CURVED STEEL BRIDGES – WHAT HAPPENS DURING CONSTRUCTION? INFORMATION FROM EXPERIMENTAL AND ANALYTICAL STUDIES IN THE UNITED STATES.

Daniel G. Linzell
Assistant Professor
Department of Civil and Environmental Engineering
The Pennsylvania State University
231L Sackett Building
University Park, Pennsylvania, USA 16802-1408

Keywords: curved girder, steel, bridge, construction, erection, fabrication, experimental, analytical

ABSTRACT

The Curved Steel Bridge Research Project (CSBRP) has been underway in the United States since 1992. The Federal Highway Administration (FHWA) initiated the CSBRP to experimentally and analytically study curved steel bridge behavior. The centerpiece of this project has been the testing of a series of full-scale plate girder specimens under realistic loads and boundary conditions. These conditions were achieved by placing the specimens into a full-scale experimental curved bridge superstructure that acted as a realistic reaction frame. During construction of the structure, a number of tests were performed and results from these tests were compared to analytical models. The comparisons were used to verify instrumentation schemes, to establish data reduction methodologies and to validate the accuracy of the analytical models. They also provided a unique opportunity to study the influences of fabrication and construction on curved bridge behavior in a laboratory environment. This paper summarizes the construction tests and representative results from the analytical comparisons are presented and discussed.

INTRODUCTION

In the United States and abroad, the shrinking availability and increased cost of land for new or replacement bridges has led to severe space limitations being imposed at many bridge sites. Oftentimes, the only structures that can maintain the design traffic speeds and can economically fit within the confines of the bridge site are curved steel bridges. This has resulted in a dramatic increase in the number of curved steel bridges that have been designed and constructed in the past 20 years.

In the United States, increased curved steel bridge design and construction in the 1980's and early 1990's indicated that the specification guiding those designs, the *AASHTO Guide Specification for Horizontally Curved Highway Bridges* (AASHTO, 1980, 1993) needed to be reexamined to see if improvements and/or additions could be made. The specification was developed in the late 1960's and early 1970's through an extensive research project funded by the FHWA that involved experimental studies of individual components and scale-model bridge systems and extensive computer-based analyses. The decision to reexamine the Guide Specifications was made in the early 1990's and at that time it was determined that a series of full-scale tests would be performed. The full-scale tests would provide accurate load and boundary conditions to specimens that were examined and would eliminate concerns regarding size effects. The project to perform these tests was coupled with a large analytical component and it was termed the Curved Steel Bridge Research Project (CSBRP). The CSBRP was initiated by the FHWA in 1992 (Zureick et al., 1994).

The main emphasis of the CSBRP was examining various curved plate girder sections under applied flexural and shear loads. However, tests that studied curved bridge behavior during construction were also planned and these tests would examine the experimental structure used for the flexural tests as it was being erected. A series of elastic tests of various subassemblies of the final structural system, which consisted of three simply-supported, radially braced plate girders would be completed. The tests would study the behavior of these subassemblies with differing levels of shoring support. They would be used to investigate levels of deformation and load redistribution in curved steel bridges during construction along with studying the effects of imperfections on behavior.

This paper will provide an overview of the structural system that was tested for the flexural portion of the CSBRP and will summarize instrumentation used for the construction tests. Analytical models used to predict response of the subassemblies will be described and their predictions will be compared to experimental results from select tests. Conclusions regarding the behavior of curved steel bridges during construction will be obtained from these comparisons and from examination of trends observed during testing.

BACKGROUND

Extensive curved steel bridge research was initiated in the United States in the late 1960's when the FHWA funded the Consortium of University Research Teams (CURT) Project. The goal of this project was the development of a curved steel bridge design specification and the first edition of this specification, the *AASHTO Guide Specification for Horizontally Curved Highway Bridges*, was published in 1980. Prior to initiation of the CURT project, limited research into the behavior of curved steel bridges had been performed in the U.S. and it was generally theoretical or analytical in nature. During the same time period as the CURT project, a number of research projects were underway in Japan and this work resulted in publication of the Hanshin Expressway Public Corporation's *Guidelines for the Design of Horizontally Curved Girder Bridges* (Hanshin Expressway Public Corp., 1988)

