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Design and Field Monitoring of a Horizontally Curved Steel Plate Girder Bridge

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The center of gravity of a single curved girder lies outside of the line drawn between its supports, which creates a tendency to rotate about its longitudinal axis and "roll" toward its outside (longer) edge when supporting its own weight. But when a second span of unequal length is added to the equation, the dissimilar span lengths create a unique distribution of force effects that cause a global "twisting" of the superstructure. Bridge 207, near Port Matilda, Penn., does not exhibit a severe degree of curvature nor does it contain any other unusual details. But the bridge's curvature combined with one span being 23 percent shorter than the other made Bridge 207 a good candidate for a closer inspection of this twisting behavior.

In addition to the design performed by HDR, a research program was initiated by The Pennsylvania State University to perform detailed monitoring of the superstructure's behavior throughout all phases of construction. With the erection of Bridge 207 completed in 2004, this article focuses on the unusual structural behavior observed during design. Results of the ongoing academic research that will correlate the theoretical behavior with actual measured response will be reported upon completion of the university's study.

PROJECT DESCRIPTION

Bridge 207, a two-span horizontally curved steel plate girder bridge, is part of the S.R. 0220, Section C11 project. The overall project includes design of 2.6 miles of new alignment for S.R. 0220 (also called Interstate 99) in Centre County, Penn. with an estimated construction cost of $75 million. This new road will be a four-lane divided limited-access interstate highway, forming a northwestern loop around the Borough of Port Matilda. Details of Bridge 207 follow:

Span Arrangement:	Span 1 = 209’8” Span 2 = 271’1”
Bridge Cross-Section:	Five steel plate girders spaced at 10’8”
Radius of Curvature:	Approximately 1,921’ to the center girder
Girder Depth:	9’
Girder Material:	ASTM A709 Grade 50 steel
Deck:	9” concrete composite deck
Cross-frames:	K-frames of WT sections spaced at approximately 18’

With its unequal length curved spans, Bridge 207 was a good candidate to observe global twisting behavior.

The superstructure is supported by a reinforced concrete two-column bent and reinforced concrete stub abutments on piles. Pot bearings were used at each support location.

CURVED GIRDER BEHAVIOR

Girder Deflections – Because the girders of Bridge 207 are horizontally curved and the supports are radial to the girders, each girder has a slightly different span length. The longer Span 2 exhibits the pattern of relative deflections that would be expected in most bridge superstructures – a direct positive relationship between span length and deflections. The longest girder, G1, shows the largest dead load deflection at midspan of Span 2, 4.87 inches. The shortest girder, G5, shows the smallest dead load deflection at midspan of Span 2, 2.93 inches.

However, the dead load deflections in the shorter span, Span 1, reveal the exact opposite trend. The longest girder, G1, actually has a peak negative (upward) deflection in this span equal to 0.96 inches. Conversely, the shortest girder in Span 1, G5, has the largest downward Span 1 dead load deflection, equal to 0.55 inches. This counter-intuitive result is caused by the unequal two-span curved girder layout. Because Span 2 is significantly longer than Span 1, its deflection behavior dominates the entire superstructure system. The "rolling" effect in Span 2 causes the opposite effect in Span 1, effectively "twisting" the entire superstructure. The exaggerated downward deflections in G1, Span 2 reduce the downward deflections in G1, Span 1. Similarly, the smaller downward deflections in G5, Span 2 reduce the downward deflections in G5, Span 1 by a lesser amount.

