Controlling Twist in Precast Segmental Concrete Bridges

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Synopsis

Discusses several precast segmental box girder bridges where substantial undesired twists were observed during erection.

Comparison of casting yard data and erection measurements indicated the excessive twist problem originated during geometry control in the casting yard.

The sensitivity of normal control procedures is illustrated and recommendations for a check procedure to control such twists is given.

The decade from completion of the Corpus Christi Bridge in 1973 to finishing of the Linn Cove Viaduct in 1983 showed the emergence of precast segmental box girder bridges as a major construction form in North America. During this period many highly informative publications [1-14] appeared in the engineering literature and provided guidance to both the designer and contractor in the basics and details of this type of construction.

Several of these publications allude to problems in geometry control which resulted in "important geometric imperfections" on certain projects.[7,8] Unfortunately, relatively little detailed information has been given. The important lessons which can be learned from such problems need to be emphasized without an attempt to assign blame to any individual involved in these projects.

The persistent nightmare for both designers and contractors involved in their first precast segmental bridge project is that somehow their graceful structure growing in balanced fashion from the central pier (Figs. 1a and 1b) will fail to meet up smoothly with its mate which is approaching it from the next pier. Unlike cast-in-place cantilever construction, the basic geometry for match cast precast segmental bridges is set in the precast yard.

While shimming can be used as a last resort to change the course of an errant cantilever, it is highly undesirable and sometimes ineffective.[12] More drastic corrections have been made using wet joints.[12] Proper geometry control and attention to erection procedures should make such recourse unnecessary.

Unfortunately, errors can be made and substantial mismatches at closure have occurred (Fig. 1c). Such closure errors are difficult to overcome and conceal. With ingenuity, serious errors have been overcome by forming and casting whole transition units in situ (Fig. 1d).

In reality, there are two very different orders of magnitude of concern on geometry control. While it is extremely important to maintain careful control during segment production and erection, the box girder bridge system is more forgiving of some types of errors.

Fig. 1a. Balanced cantilever erection using a launching truss.

Fig. 1b. Precast segmental box girder bridge being erected in balanced cantilever fashion using a crawler crane.

Fig. 2 illustrates the relative stiffnesses of an actual box girder bridge system with approximately 200 ft (60 m) spans resulting in 100 ft (30 m) balanced cantilevers during construction.

Fig. 2a indicates that if the tips at one end had to be forced into a mating position through a 1 in. (25 mm) vertical deflection, relatively low forces of 40 kips (178 kN) in each web would produce the

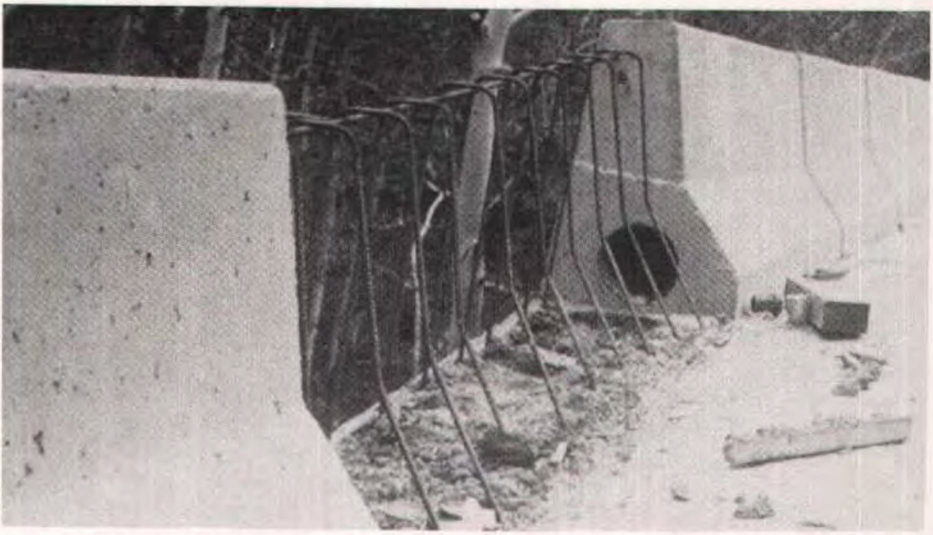


Fig. 1c. Closure error between two cantilever arms of a precast segmental box girder bridge.

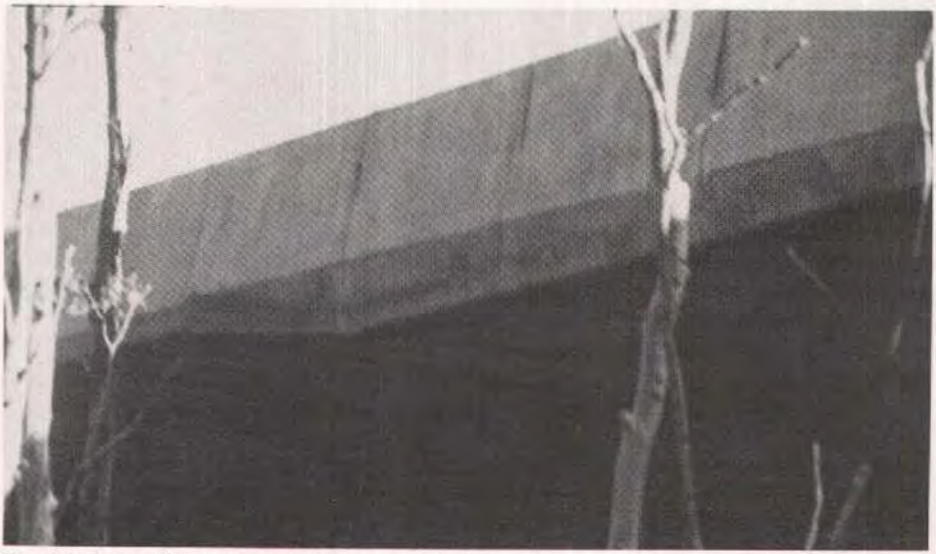


Fig. 1d. Remedial measures to correct for closure errors.

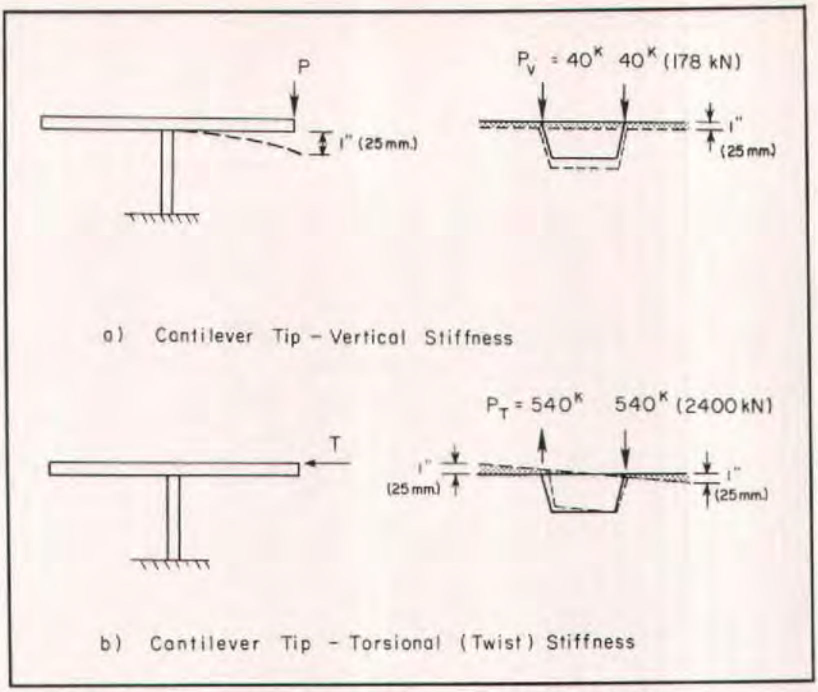


Fig. 2. Relative stiffnesses of a typical box girder bridge system.

required deflection. Such forces can be easily developed using strongback systems between the two cantilevers such as shown in Fig. 3a.

Somewhat larger but similar magnitudes of forces are required to provide lateral or horizontal adjustments with simple equipment as shown in Fig. 3b. In fact, many box girder bridges are closed using final adjustments of this magnitude without overall damage to the bridge system.

Such locked-in forces are reduced by creep and do not affect the ultimate capacity of the section. In many cases pier fixity can be released[10] and lesser forces are required.

In contrast, Fig. 2b indicates that if the tips have an unwanted twist and a torque is required to displace each tip 1 in. (25 mm) in a twist mode, the required forces on the webs are 540 kips (2400 kN). The basic torsional stiffness of the box girder system, which is such an asset in resisting load upon completion, makes it virtually impossible to compensate for twist type geometry errors through application of closure forces. Forces of the magnitude shown in Fig. 2b could produce substantial shear and torsion damage to the structure.

