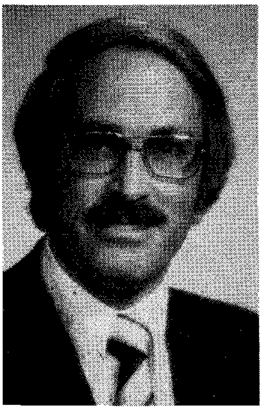
Geometry Control for the Intercity Bridge



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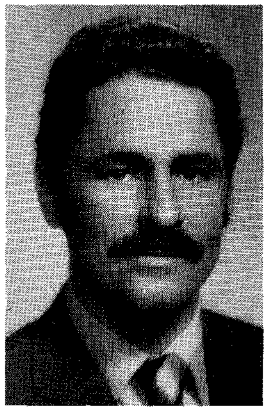

The authors, who were resident engineers for the construction of the Intercity Bridge, discuss the manufacture of the precast segments, the erection method, and the procedures used to attain the horizontal and vertical alignment of the assembled girder throughout construction.

The Pasco-Kennewick Intercity Bridge, which crosses the Columbia River in south central Washington State, is a cable-stayed concrete girder. The main portion of this girder consists of precast concrete segments.

A detailed description of this structure may be found in this current issue of the PCI JOURNAL[1] and elsewhere.[2-5] Described here are the precast units, the manufacturing process, the erection method and the procedures used to control the geometric shape of the assembled girder throughout the construction process.

The precast concrete section of the continuous 2503-ft (763 m) girder is 1686 ft (514 m) in length, and suspended entirely by cables from two towers 981 ft (299 m) apart (Fig. 1). This section of the girder consists of 62 individual precast concrete seg-