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SPAN 1											SPAN 2										
Girder	Girder Length	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L	Girder	Girder Length	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L
G5	207'4"	0.27	0.46	0.55	0.52	0.38	0.18	-0.02	-0.15	-0.15	G5	268'1"	0.49	1.19	1.95	2.54	2.89	2.93	2.62	2.0	1.11
G4	208'6"	0.2	0.33	0.35	0.28	0.12	-0.08	-0.25	-0.32	-0.24	G4	269'7"	0.62	1.46	2.34	3.01	3.39	3.41	3.05	2.32	1.28
G3	209'8"	0.13	0.19	0.15	0.03	-0.15	-0.35	-0.48	-0.49	-0.34	G3	271'1"	0.76	1.73	2.73	3.47	3.88	3.89	3.47	2.63	1.45
G2	210'10"	0.05	0.04	-0.05	-0.22	-0.43	-0.62	-0.72	-0.66	-0.42	G2	272'7"	0.9	2.01	3.12	3.93	4.37	4.36	3.88	2.94	1.62
G1	212'0"	-0.02	-0.1	-0.26	-0.47	-0.71	-0.91	-0.96	-0.84	-0.51	G1	274'1"	1.03	2.29	3.52	4.4	4.87	4.85	4.3	3.26	1.8

Steel Dead Load Deflections (inches)

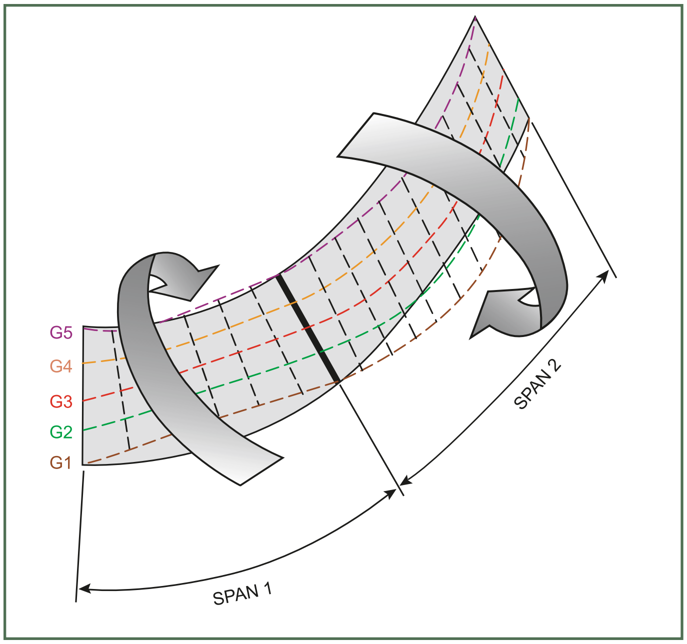
Once understood, this behavior can be visualized as a global torsion of the steel girder superstructure. As the larger curved span rotates outward towards the longer girder, the shorter span attempts to rotate in the opposite direction. The resulting deflections in the shorter span display an inverse relationship between span length and dead load deflection. When this behavior was observed in the initial output of the 3-D modeling software used to analyze and design Bridge 207, it became obvious that the girder reactions and moments also would vary from typical results in tangent girders and symmetric curved girder span arrangements. These specific results are described below.

Girder Reactions – The girder end reactions at the abutments display a trend similar to that seen in the deflections. The abutment reactions in Span 2, the longer span, are positively related to the girder span lengths. The longest girder in Span 2, G1, has a self-weight dead load reaction of 105 kips at the abutment. The shortest girder in Span 2, G5, has a corresponding reaction of only 50 kips. This pattern is in agreement with the intuitive notion that reactions should increase with increasing girder lengths. In addition, the large disparity in G1 and G5 reactions highlights the "rolling" behavior of the curved girder system toward the outside girders.

The abutment reactions in Span 1, the shorter of the two spans, are inversely related to the span lengths of each girder. At this location, the G1 self-weight reaction is 23 kips, while the shorter G5 reaction is 27 kips. Whereas Span 2 exhibited a tendency toward exaggerated outward roll in the longer girders and reduced reactions in the shorter girders, the shorter Span 1 demonstrated the opposite effect. Hence, the global twisting of the curved girder system generated a pattern of reactions at Abutment 1 that differed from expected trends.