There are some cases where attempts have been made to forcibly twist such units with resulting damage to shear keys and webs. Thus, it is extremely important that geometry control procedures specifically ensure twist control. Many widely publicized procedures have ignored or incorrectly portrayed the need for such controls. Podolny and Muller[7] have strongly urged that such twist checks be an implicit part of the geometry control.

In studying problems which have occurred in several major bridges, the author became aware of the appreciable sensitivity of the geometry control system in short line match cast construction

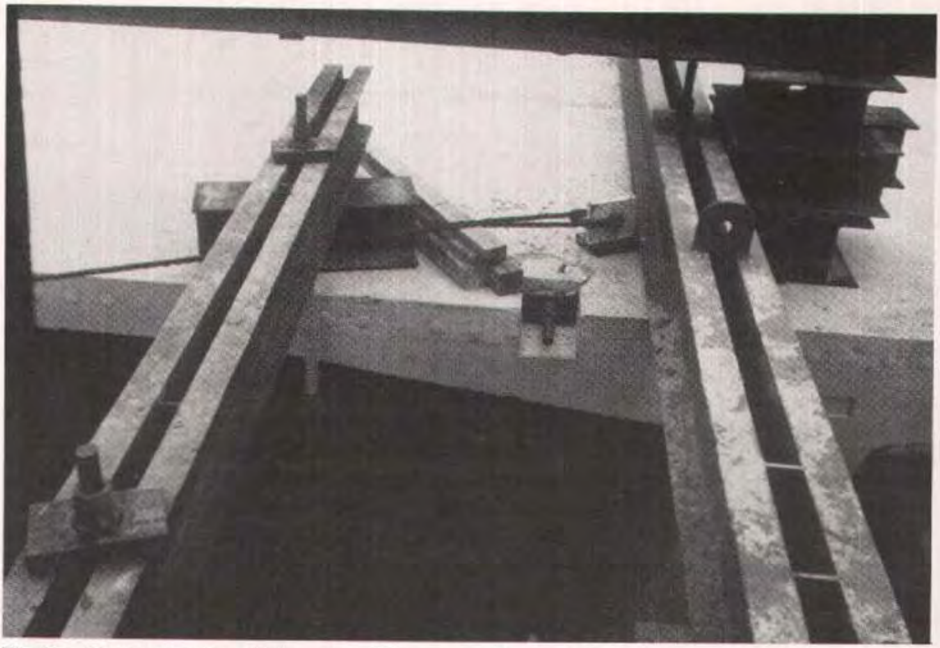


Fig. 3a. Supplementary "strongback" beams with threaded rods spanning between cantilever tips to align tips vertically prior to closure placement.

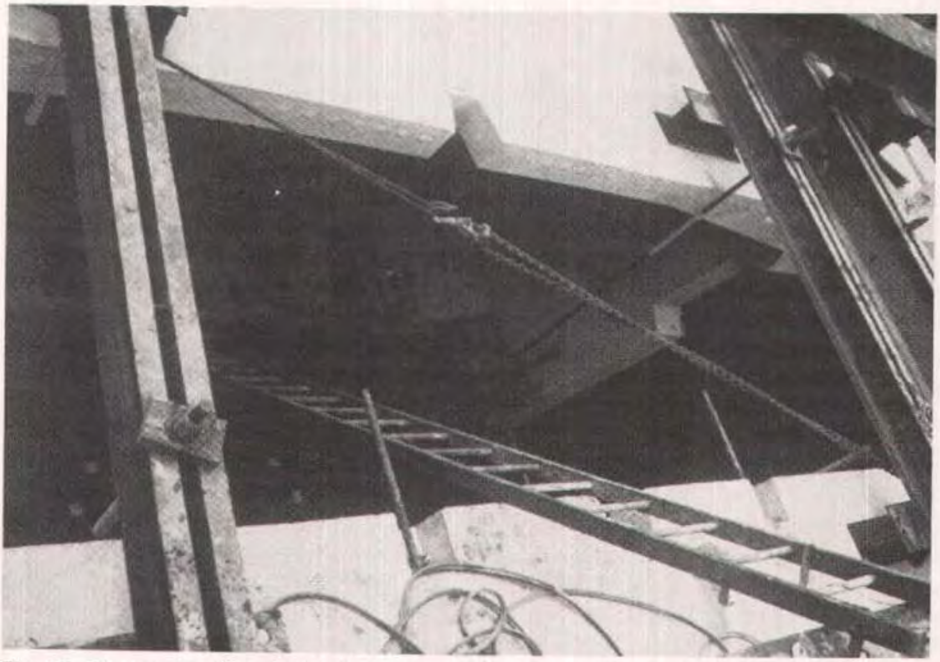


Fig. 3b. Diagonal pulling device between cantilevers to align tips horizontally prior to closure placement.

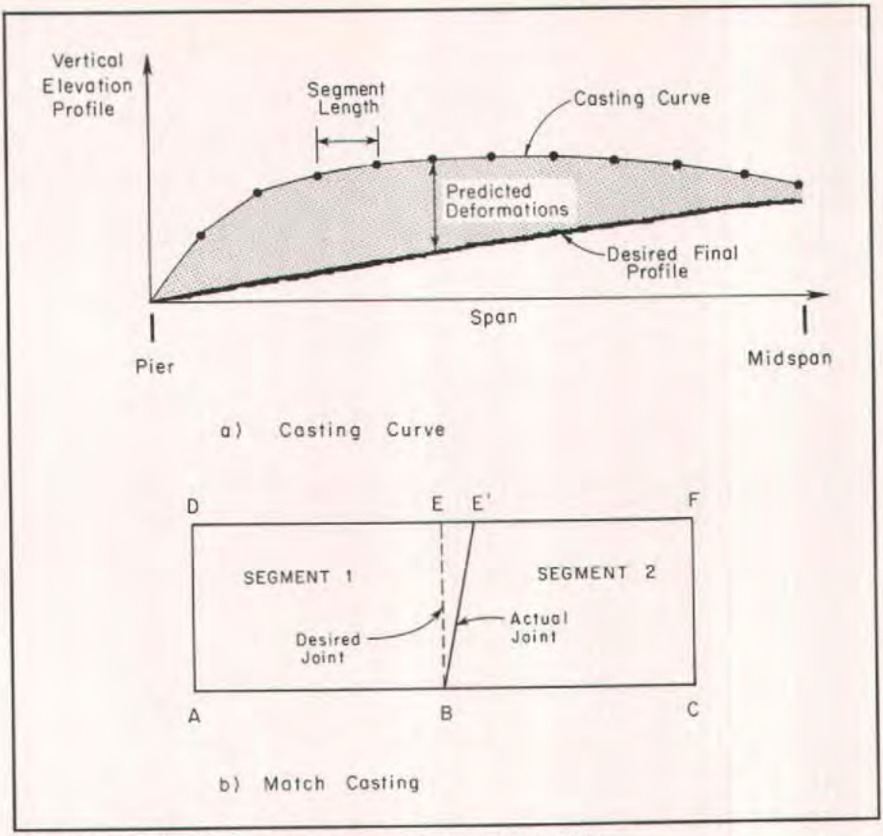


Fig. 4. Basis of match casting in segmental construction.

to certain kinds of errors. The purpose of this paper is to illustrate that sensitivity and point out the relatively simple control procedures that can be used to minimize twist errors in segment production.

MATCH CAST PROCEDURES

The basics of match casting have been thoroughly described by others[3,6,7,10] but a brief description will be given here so that the reader who is not familiar with this widely used process will better understand the problem.

In any completed bridge there is a desired final elevation or grade profile as shown in Fig. 4a. The profile may include horizontal curvature, vertical curvature, and varying superelevation; however, only the vertical curvature profile of one web is shown here for simplification. This desired final grade must be adjusted to determine the desired profile for the actual casting of the segments.

The adjustments should consider deformations upon erection due to the effects of dead load, as well as the effects of prestressing forces and losses, creep, shrinkage, and relaxation. Considering these effects and the sequential nature of erection, a theoretical casting curve as shown in Fig. 4a is determined.

This curve represents the desired profile along each web during casting so that the pieces will be initially deformed in a pattern opposite to the deformations that will take place upon erection. Thus, the bridge cast, so as to meet the casting curve, should have the desired profile after initial erection deformations have occurred.