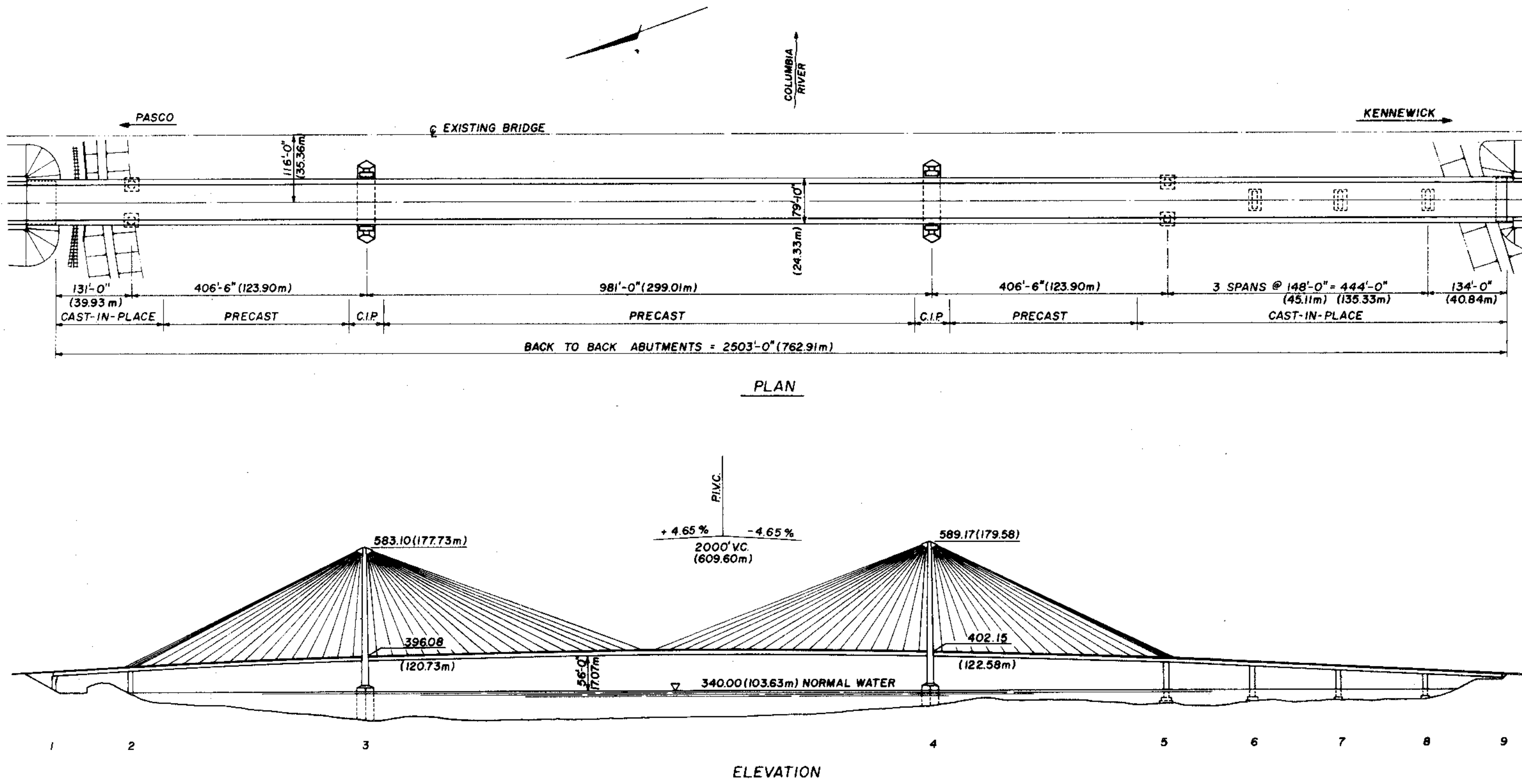

Fig. 1. Elevation and plan drawings of the Intercity Bridge.

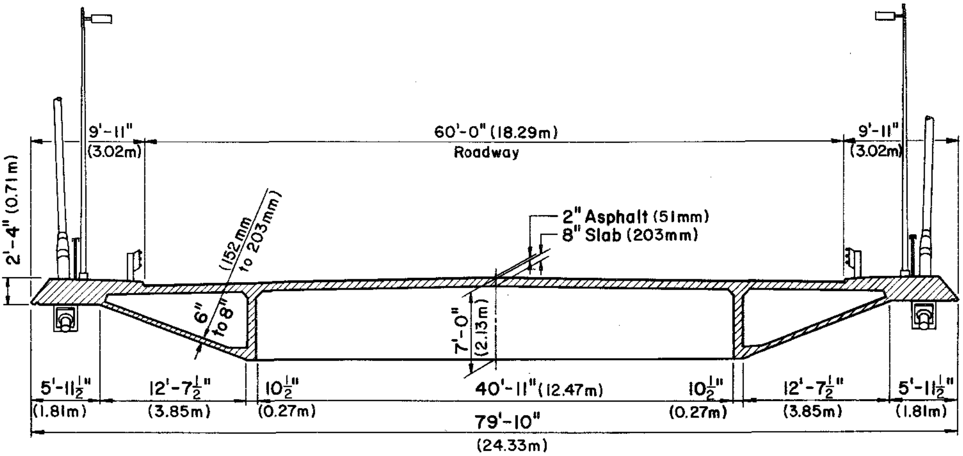

Fig. 2. Typical precast girder section.

ments which were manufactured in a job site casting yard, loaded onto barges and lifted into place.

The segments were assembled outward in both directions from the main towers in a balanced manner and joined to cast-in-place approach spans. The segments were also connected at midspan by an 8-ft (2.4 m) wide cast-in-place joint.

The vertical profile consists of approach grades of 4.65 percent and a 2000-ft (610 m) vertical curve which crests over the channel. The segmental portion lies wholly within the vertical curve.

Discussed herein is the problem of manufacturing and assembling the precast segments so that the correct horizontal and vertical alignment and the proper internal forces would be attained. Problems have occurred in the construction of precast segmental bridges recently where correct geometry was not achieved.[6]

Description of Precast Segments

The precast segment is composed of two longitudinal triangular boxes along each outside edge of the section, joined together by a top slab and three transverse beams (Fig. 2). The typical segment is 80 ft (24 m) wide by 27 ft (8 m) long. All segments are 7 ft (2.1 m) deep.

The entire segment, exclusive of prestress anchorage blockouts, was cast monolithically. The segments were match-cast against one another using the short-line method. Segment weight averaged 300 tons (272 t) each.

The match-cast joint contains no shear keys. To facilitate alignment, four 2-in. (51 mm) diameter steel "pintles" were planned in the top slab at each joint. During construction, the outer two pintles were deleted, to minimize possible interference due to differential shrinkage.

The segments were bonded together with epoxy. To control alignment and bondline uniformity, an initial post-tensioning stress of 30 psi (0.21 N/mm^2) minimum was specified to be applied across the unhardened epoxy by means of longitudinal prestressing bars passing through the joint. The actual initial prestress was 85 psi (0.59 N/mm^2) which was sufficient to squeeze all the excess epoxy from the joint.