Scale model and component laboratory testing was a major component of both U.S. and Japanese research during the 1960's, 1970's and early 1980's. Scale model tests examined prototypes of twin and multiple girder bridges of various radii, spans and unbraced lengths (Brennan, 1970, 1971, 1974), (Brennan & Mandel, 1979), (Brennan, et al., 1970), (Culver & Christiano, 1969), (Heins & Spates, 1970), (Mozer et al., 1973), (Nakai & Kotoguchi, 1983). The models were tested under a number of simulated dead and live load combinations. Component tests involved either single girders or portions of single girders and they were used to study specific modes of failure and the effects of varying certain parameters on curved girder response (Mozer & Culver, 1970), (Mozer et al., 1971), (Fukumoto & Nishida, 1981), (Nakai et al., 1983, 1984a, 1984b).

Additional laboratory studies of curved steel plate girder specimens have been completed since first publication of the AASHTO and Hanshin specifications. These tests involved either isolated girders or portions of isolated girders (Yoo & Carbine, 1985), (Thevendran et al., 1988), (Shanmugam et al., 1995).

Past laboratory studies did not focus on the behavior of curved steel bridge systems during construction. There also have been limited field studies of curved steel bridge construction behavior (Galambos et al., 1996), (Huang, 1996), (Pulver, 1996), (Hajjar & Boyer, 1997). Results from the tests and analyses described herein should provide additional insight into the behavior of curved steel plate girder bridges during construction.

TESTING PROGRAM

Experimental Structure

The structure tested for the CSBRP is shown in Figure 1. Its design was controlled by the desire to impose realistic loads and support conditions to curved plate girder specimens under flexural loads. The final experimental structure would be proportioned so that the specimens failed while the rest of the system (the "testing frame") remained elastic. A number of design alternates were investigated. Full-scale single and twin-girder systems were initially studied. However, those options were eliminated due to concerns regarding the amount of bracing required for stability and to concerns about uplift and premature yielding.

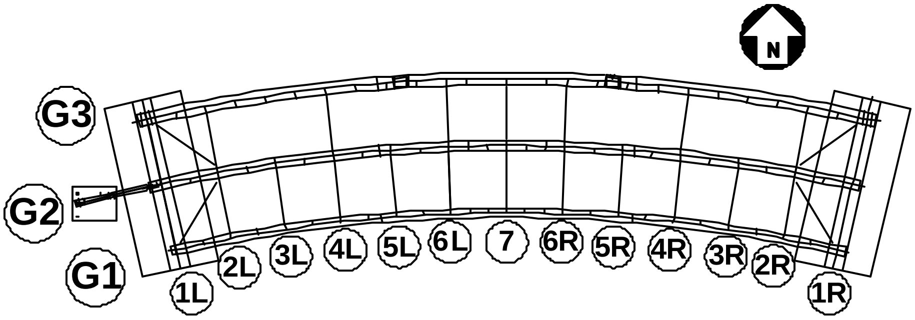


Figure 1. Bridge plan (courtesy FHWA/HDR, Inc.).

A simply-supported, three-girder system was selected for the experimental structure. The structure was designed so that under predominating flexural loads the mid-span portion G3 failed while the rest of the structure remained elastic. Therefore, plate girder specimens of various cross sections could be spliced at mid-span of G3 and their behavior examined.

Girder spans were 26.2 m (86'-0") for G1, 27.4 m (90’-0”) for G2 and 28.6 m (93'-11") for G3. Radii of curvature were 58.3 m, 61m and 63.6 m (191'-3", 200’-0” and 208'-0”), respectively. Web plates were between 121.9 cm x 0.8 cm (48” x 7/16”) and 121.9 cm x 1.3 cm (48” x 1/2”) and flange plates were between 40.6 cm x 1.7 cm (16” x 11/16”) and 61.0 cm x 5.7 cm (24” x 2 1/4”). Radial cross frames were placed between the interior and middle girder (G1 and G2) and between the middle and exterior girders (G2 and G3). Extra lines of cross frames were required between the G1 and G2 to stiffen and stabilize them and achieve the desired load distribution pattern. A typical cross frame is shown in Figure 2. Each frame contained five 413 MPa (50 ksi) tubular members.