This, naturally, assumes that segments will be correctly fabricated. The effect of very small systematic differences in segment lengths along the top and bottom fibers could produce extreme deflection variations at span centerlines. This sensitivity has been eliminated by the use of match casting.[1]

As shown in Fig. 4b, Segment 1 would be cast first. Assume that an error was made in casting Segment 1 so that the

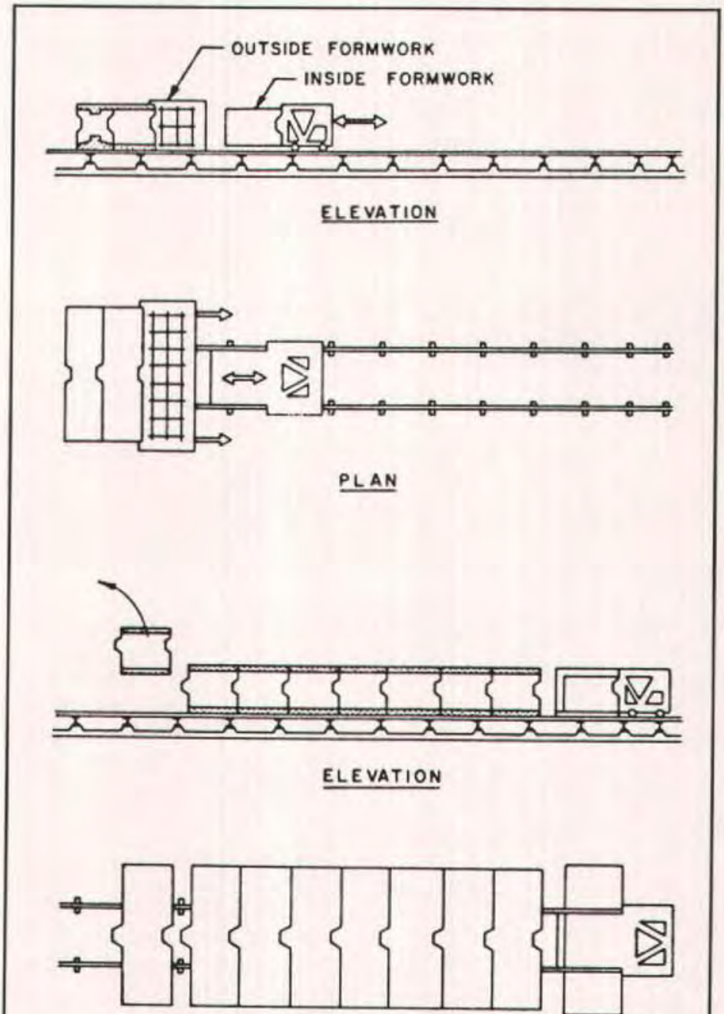


Fig. 5. Match casting systems (from Ref. 6).
(a) Schematic of long line casting system.

actual segment is a prism ABE'D. If the segment is used as the face of the form for casting Segment 2, and if the correct elevation requirements are set for the line DE'F, when Segment 2 is cast it will directly compensate for the previous error. The overall construction will be correct in spite of a potentially serious error in the distance DE = DE'.

There are two general procedures for producing match cast segments. In the "long line" concept shown in Fig. 5a, a base form is set for an entire cantilever span at the desired grade indicated by the casting curve of Fig. 4a.

Match casting of all units for a cantilever span would proceed and generally segments would not be moved until most of the span had been cast. In this procedure, the entire span can be seen with all units in their correct relation. There is minimal danger of twist geometry control errors because the basic geometry is apparent when the form soffit is set.

The long line procedure was used very successfully in casting the variable depth segments for the Kentucky River Bridge.[6] A modified long line in which about one-half of the cantilever span segments were cast before relocation on the soffit was used in the pioneer Corpus Christi Bridge.[9]

In contrast, in the "short line" concept shown in Fig. 5b, all segments are cast in a level position in one set location against a very stiff fixed bulkhead. The newly cast segment is then moved to form the end form of the next segment to be cast. The newly cast segment is carefully positioned and adjusted using various jacks to develop the proper horizontal, vertical, and twist angles with respect to the casting bed in order to ensure the correct geometrical relationship between these two pieces as called for by the casting curve.[10]

The bottom and side forms are then positioned to span between the stiff fixed end bulkhead and the previously match cast segment. The forms should be flexible enough to warp as required yet still have the rigidity to hold the fluid concrete in correct position. The

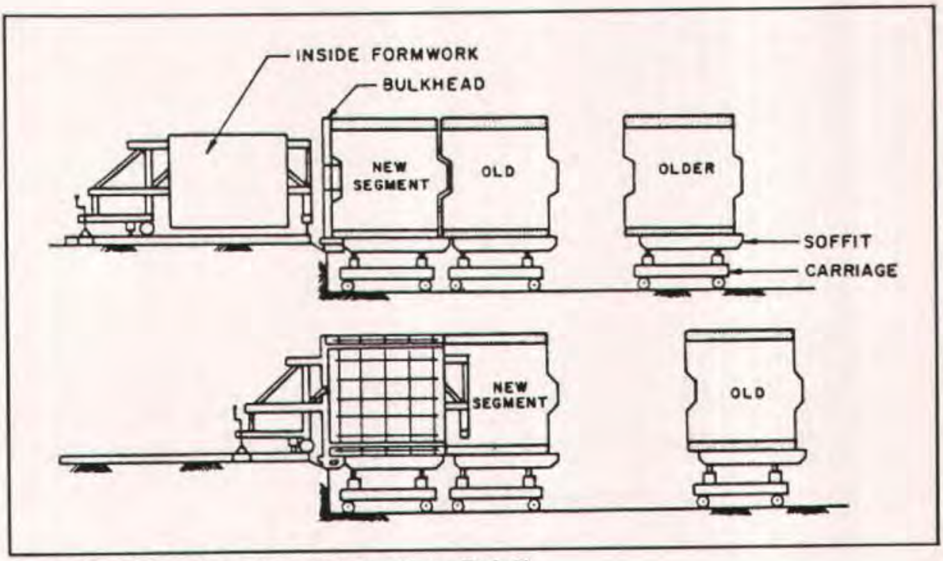


Fig. 5 (cont.) Match casting systems (from Ref. 6).
(b) Schematic of short line match casting system.

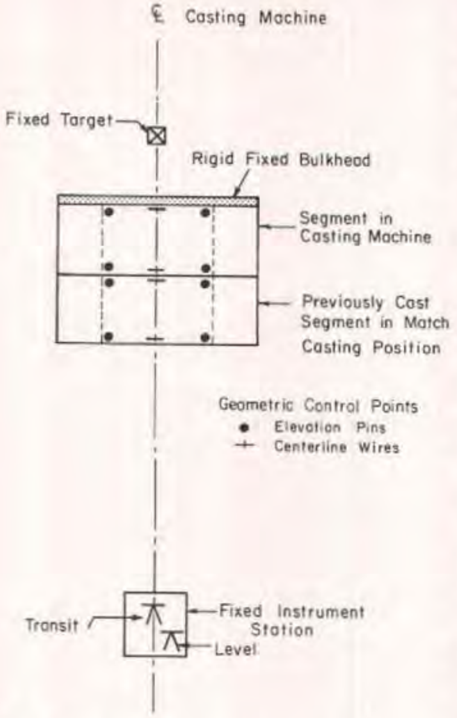


Fig. 6. Short line method geometric control.

other previously cast specimens have been moved to a storage location and no overall physical check of the relations of all pieces for a span is obtained until the segments are erected.

Geometric control in the short line method is provided by insertion of reference pins and wires into the fresh concrete of the segment being cast. The locations are generally near the segment front and rear edges over the webs and centerline as shown in Fig. 6. After the fresh concrete hardens, the elevations of the pins are carefully read using surveying instruments and the centerline locations are scribed into the centerline wires before the segments are separated or moved.

Once the survey is complete, the segments are then separated and the newly cast segment is moved into the match cast position and adjusted in altitude to cast the next segment in the span. It is carefully set into position at the appropriate angles to become the end form and the cycle begins again.

On many projects it has been common to read the pin elevations using a rod equipped with either 1/32 in. divisions or 1 mm divisions. Thus, the smallest scale reading corresponds to 0.032 — 0.040 in. (0.8 — 1.0 mm). In complex geometry cases, the use of an Invar rod with hundredth of a foot increments and accurate interpolation to the nearest one-thousandth of a foot using a parallel plate micrometer is recommended to provide readings in the 0.012 in. (0.3 mm) range.

In actuality, with the distances, climatic conditions, and instrument accuracies involved, such precision is difficult to attain and maintain on a consistent basis unless very careful checks are included. It is highly recommended that independent sets of readings be made by two different crews and cross-checked before the segments are moved. Once the segments are separated, no further geometric check is possible. All control must rely on the accuracy of these "initial readings."

The control process is further illustrated in Fig. 7. Fig. 7a shows the desired relation along one web of three segments of a span with respect to their locations and desired elevations of the casting curve. Subsequent addition of other segments along with the effects of prestressing forces, creep, shrinkage, etc., will result in segments moving into the final desired position.

Segment 1 will be firmly attached to the pier. Segment 2 needs to be cast in such a fashion that when erected and before deforming it will initially make the angle α_2 with respect to Segment 1. Segment 3 must be cast in such a way that it makes the angle α_3 with respect to Segment 2.