It was found necessary to retension the first few bars in the stressing sequence before the epoxy cured in order to overcome losses in prestress due to creep in the unhardened epoxy. The bond line width varied between 0.2 and 0.6 in. (0.5 and 1.5 mm) depending upon the type of epoxy, and temperature conditions at the time of application. The more thixotropic epoxy used at lower temperatures resulted in the thicker bond line.

To provide room for the equipment for lifting the first segment, a 56-ft (17 m) long section of girder was cast on falsework between the tower legs. The first 27-ft (8 m) segment to be erected against this cast-in-place section was in fact a two-piece segment, one 3 ft (1 m) and the other 24 ft (7 m) long.

The 3-ft piece was match-cast against the 24-ft section, while the latter was still in the form.

To establish the proper initial alignment, the 3-ft subsegment was positioned 2 ft (0.6 m) away from the end of the 56-ft long cast-in-place section and supported by the same falsework. After orienting the 3-ft piece, the 2-ft space was cast in with concrete. This was repeated at the opposite end of the 56-ft section.

After post-tensioning longitudinally, the resulting 66-ft (20 m) long piece was lifted off the falsework by means of the first four mainstay cables. Segment assembly continued with lifting and placement of the 24-ft subsegments.

Control of Segment Casting

Control of geometry in essence took place in the casting yard since little could be done to correct and control geometry during assembly. The vertical and horizontal alignment of the suspended portion of the structure was completely dependent upon the angle established each time between the cast and match-cast segments.

Very small angular errors between segments would project ahead, resulting in large final offsets. The setting of the match-cast segment with respect to the precast form therefore required a high degree of precision.

In order to achieve this degree of accuracy, it was decided that no measurements would be taken directly on the concrete surface of the segment, due to surface irregularity. Instead, various steel and brass control points were set into each segment as concrete was placed. Precise reference measurements were then taken on these points, after casting and prior to removal of the segment from the form. These measurements were then used to establish the correct position of the match-cast segment relative to its as-cast position.

All primary horizontal and vertical control work during casting was verified with independent measurements which served to detect errors. A single error in alignment during match casting would not otherwise be detected until erection, with serious consequences. This independent control network could also be utilized in the event one or more of the primary control points were physically damaged.

All measurements taken during construction employed modern, high quality surveying instruments. These included a one-second theodolite, an electronic distance meter, a precision tilting level, an automatic level, and invar rods. These instruments were used and maintained in accordance with the best surveying practices, making possible the high order of geometric precision required by this structure.

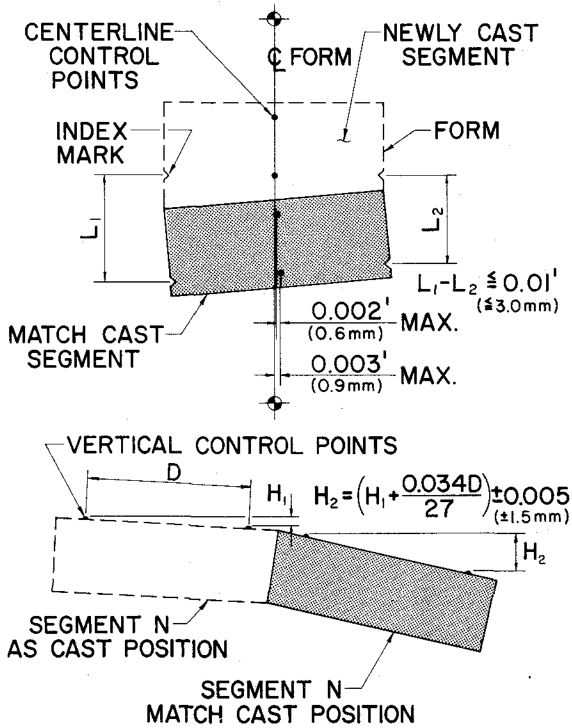

Fig. 3. Segment positioning for match-casting and match-casting tolerances.

Horizontal Alignment

Primary horizontal control consisted of the form centerline, which was established as the line which best fit the center of the form. This line was then extended the length of the casting yard, and marked on concrete monuments. It was used as the bridge centerline for all segment control.

Horizontal control measurements were made on the newly-cast segment the morning after placing concrete, as soon as the steam cure hoods were removed. Bolts which had been cast into the deck were marked with a fine punch mark on centerline. The centerline points were then used to set the segment in match-cast position.