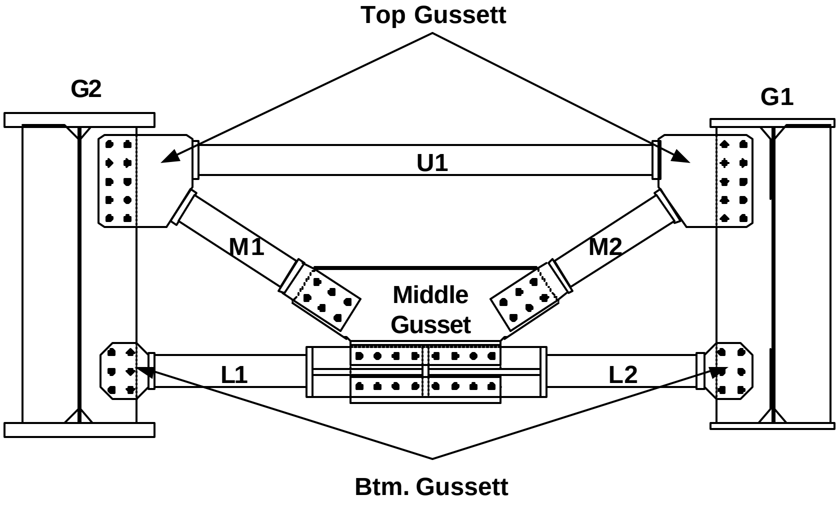


Figure 2. Typical Cross Frame Elevation.

Girders were transversely stiffened at cross frames connection points and halfway between them, at load application points and at the supports. Supports consisted of radially oriented steel abutments tied to the floor using DYWIDAG bars. A combination of spherical and Teflon bearings were used to minimize frictional forces at the abutments. Lower lateral bracing was placed in exterior bays of the span to minimize differential radial displacement between adjacent girders.

ASTM A572 Grade 50 steel was used for G1 and G3 while G2 was fabricated from AASHTO M270 Grade 70W steel. Increased strength was required for G2 due to anticipated load shifts to that girder when flexural test specimens approached their limit load.

Instrumentation

Extensive instrumentation was required to ensure that behavior was accurately measured during both the construction and flexural tests. Load cells were placed at the abutments and at intermediate shoring locations. Strain gages were affixed to the girders (Figure 3), cross frames and lower lateral bracing. Both vibrating wire and resistance strain gages were used on the girders for the flexural tests. Only vibrating wire gages were installed for the construction tests. Vibrating-wire gages were used at discrete locations for two reasons: (1) they helped conserve data acquisition space; and (2) they provided dependable long-term strain measurements.

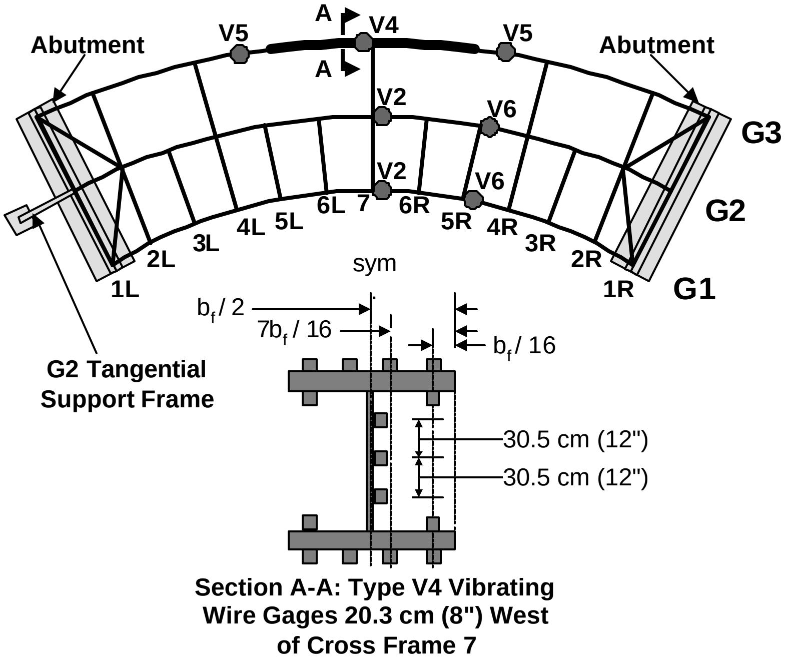
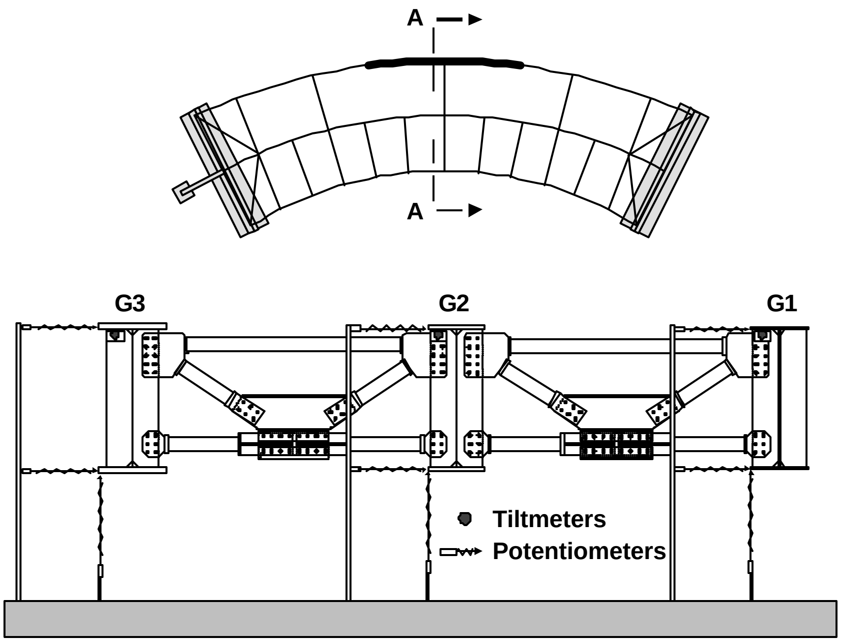