In every case the bulkhead end top surface and the longitudinal centerline of the segment being cast in the casting

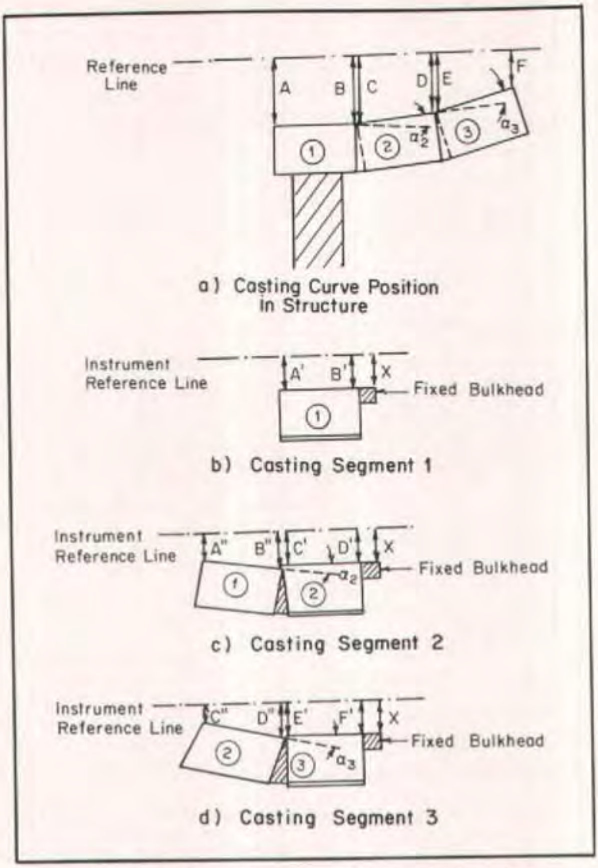


Fig. 7. Vertical elevation geometric control during casting operations.

machine are in the horizontal plane at the elevation set by the fixed bulkhead (X). Fig. 7b shows the level casting of Segment 1.

After initial curing, the control elevations of the pins (A′, B′) are read and Segment 1 is then moved to the match casting position shown in Fig. 7c. The values of the control elevations A″ and B″ are determined by consideration of the desired relations between A, B, C, and D and the actual cast relations of A′, B′, and X.

After Segment 2 is cast and has hardened, the relative relations of the two segments are determined by careful measurement of A″, B″, C′ and D′. Segment 1 then goes to storage as shown in Fig. 7d. Segment 2 is set into its desired configuration using the control elevations C″ and D″ which are based on the desired geometry between Segments 2 and 3 considering the actual geometry of all previously cast segments.

Note that any error in measurement of an angle would result in a closure error proportional to the distance of the joint from the centerline of the pier. Thus, segments near the piers are particularly crucial.

The procedure can operate very smoothly. The success attained in control of the complex geometry of the Linn Cove Bridge shown in Fig. 8 indicates that proper control measures will ensure short line casting success. This particular bridge involved reverse curves and rapid superelevation changes which further complicate geometry control. A combination of precise, checked measurements and careful evaluation of geometry including large scale plots in which three dimensional checks are made provided proper control.

SEGMENT TWIST CONTROL

In order to clarify the proper geometric control procedures required to produce a bridge with the desired twist profiles, it is necessary to first define certain terms:

- *Superelevation (S)* is defined at a specific longitudinal station along the bridge as the difference in vertical elevations of the top surface directly above the center of the inner and the outer webs (see Fig. 9). Note that since the top surface is always assumed to be a straight line at any transverse section, the intersection of the top surface and longitudinal centerline of the unit being cast is assumed to be the center of rotation regardless of the amount of superelevation or the change in superelevation. Thus, each web is displaced one-half of the superelevation in opposite directions. The rotation produces a horizontal offset in the base form.
- *Superelevation Angle (σ)* is defined at a specific longitudinal station along the bridge as the superelevation (S) divided by the horizontal distance between the center of the inner and outer webs (L_B). Thus, $\sigma = S/L_B$ (see Fig. 9).
- *Twist Angle (γ)* is defined as a transverse rotation which takes place between two specific longitudinal stations along the bridge and is the change in superelevation angle between those stations (see Fig. 10).
- *Twist (T)* is defined as a simplified term similar to superelevation in which the twist angle between two longitudinal sections (γ) is multiplied by the horizontal distance between the center of the inner and outer webs (L_B) so that the effective surface warping can be ex-

Fig. 8. Complex geometry at Linn Cove Bridge.

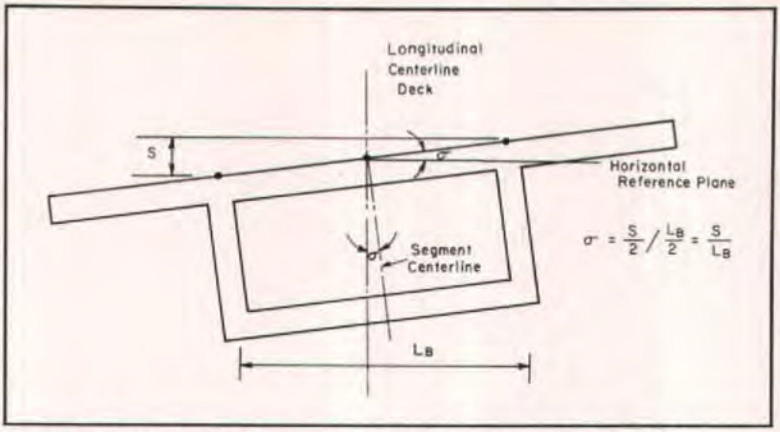


Fig. 9. Definition of superelevation S and superelevation angle σ.

pressed by a unique linear dimension rather than an angular dimension. Thus, $T = \gamma L_B$ (see Fig. 10).

The twist in a segment can be accidental due to errors in casting or can be deliberate when there is supposed to be a change in superelevation along the bridge. When changes in superelevation occur there must be a difference in transverse slope from segment front to rear face introduced into the segments. As shown in Fig. 11a, the top surface of a segment with such a twist actually becomes a warped surface. The edge adjacent to the fixed bulkhead is always cast level.

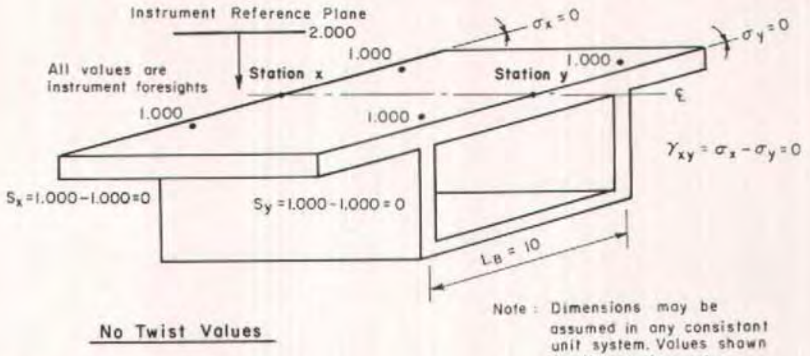
The previously cast match casting position segment (conjugate unit) must be rotated about its longitudinal axis to provide the desired twist angle, γ, in addition to being rotated about the axis of intersection with the next segment to provide the desired camber. As shown in Fig. 11b, the top surface of such a segment has a very complex geometry as compared to the case with no twist.

The difference between the front and rear face transverse slopes is a measure of the twist in a particular segment. With variable superelevation, this twist should match the superelevation change desired in the segment. With flat or constant superelevation sections, the twist should be zero. Many box girder spans are designed to have either no superelevation or a constant superelevation within the span.

In either case there is no desired twist so that the segments may be cast with a flat fixed bulkhead and with the match cast unit in the appropriate orientation to produce the desired horizontal and vertical curves but with the match cast unit in a transversely flat position ($\gamma = 0$). If all segments are cast this way they can be rotated uniformly upon erection to provide the desired constant superelevation. However, as indicated by Bender and Janssen,[10] counteracting horizontal or vertical curvature may be required in determining the casting curve.