As the entire length of the bridge is in tangent, the match-cast segment was merely placed on form centerline. The segment was permitted a maximum transverse offset of approximately 0.003 ft, (0.9 mm) and a horizontal rotation of not more than 0.002-ft (0.6 mm) difference between points (Fig. 3).

Horizontal alignment of the match-cast segment was independently verified by means of index marks cast into the sloping sides of the deck overhang. These marks were made by vee-shaped bars welded to the side forms. When the segment was set ahead for match-casting, the distance from the index mark in the form to its corresponding indentation in the segment was measured on both sides of the segment.

The measurements served to set the desired 27-ft (8 m) length of the new segment (Fig. 3). In addition, the difference in the measurements indicated the amount of horizontal rotation, using in effect the 80-ft (24 m) width of the segment instead of its 27-ft (8 m) length as a base. These side-to-side differences were not permitted to exceed 0.01 ft (3 mm). They always confirmed the rotation measured on the centerline points.

The acceptable tolerances for match-cast construction depend upon many factors, including type of construction, size of segments, and span lengths. Tolerances chosen were based on the greatest degree of accuracy which the contractor could achieve with his equipment for positioning and holding the match-cast segment. While these tolerances were judged adequate to obtain the desired alignment, even closer tolerances would have been preferable. It is doubtful, however, if much closer tolerances could have been achieved without a considerably more complex and expensive form system.

After each segment was completed, the alignment of the match-cast segment was rechecked and compared with its position as set up. Random movements of its centerline points were observed. They were as much as 0.01-ft (3 mm) transverse offset and 0.005-ft (1.5 mm) horizontal rotation. In addition, the measured side distances increased by between 0.01 and 0.02 ft (3 to 6 mm).

A study of match-cast segment movement during placement of concrete in the new segment produced no conclusive evidence that any such move was occurring. It was therefore assumed that the observed displacement of the centerline points was due to the effects of steam curing temperature. Because of the contractor's schedule, it was not possible to allow a segment to cool and remeasure these points. Therefore, it was decided not to attempt to adjust the horizontal alignment of the segment, based on these observed shifts.

Vertical Alignment

Vertical alignment of the cast-against segments was simplified by a lack of variable superelevation, and by the suspended portion being completely within a 2000-ft crest vertical curve of almost constant radius. To set vertical alignment, it was only necessary to advance the segment to the match-cast position, tilt the forward edge downward a predetermined amount, and maintain the as-cast transverse orientation.

Vertical geometry control points cast into the segment consisted of a basic grid of four points located over the longitudinal girders, approximately 0.5 ft (150 mm) from each vertical face. They formed a grid about 26 x 42 ft (8 x 13 m). In addition, a brass monument was placed behind each trumpet. Control points are shown in Fig. 4a.

After a segment was cast, precise elevations were measured on the centerline bolts, the grid of four points, the brass monuments, and on an auxiliary grid of four chiseled crosses placed on the outermost pedestrian rail plates. The elevations were measured to an accuracy of 0.001 ft (0.3 mm). They were read twice, with the instrument man and rod man exchanging places.

The grid of four points was used to position the match-cast segment vertically. The as-cast longitudinal difference in elevation between points was rotated by 0.034 ft per 27 ft, using the actual spacing between points (Fig. 3). The as-cast transverse difference between points was held constant.

Any warping in the segment as set for match-casting, or during erection, relative to its as-cast position, could be detected by an analysis of second transverse differences in elevation between these points. The contractor was permitted a maximum warp of ±0.01 ft (±3 mm), and a maximum