Relative Moment Magnitudes – The positive moment distribution in the two spans displayed trends very similar to the end reactions. The magnitudes of the Span 2 positive moments were directly related to the individual girder span lengths. The peak Span 2 steel self-weight positive moment was 17,600 kip-ft in G1, and 9,000 kip-ft in G5. However, in the shorter Span 1, the peak steel self-weight positive moments were 3,800 kip-ft in both the innermost and outermost girders. Again, the torsional twisting of the steel girder system was responsible for these Span 1 positive moment patterns.

Locations of Points of Inflection – The twisting of the superstructure revealed in the deflections, reactions and moments also changes the location of the points of inflection. In either a tangent girder system or a curved girder system with equal spans, the transverse lines connecting the points of inflection within a span are radial to the girders (or nearly so) in plan. However, the torsional behavior of Bridge 207 under steel self-weight skews the points of inflection from this radial geometry. The G1 point of inflection is near 0.55L of Span 1. The G5 point of inflection is at 0.63L of Span 1. This result has implications for setting the locations of bolted field splices and deck pour limits.



The dominant outward rolling effect in the longer Span 2 causes the opposite effect in Span 1, effectively twisting the entire superstructure.

CONCLUSION

Curved steel plate girder bridges are complicated three-dimensional systems. The girder curvature causes deflections and internal forces in curved bridges with unequal span lengths that sometimes differ from what would be seen in tangent structures of similar size or curved bridges with symmetrical spans. An understanding of the rotational behavior of curved girders is crucial for engineers who analyze and design these structures.

The Pennsylvania State University continues to collect and analyze field data related to Bridge 207. Monitoring equipment was placed at strategic locations throughout the superstructure and detailed information recorded during all phases of the construction, including completion of girder erection and placement of the concrete deck. With a focus on axial stresses of specific cross-frames, warping stresses of the girder flanges and global deformations and rotations of the steel superstructure, the goal of the study is to gain insight into the behavior of curved girder bridges during construction and facilitate more accurate and effective construction procedures in the future.

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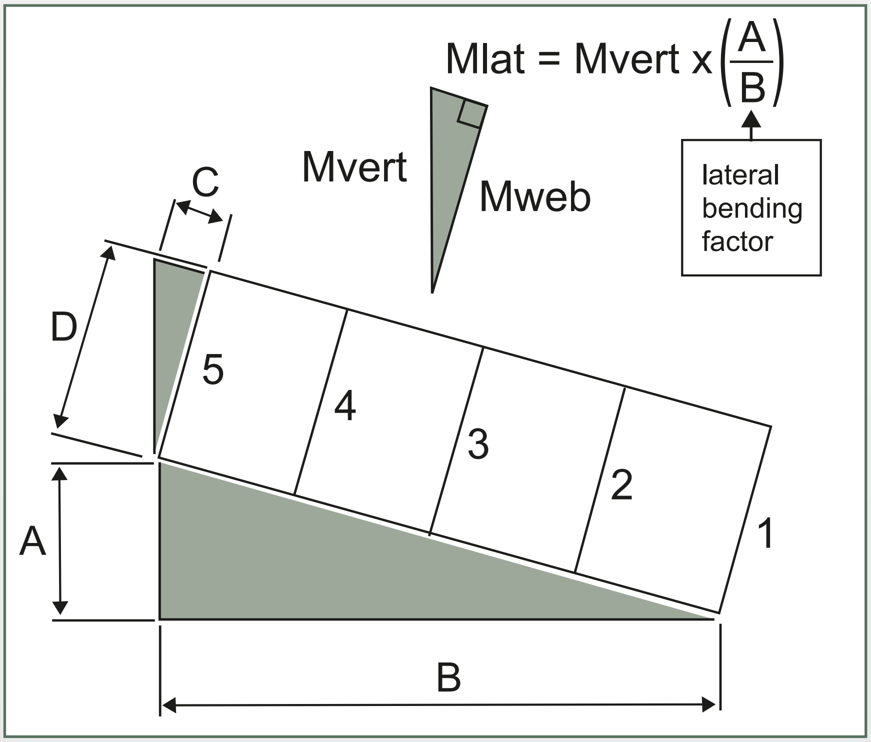
Bridge 207: A Model for Second Order Lateral Bending Effects in Curved Girders



Given the girder depth and relative vertical deflections of the five girders, a spreadsheet was used to calculate the global rotations of the superstructure and lateral bending factors at 10th points along each span.