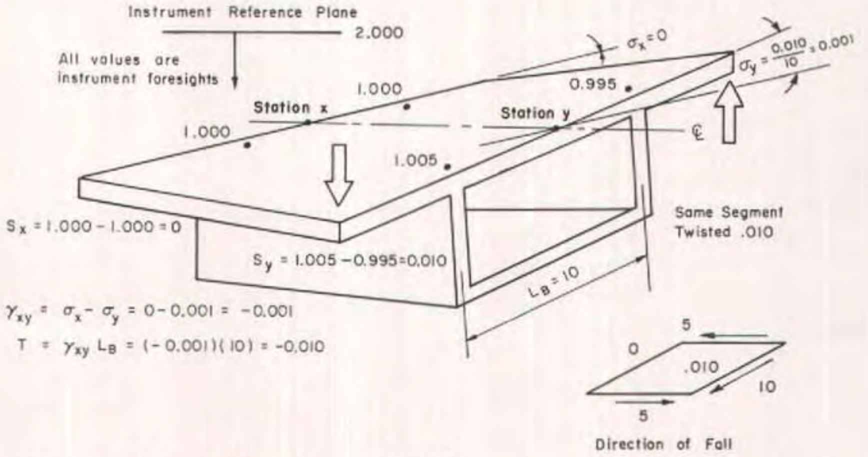
Even when the theoretical twist is zero, there is a danger that due to errors during fabrication, placement or curing, the actual twist in a segment may not be zero. In every segment the final survey results taken just before separation of the match cast units must be carefully examined to determine the actual as cast segment twist T_i.

A suggested procedure in which the surveying values are given in terms of foresights from a reference plane is shown in Fig. 12. As shown, the twist in each segment can be easily determined

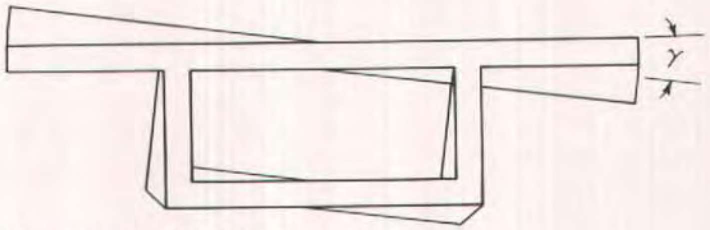


Note : Dimensions may be assumed in any consistant unit system. Values shown for illustration only.

(a) Segment with no twist.

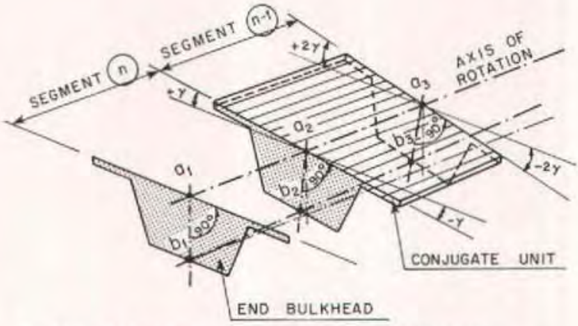


(b) Segment with twist angle γ and twist T.

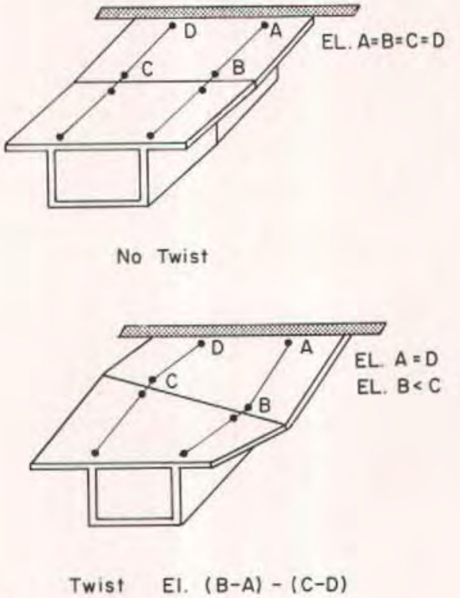


(c) End view of twisted segment.

Fig. 10. Definition of segment twist.



(a) Isometric view with variable superelevation (from Ref. 7).



(b) Complications with twist.

Fig. 11. Short line casting — Variable superelevation.

from the survey foresights made in the mated position in the casting yard. Note that the twists are determined between similar locations on adjacent segments in order to include joint effects.

The algebraic summation of the as cast twists for all segments of a cantilever span should be determined ($T = \Sigma T_i$), continuously plotted for comparison with the desired twist, and appropriate corrections made when setting up for each match casting to control twist tendencies. Since twist errors are more difficult to compensate for in erection than either vertical or horizontal alignment errors, priority should be

$$\text{Twist Angle} = \alpha - \beta = \frac{S_c}{L_B} - \frac{S_{MC}}{L_B} = \frac{S_c - S_{MC}}{L_B}$$

Segment I

$$\text{Twist} = S_c - S_{MC} = [FS(D) - FS(A)] - [FS(D1) - FS(A1)]$$

$$\text{Cantilever Twist} = \sum_{i=0}^{i=N} \text{Segment I Twists}$$

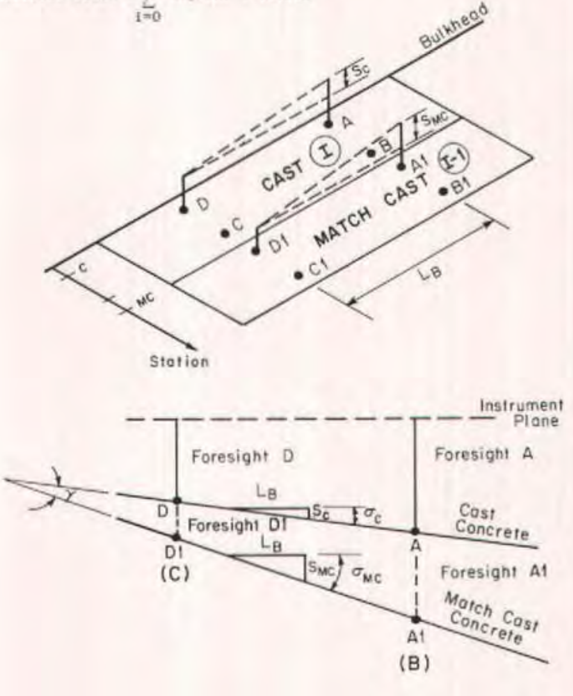


Fig. 12. Determination of segment twist directly from casting yard measurement.

given to casting adjustments to eliminate twisting tendencies.

SENSITIVITY OF CONTROL PROCEDURES

The practical implementation of the geometry control procedures in match casting relies on the casting curves described previously (shown in Fig. 4a) and the computation of the actual "as cast" geometry based on the surveying measurements made before separation of the two match cast segments. Using linear algebraic relations or graphical plots to a large scale, the actual as cast profile of the segments cast to date can be computed.

It is recommended that the as cast profiles be plotted to careful scale on the desired casting curve as shown in Fig. 13. The as cast profile will normally vary around the desired line. The amount of variation at any particular time must be considered in choosing the elevations to which the previously cast segment is to be tilted so as to obtain the desired geometrical configuration to bring the cantilever span close to the

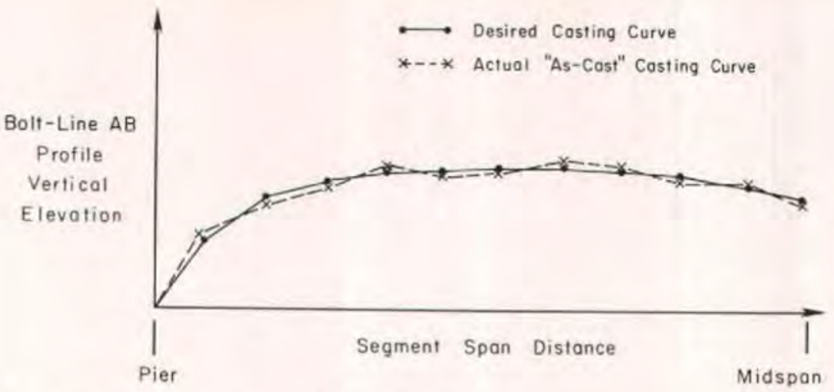


Fig. 13. Practical utilization of casting curves.

desired casting curve.

The extreme sensitivity of the casting curves to very small errors in measurement of the initial segments has not been fully appreciated. The angle between any two segments must be projected to the end of the cantilever spans to determine its full effect on deflection of the closure segment. Very often the length of the pier segments is shortened to minimize lifting weight which would otherwise be excessive because of the heavy diaphragms.

In addition, in many cases the more sensitive central units are cast first when the construction crews are just beginning to become familiar with the process and are more prone to error. Fig. 14a shows the as cast computed profiles for bolt lines AB and DC for an approximately 100 ft (30 m) cantilever of an actual bridge.

The calculated profiles were determined by linear algebraic extrapolation formulas from the initial elevation readings made on the match cast hardened segments before separation. In this particular span the desired superelevation in the first seven segments was variable. This is why the bolt line elevations on AB and DC differ so much.

After the seventh segment the difference in the elevations between the two bolt lines remains approximately constant as there was to be a constant superelevation in the remainder of the span. Both of these calculated as cast casting curves were close to the desired casting curves upon which the precaster based his segment casting decisions.

There was some discrepancy in the initial segments but corrections were quickly made and the units were manufactured with an apparent close match to the planned profile. It will be shown subsequently that, when the units were actually erected, substantial unwanted twists were apparent. Extreme difficulty was experienced in closing the spans.