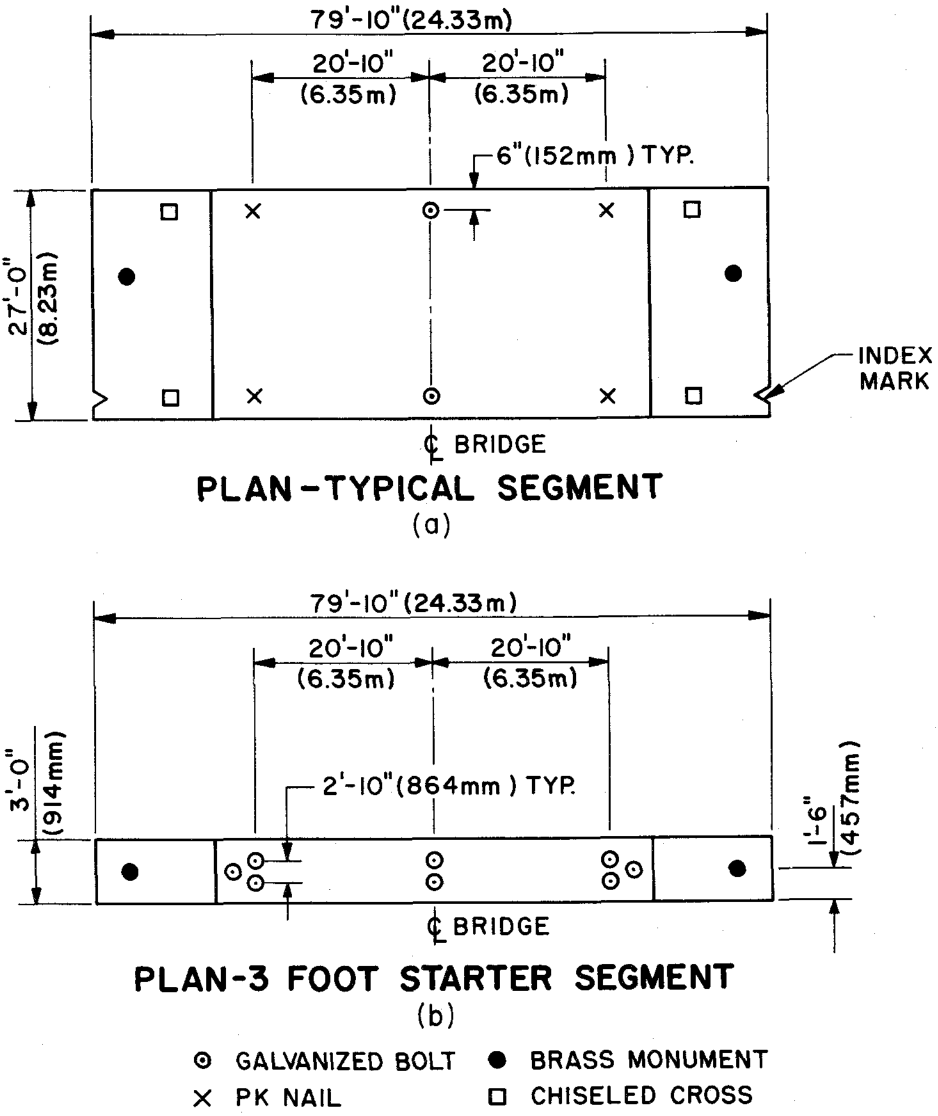

Fig. 4. Geometry control points in 3-ft (≈1 m) and typical 27-ft (≈8 m) segments.

longitudinal error of ±0.005 ft (±1.5 mm).

The auxiliary grid of four chiseled crosses was used only in the case of damage to the original grid of points. The two brass monument elevations were referenced directly to profile grade. They were then used during erection to measure deviation from final profile, and transverse rotation.

Aligning Starter Segments

The 3-ft (1 m) starter segment required an exceptional degree of precision in setting. As previously stated, the starter segment was cast against the first 24-ft (7 m) segment in the form. All reference measurements were made on the segment in this position.

Control points cast into the starter segment consisted of three pairs of bolt heads, one on centerline and one over each longitudinal girder. In addition, a brass monument was set in each sidewalk, and a bolt in each gutter, all on a line perpendicular to centerline. Layout of these points is shown in Fig. 4 b.

After casting, reference readings were made on the three pairs of bolts using a special gage which was capable of measuring the slope of the starter segment within 0.001 in. (0.02 mm) across its 3-ft (1 m) length. Reference elevations were measured on all control points, using the casting yard datum.

Form centerline was marked on the center pair of bolts. A line perpendicular to form centerline was marked on the brass monuments and gutter bolts. The distance from the theoretical trumpet work points in the 24-ft (7 m) segment to a centerline point in the starter segment was measured, for use in correctly setting the starter segment horizontally during erection.

During erection, the starter segment was positioned at a slope calculated at the station of the center of the combined 3-plus-24-ft segment. This slope was applied to the original starter segment gage readings, and a tolerance of ±0.010 in. (±0.2 mm) was permitted.

Control of Volume Changes

Provisions were made during storage of the segments in the casting yard to control volume changes due to shrinkage and creep. The objective was to minimize warping which could produce adverse effects on the assembled geometry.

The top slab of the segment was kept continuously wet during the first 14 days after casting. This allowed the concrete to attain sufficient strength before shrinkage strains developed as the concrete dried out.

Each segment remained in storage for approximately 6 months prior to shipment to the site. Most of the shrinkage occurred during this period, thereby reducing the risk of misalignment due to uncontrolled shrinkage after erection.

