a given bent cap whether designed by working stress or load factor methods. The only variables that have an effect on shear reinforcement requirements are the column flare and critical design section location. In the recommendations of this report, these two variables combine to widen the support and thus increase the length of bent cap calculated to have zero shear and minimum shear reinforcement.

The findings from this study should be of value to structural engineers involved in the design and construction of reinforced concrete bridges. The research findings relate primarily to design assumptions rather than code provisions; and none of the recommendations are in conflict with current practice. As a result, implementation should be relatively easy. No changes are recommended in the method of distributing loads to the bent cap. With respect to the spreading of reinforcement and the effective flange width, the code has no specific provisions for bent caps but the recommendations herein are slightly more conservative than what might be inferred from the code. The findings with respect to support effectiveness and the location of the critical design section simply clarify the code.

Because the findings result from a carefully designed and executed experimental program as well as from consideration of the results of a sophisticated analytical study, it is believed that they are highly reliable and can be used immediately for improved design methods.

The NCHRP Projects Engineer responsible for Project 12-10 is Robert J. Reilly, who can be reached at (202)389-6741 to answer questions.