What has not generally been appreciated is the extreme sensitivity of the chain of measurements and calculations which must be made to control this process. In Fig. 14b the calculated profiles shown in Fig. 14a are shown along with a fictitious dashed line curve.

This dashed line curve illustrates what happens to the computed elevations along bolt line DC if an initial surveying error was made on the pier piece which resulted in the initial elevation of D being taken as $\frac{1}{32}$ in. (0.8 mm) higher than actual and the initial elevation of C being taken as $\frac{1}{32}$ in. (0.8 mm) lower than actual.

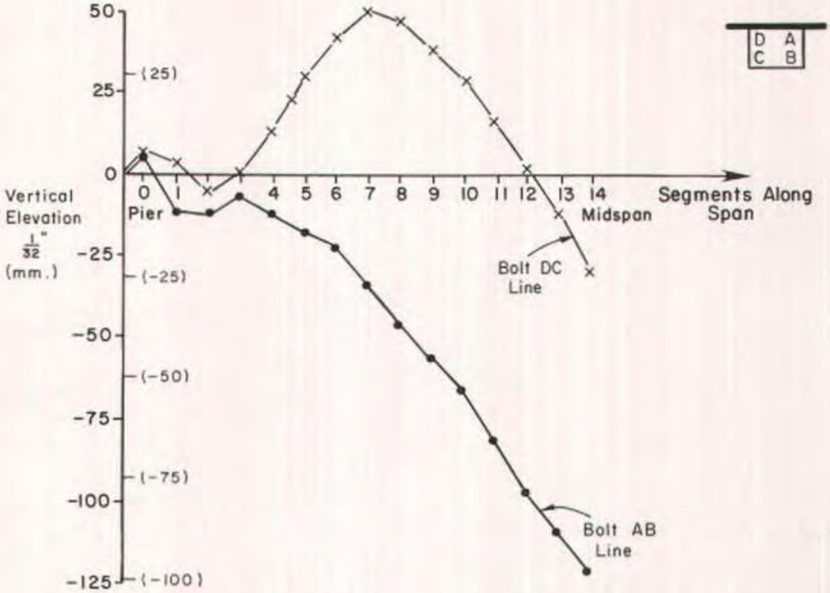


Fig. 14a Computed bolt line profiles from casting yard measurements.

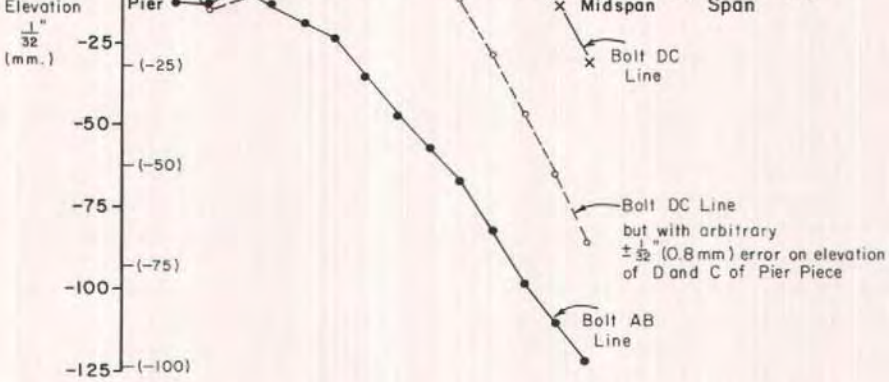


Fig. 14b. Sensitivity of computed bolt line profiles to measurement errors.

Surveying errors of this order of magnitude are certainly possible since they represent the least level of reading sometimes used in plants. While they might be detected when the piece is being put in the match cast position, it is not always likely.

Such measurement errors would result in false calculated rotation of the pier segment and cause the piece to be set in an incorrect match cast position. The entire cantilever would then be rotated downward. Because the pier segment in this bridge was only about one-half the length of the other segments and because of the long length of the cantilever, the angular magnification is very high.

The very small assumed discrepancies in pier segment readings result in about 1½ in. (38 mm) change in the calculated elevation of the web DC at midspan. The arbitrarily assumed initial reading error is certainly at the most critical location but is not even a worst case in terms of magnitude, given the field conditions ordinarily experienced.

Closure operations to overcome such discrepancies would be in the realm of the possible given the vertical deflection stiffness shown in Fig. 2a. As a last resort there would be a possibility of shimming corrections in the field if erection surveys indicated a consistent tendency for such an error during erection.[10]

However, the actual problem is very much more serious when twist is considered. The difference in elevations of the deck above the webs at any transverse section of the bridge is the superelevation. The second difference or change in superelevation between two transverse sections of the bridge is the twist. The desired change in superelevation in any segment can be determined from the planned differences in elevations along the bolt lines.

Fig. 15 shows the desired cumulative twist or change in superelevation called for in the plans for the same cantilever span as previously shown in Fig. 14. The apparent twists in the actual as cast units are plotted based on the second differences from the calculated elevations of bolt lines AB and DC as determined by linear algebraic extrapolation from the individual segment measurements taken before separation.

It can be seen that after an initial poor start the cumulative twist was apparently corrected and the final values are indicated to be very close to those desired. In reality, such was not the case.

Fig. 16 indicates the extreme sensitivity of twist calculations based on extrapolated elevations to small surveying or calculation errors. Again, taking a very arbitrary ± $\frac{1}{32}$ in. (0.8 mm) measurement error in bolt line DC of the pier segment as previously illustrated in Fig. 14b, the cumulative twist is calculated as the sum of the second differences in elevation between the two bolt lines. On this basis, the computed value of the twist is greatly changed as shown by the lower dashed curve of Fig. 16.

In reality, a much simpler and more accurate measurement of the twist is available. As previously shown in Fig. 12, the twist in each segment can be simply and directly determined from the foresights made in the mated position in the casting yard. The cumulative twist is simply the algebraic sum of the individual segment twists.

The small measurement errors in pier segment elevations assumed in this example would actually only introduce a twist change in the entire span of $\frac{2}{32}$ in. (1.6 mm) since the cumulative twist reflects only the algebraic summation of twists in each segment. Because of the geometric extrapolation of the angular pier error to all segments when vertical deflections are extrapolated, the twist determined from the computed extrapolated elevations indicates over 25 times the actual effect.

This oversensitivity to computations for twist from the extrapolated geometry of the bolt line can work in reverse to mask errors. Even more dangerously, it can actually result in twists being cast in segments to counteract the apparent twists resulting from erroneous elevations. Fig. 17 shows the same span. The two upper curves represent the desired cumulative twist and the twist which the precaster assumed he was providing by examining his computed casting curves plotted from calculated (extrapolated) bolt line elevations.

There is good agreement. However, a simple check was bypassed. As shown in Fig. 12, the twist for any segment can be determined directly from the mated match cast segment's bolt foresights. The simple algebraic sum of the twists for each segment gives the cumulative twist for the span.

Fig. 17 also shows the actual twist measured in the field after erection as well as the cumulative twist determined by simple summation of the segment twists as measured in the precast plant using the relations shown in Fig. 12. As can be readily seen, this simple check would have immediately indicated that a severe problem was developing during casting.

Corrective action could be taken during the casting phase to correct for the unwanted twist by counter-rotating the next segments to eliminate the error. The simple check correctly mirrors the subsequent chaotic field conditions. The magnitude of the as cast twist discrepancy over the webs as indicated is further magnified by the ratio of the distance between tips and webs to result in almost a doubling of the error at the segment outer tips. As can be seen from Figs. 1c and 2, errors of this magnitude in twist cannot be easily accommodated.

It is interesting to note that the pattern of the discrepancy between the assumed and the actual twist shown in Fig. 17 is similar but of much greater magnitude

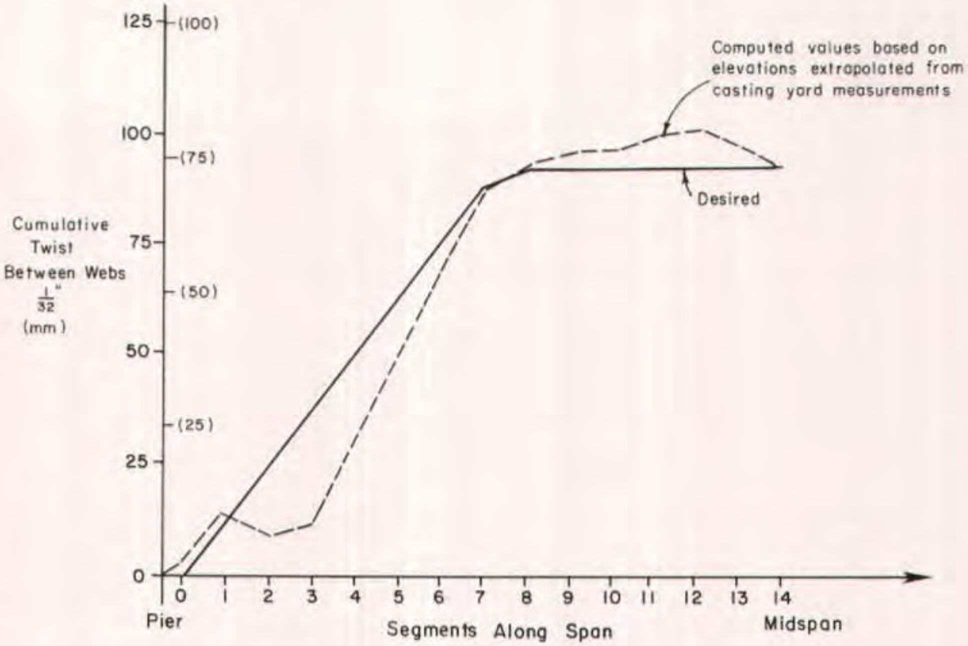


Fig. 15. Desired and computed cumulative twist values.