During the storage period, the segments were supported by continuous concrete footings under the longitudinal stems. The footings extended approximately 2 ft (0.6 m) above ground to permit air to circulate freely around the segments.

Extra care was taken to provide uniform reactions to minimize warping due to uneven support. Measurements made on the grid of four vertical control points showed a maximum differential deflection diagonally across the segments in storage of 0.02 ft (6 mm).

Erection Control

The suspended geometry is essentially predetermined by the match-cast segments, fixed stay cable lengths, and as-built towerhead location. Thus, geometry control in this phase consisted basically of monitoring the vertical and horizontal alignment of the suspended portion each time a segment was installed.

Theoretical Deformed Profile

In order to achieve accurate alignment it was necessary to know the theoretical deformed profile of the suspended beam at each stage of erection. In addition, the theoretical deformations due to erection equipment and temperature effects had to be established.

The deformed shape of the structure changed dramatically with the addition of each new segment. With the aid of a computer, the analysis began with the desired profile and run of forces in the completed structure. The calculations proceeded in reverse sequence, dismantling the structure conceptually one segment at a time until only the towers remained.

The changes in member forces and deformed shape were tabulated and summarized to yield the forces and deformed shape of each erection stage. The results of the calculations of deformed shapes were then plotted for use in the field.

The geometry of the structure was also influenced significantly by temperature changes. The cables were fabricated to a predetermined length corresponding to a structure temperature of 55 F (13 C). The cables were installed to this as-fabricated length without regard to ambient temperature. The change in cable force due to temperature was calculated.

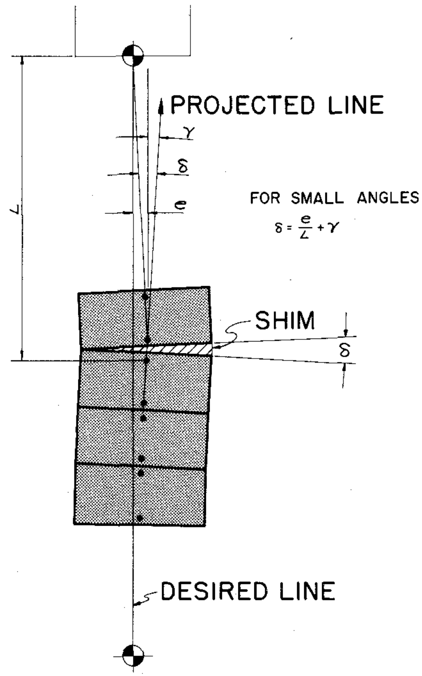

Fig. 5. Correction of alignment by shimming between segments.

Measurements During Erection

A complete vertical profile was measured after each segment was installed and its main stay cables stressed. The brass monuments located behind each trumpet, as described above, were used for this purpose. Their true station was measured on each segment in the casting yard and, using the previously measured relationship of monument elevation to profile grade, a theoretical monument elevation was calculated. When the monument was at this elevation, the segment was on profile grade. The profiles of the upstream and downstream sides of the suspended spans were then plotted, and compared to the expected profiles.

Plumb bobs were suspended in each tower. They were fastened to the exact center of the top of each towerhead. The plumb bob wire extended 225 ft (69 m) through the tower, and terminated at the base of the tower above the pier cap. A weight was attached and suspended in a bucket of oil for dampening. A graduated tape was set behind the wire at the base with its zero mark on pier centerline. By sighting the wire in front of the tape, the longitudinal towerhead displacement, relative to pier centerline, could be measured. These measurements were made after erecting each segment.

Horizontal alignment of the suspended beam was also measured after installing each segment. The punch marks on the centerline bolts on each segment were observed, and their deviations from true bridge centerline noted. These results were then plotted, with a greatly expanded transverse scale, and reviewed prior to installing the next segment.