Cross-frames in tangent steel plate girder bridges help maintain the stability of the girders during erection, help distribute traffic loads to adjacent girders, and help the superstructure to resist lateral loads such as wind. In curved or skewed superstructures, however, the cross-frames serve an additional critical function as main load carrying members. The tendency of a curved girder within a superstructure to rotate about its longitudinal axis is resisted by the cross-frames connecting adjacent girders. Because the cross-frames help maintain the internal stability of the steel girder superstructure, they are treated as primary load carrying members. As such, they impart lateral loads on the girders. These cross-frame loads create lateral bending moments in the girders that are resisted primarily by the girder flanges. In typical curved girder analysis, the total tip stress in the girder flanges is the sum of the stresses caused by the vertical bending moments and the lateral bending moments.

However, there can be a third source of stress in the girder flanges that typically is not captured by standard computerized analysis. Unless they are specifically detailed to avoid this condition, most curved steel girders are not vertical (plumb) in their final condition. Curved girders that are fabricated to be erected plumb in the no-load or steel-dead-load only condition will tend to rotate into a position where their webs are not plumb in the final condition. If in the final position the webs are very close to plumb (which is the case for many girders with large radii and/or shorter spans), this phenomenon will have very little effect on the girder stresses.

But as the magnitude of the web out-of-plumbness increases, the lateral component of the vertical bending moment can become a significant component of the girder stresses. This lateral component of the vertical bending moment is a secondary effect caused by the true deflected shape of the superstructure and is not captured by typical curved girder analysis methods. A separate method for quantifying the lateral component of the vertical bending moment is needed. This fact is often overlooked by designers, but is beginning to be recognized by some industry agencies. The AASHTO/NSBA Steel Bridge Collaboration document "Guidelines for Design for Constructability" (2003) directly addresses the additional stresses caused by out-of-plumb girders and directs the designer to evaluate them.

CONSIDERATION OF OUT-OF-PLUMB EFFECTS

Current software and analysis techniques do not directly address the lateral component of the vertical bending moment in an out-of-plumb steel girder. The approach taken on Bridge 207 to quantify and incorporate the additional lateral flange bending moments caused by the web out-of-plumbness is simple and rational. Given the girder depth and vertical deflections of the five girders, a spreadsheet was used to calculate the global rotations of the superstructure at 10th points along each span. These rotations were used to calculate "lateral bending factors," which quantified the lateral components of the positive vertical bending moments. In effect, the spreadsheet resolves the plumb vertical bending moment into a lateral component and a component aligned with the out-of-plumb web.

The products of the lateral bending factors and the vertical bending moments from the 3-D model were the additional lateral bending moments caused by the out-of-plumb nature of the girder webs. A second spreadsheet incorporated the resulting additional lateral stresses into the girder stress checks and calculated new performance ratios for critical locations along each girder.

The proposed approach for incorporating the additional lateral flange moments caused by the out-of-plumb webs ensures that the girder stress checks include all relevant stresses. The girder curvature combined with unequal span lengths causes deflections and internal forces that sometimes differ from what would be seen in tangent structures of similar size or curved bridges with symmetrical spans. A designer who uses a conventional program to perform girder stress checks must remember to allow some additional conservatism in the resulting girder design to account for this additional lateral bending stress. The above spreadsheet method is a simple way to perform this final calculation.

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