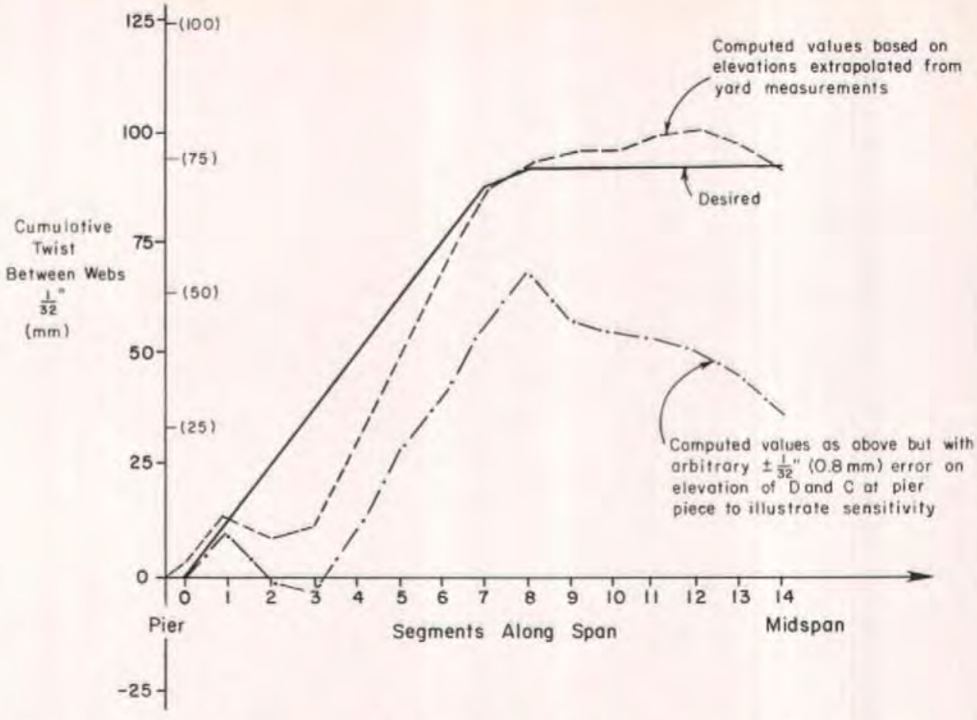


Fig. 16. Sensitivity to measurement errors of twist calculations based on extrapolated elevation calculations.

than the hypothetically based discrepancy shown in Fig. 16. The purpose of these comparisons is not to pinpoint cause but to illustrate the sensitivity of the commonly used procedure of controlling profiles by extrapolating elevations along each web and neglecting the simple twist summation check of Fig. 12.

In addition to the usual control procedure of plotting the extrapolated measured elevations on the casting curves for each bolt line, all control of segmental precasting operations should utilize a third or cross check plot which compares the desired cumulative twist to the actual twist determined from the simple algebraic summation shown in Fig. 12. This plot will illustrate simply and readily the development of undesirable twist trends. Corrective measures to eliminate twists by selecting setup elevations which introduce corrective counter rotations can then be applied during segment production.

APPLICATION TO CONSTANT SUPERELEVATION BRIDGES

It might be assumed that such twist check procedures are not required for level or constant superelevation bridges since there should be no twist in such a bridge. Figs. 18 and 19 show twist measurements from two different projects in different states. Both spans were to have no change in superelevation and hence zero twist. Fig. 18 shows computed and measured values from another span of the bridge shown in the preceding

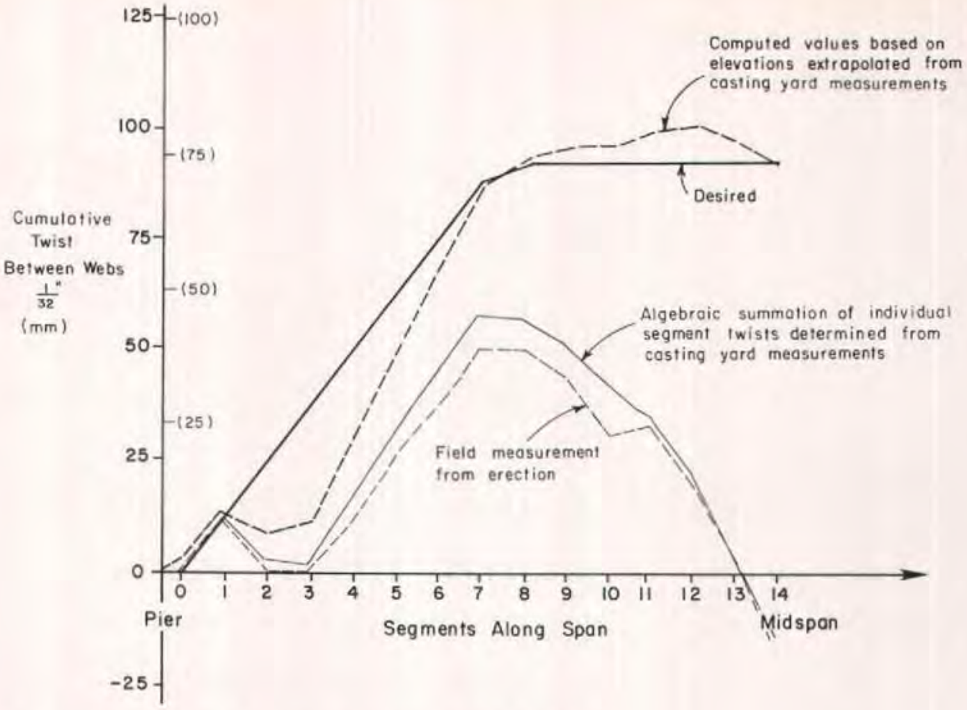


Fig. 17. Desired and measured cumulative twist values.

example. This particular span was to have no change in superelevation and thus all segments were to be cast without twist (Curve A).

The calculated elevations based on the linear extrapolation of the bolt profile measurements made during the match casting process indicated a relatively small twist on the order of ¼ to ⅜ in. (6 to 10 mm) might develop (Curve B). During erection substantial twist was measured (Curve C). As shown in Fig. 18, when the measured twist between webs was approximately 2 in. (50 mm), corrective action was taken to insert shims in the joints to counteract the twisting.

Note that the measured twist in the field up to this point coincides very closely with the predicted twist (Curve D) as determined by the algebraic summation of the individual segment twists as found from the procedure of Fig. 12.

The application of considerable shimming was successful in this case in limiting the twist to about half of the potential twist cast into the specimen. Such shimming should be minimized or eliminated because of the potential damage to the long term integrity of the joints. It would be far better to use a twist control check and corrective action during casting.

Fig. 19 is taken from a different project for a bridge with no design superelevation. The algebraic summation of the individual segment twists determined from casting yard measurements indicates that substantial undersired twists were cast into the segments. Again, the lack of an effective check procedure did not alert the precaster or the contractor to the magnitude of the possible problem.