There was no attempt made to shim any segment to correct horizontal

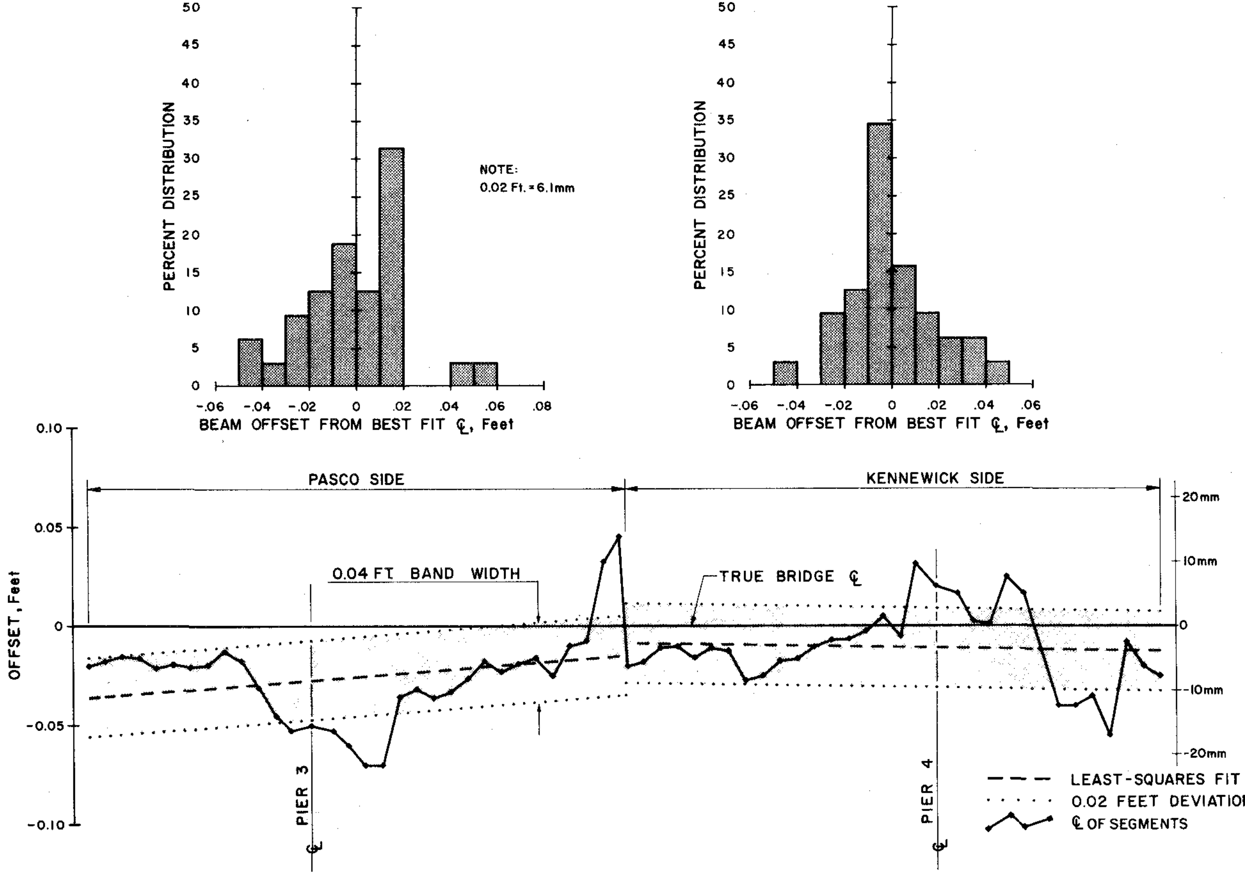

Fig. 6. Horizontal alignment attained in suspended segments.

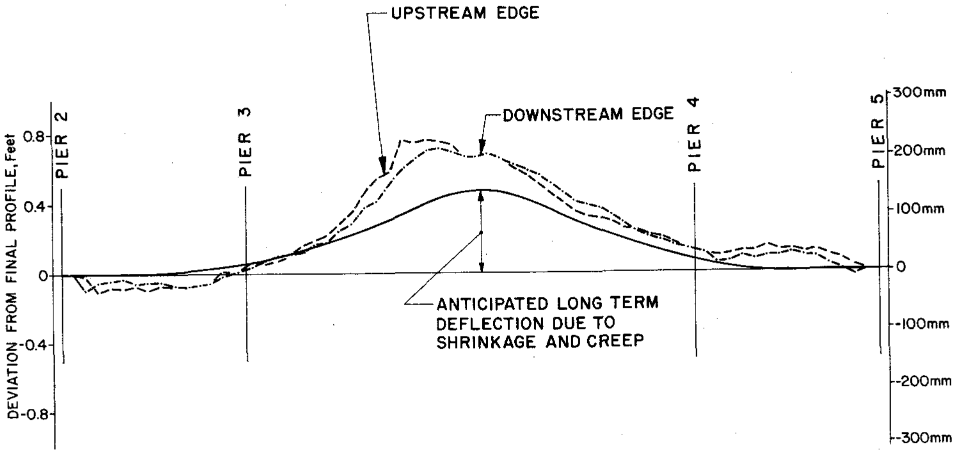

Fig. 7. Vertical alignment attained in suspended segments.

alignment during erection. It was felt that any shimming in the match-cast joint would risk distorting (warping) the segment, and should only be considered as a last resort.

The greatest amount of angular correction which could be achieved in a single joint would amount to a taper of from 0.00 to 0.03-ft (0 to 9 mm) across the 80-ft joint width. The segment angle change resulting from this is small, and the change in offset at the end of the shimmed segment is negligible. Thus, any shimming would need to be done early enough in the assembly process so that the corrected horizontal angle would project several segments ahead and correct the error in offset (see Fig. 5).

Attained Horizontal Alignment

The final horizontal alignment attained after mainspan closure is depicted in Fig. 6. The alignment is also shown separately for the Pasco side (beam suspended from Pier 3) and the Kennewick side (beam suspended from Pier 4). These drawings contain a plot of the offset of segment centerline relative to true bridge centerline at each joint. The transverse scale is expanded approximately 2700 times for clarity.

In addition, a linear least-squares fit line is plotted. This shows the actual straightness of the beam which was attained through the process of match-casting the precast segments. The accompanying histograms show the distribution of the centerline points relative to the least squares fit line.

On both suspended beams, approximately 75 percent of the points fall within 0.02 ft (6 mm) of this line. The remainder of the points, with the exception of the mainspan end of the Pasco side, follow a random pattern. The mainspan end of the Pasco side exhibited a tendency to veer to the east, and some shimming of subsequent segments would have been necessary to correct this trend had this span been any longer.

Attained Vertical Alignment

As stated previously, the vertical geometry of the suspended spans is dependent upon the accuracy of the fabricated cable lengths, the horizontal distance from the centerline of the supporting tower to the cable anchorage at the deck, and the elevation of the towerhead. The girder itself is relatively limber in this direction.

During casting operations, the vertical angle between adjacent segments was established. It was felt that small errors in this angle would produce localized unanticipated beam moments and cable forces, but that such an error would not project to the end of the beam.

During erection, the vertical profile was measured after installing each segment and compared with the theoretical profile. The vertical angular relationship between segments was always within acceptable limits, and no shimming was necessary.

During sidespan and mainspan closures, where newly erected segments joined previously constructed sections, vertical adjustments were made to the girder by adjusting cables. Cable adjustments were calculated with the aid of a computer and were based upon measured profiles.

A vertical profile of the completed structure after placing the 2-in. (51 mm) asphalt concrete wearing surface, is shown in Fig. 7. This profile shows the "camber" of the east and west edges of the bridge plotted as deviations from the planned final vertical profile. Not all of the superimposed dead load had been added at this stage. The anticipated camber when all superimposed dead load has been added is also plotted.

Closing Remarks

Geometric control of precast segmental construction requires a high degree of accuracy and careful attention to details. The form system and the method of supporting and positioning the match-cast segments must be sufficiently rigid to achieve the required tolerances. A well-planned alignment control program must consider the tolerances to be met, the precision of the equipment to be employed, and the skill of the personnel assigned. A geometry control network which may be used throughout casting, erection and subsequent studies should be planned. Independent methods of checking all work must be arranged. Allowances must be made in the contractor's schedule for geometry control work.

During erection, detailed measurements of the deformed structure should be taken at each stage to ensure that the alignment is under control at all times. The possibility of shimming between match-cast segments should be considered a "last resort" measure, and implemented only after due consideration is given to the design of the shims and the possible warping they might produce in the segments.

The precast segments for the Pasco-Kennewick Bridge were manufactured and assembled under very close geometry control, to produce a final horizontal and vertical alignment within acceptable tolerances without resorting to the use of shims. The result is a finished structure that will furnish the full level of service anticipated in its design.

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GLASS-FIBER REINFORCED CONCRETE PANELS HELPED the First Mutual Savings Bank of Redmond, Washington, expand an existing branch bank building to provide a meeting room and allow for future needs. The appearance of the building was unified by facing the entire structure with precast, lightweight "Cemlite" panels, with native stained cedar accents. Though large, the lightweight panels could be handled with small lifting equipment, and needed less structural support than other masonry panels would require. Architect: **Klontz/Wrede,** Seattle, Washington; Structural Engineer: **Anderson-Bjornstad-Kane-Jacobs, Inc.,** Seattle, Washington. Precast Manufacturer: **Olympian Stone Company;** Redmond, Washington. Completed November, 1977.