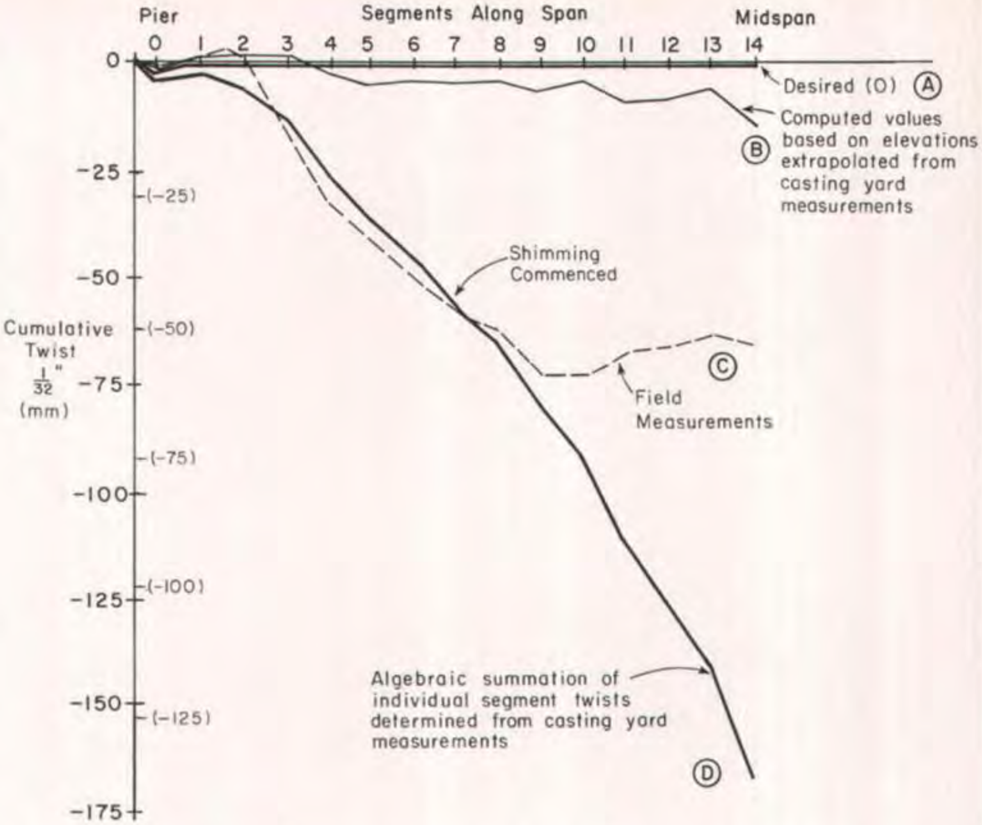


Fig. 18. Twist measurements with effective field shimming as a control measure.

Field measurements agree very well with the predicted twist pattern in spite of corrective shimming being applied at the stages indicated to control both vertical elevation and twist. The shimming measures used to control twist made relatively little difference in this span. The ineffectiveness of shimming has also been reported by Harwood.[12]

Note that this supposedly flat, level cantilever had a twist between bolt lines on the webs of approximately 1½ in. (32 mm). A number of problems involving jointing and shear keys on this bridge may have been aggravated by the unwanted twist tendencies and the need to overcome them in closure.

While the ideal procedure is to use the algebraic summation of the individual segment twist measurement check as a control during the casting process to eliminate this problem, the twist check can be used to evaluate the potential twist of already cast units prior to erection. The procedure is a simple direct check which does not involve the extrapolation procedures involved in computation of elevations of segments in short line casting. The knowledge of twist tendencies in the units would allow the owner, the precaster and the erector to plan accordingly and to resolve problems at an early stage.

In all of the bridges illustrated in Figs. 14 through 19, the precasters had elected to base setup geometry control on a series of algebraic extrapolation equations which correctly projected bolt line elevations but did not require three dimensional twist consistency. The lack of a simple twist check combined with reliance on algebraic rather than three dimensional graphic controls resulted in units being cast with substantial twists even though in zones with no change in superelevation.

CONCLUSIONS

With continued development and widening usage of precast segmental box girder bridges, more highway departments, engineering firms, contractors and precasters are becoming involved with such construction. While geometry control procedures have been published in several references, the sensitivity of some elements of the control process has not been widely appreciated.

The examples cited of problems which occurred in several American bridges during the past decade indicate that twist can be a serious problem in short line match casting. Because of high torsional stiffness of box girders, correction of substantial twist closure errors is very difficult. However, a rela-

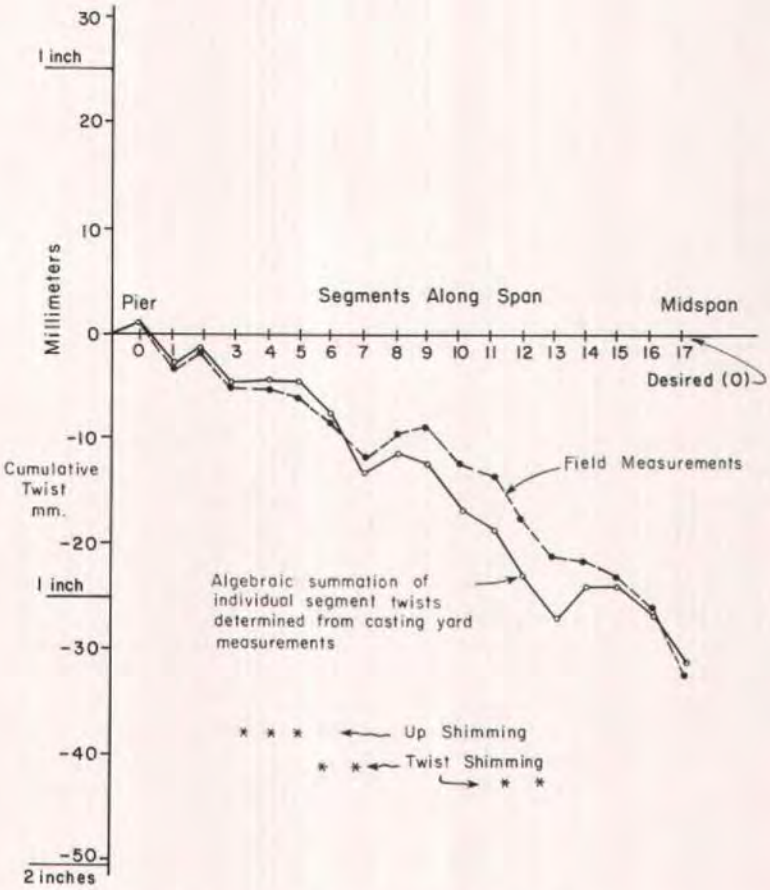


Fig. 19. Twist measurements from a different project.

tively simple check can be made during the match casting process which will provide sufficient warning and information so that twist can be immediately controlled.

Proper geometry control procedures during precasting should include both the conventional casting curves for the bolt lines and a separate tabulation or (preferably) graphical plot (like that in Fig. 17) of the cumulative twist of the segments. Twist values should be determined as shown in Fig. 12 from the elevation foresights taken in the match cast position before separation of the units. Such a direct summation of the cumulative twists of each segment is a much more reliable indicator of twist tendencies than are changes in cross slopes calculated from the extrapolated bolt line elevation values of conventional casting curves.

Such extrapolated bolt line elevations are overly sensitive to minor measurement errors in pier segments and near the piers. Conventional linear equations and graphical solutions for web bolt line elevation curves assume planar deflections. Adding the cumulative twist check forces the process to consider warping tendencies and ties the two web bolt line elevation curves together with a simple check operation.

The most effective procedure for controlling twist is to eliminate any unwanted twist tendencies for the cantilevers during the match cast process. The major elements of such a control process are:

1. Where possible, design spans for zero or constant superelevation so that no planned twist is introduced. This simplifies the problem to control of smaller accidental twists.

2. Precision in surveying to eliminate or minimize subsequent computational errors. This requires highly accurate procedures such as substantial fixed instrument platforms, fixed reference targets and precision leveling techniques to strive for measurements in the one-thousandth of a foot (0.012 in. or 0.3 mm) range.

3. Repeated, independent checks of both measurements and computations of geometry before moving segments.

4. Determination of individual segment as cast twists using the relations outlined in Fig. 12.

5. Plotting of a cumulative twist curve which gives the algebraic summation of the twists found in Step 4 of all individual segments in a cantilever as they are cast.

6. Comparison at each casting stage of desired and actual cumulative twists.

7. Giving priority in computing set up elevations for the previously cast unit in the match cast process to the elevations required to correct twist errors by a counter-rotation. After the proper relation of the bolt lines to counteract twist errors are determined, then the offsets required for vertical deflections should be computed. The match cast segment is then positioned to these elevations in the match casting position.

8. If any residual twist error of magnitude greater than what can be handled in the closure process remains after all segments for a span are cast, as a possible corrective measure, shimming of the joints during erection with shims on the top surfaces of keys in one web and the bottom surfaces of keys in the other web can be attempted. Since this shimming can weaken the joints and offset the benefits of the match casting process, it should be avoided if at all possible. As a last resort during erection, an intentional wet joint can be cast between two of the match cast segments. Harwood reports[12] on the use of approximately 2 in. (50 mm) wide wet joints between several segments to correct alignment and twist tendencies on a major bridge project. This is a difficult and costly way to correct a problem which need not occur. In extreme cases where a serious error was made in a limited number of segments, a corrected segment could be recast before erection. Proper attention to Steps 1 through 7 should eliminate any extraordinary corrections.

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* * *

NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by March 1, 1986.

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