Figure 3. Girder Strain Gage Locations.

Girder deformations were measured using standard displacement and rotation transducers and laser and total station systems. Potentiometers, LVDT's and tiltmeters were affixed to the girder webs and flanges at mid-span and at the abutments (Figure 4) while targets for the laser and total station systems were placed at set increments along the webs and flanges. Using these three systems gave detailed deformation data at select locations while concurrently providing a global picture of the deformed shape of the structure under load.



Section A-A: Mid-Span Deformation Instrumentation

Figure 4. Girder Mid-Span Deformation Instrumentation.

The number of instruments for any given construction test varied; since components were added to the structure and instrumented it was being erected. The first construction test acquired approximately 70 individual data points while the final construction test acquired approximately 1050 data points.

Construction Testing

Construction tests were performed as the experimental structure was being erected and framing plans that were examined were subassemblies of the structure shown in Figure 1. Both two and three-girder systems were examined and a total of six different framing plans were involved with nine tests being completed (Figure 5). Loads for the tests involved the self-weights of the components that were installed; no external loads were applied.

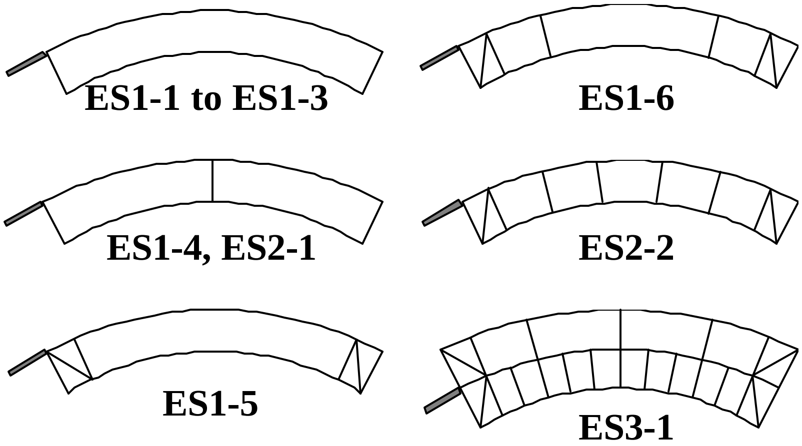


Figure 5. Construction Testing Framing Plans.

The construction tests were initiated with each framing plan being shored to its theoretical “no-load” position. The “no-load” position was estimated using preliminary analytical studies and measurements of the as-built structure during its pre-assembly at the fabrication shop. Testing began once the “no-load” position was established.

Testing procedures differed for the three series of tests that were completed. A total of six ES1 series tests were performed. ES1 series tests focused on deformation and load redistribution that would occur in a twin girder system with differing levels of shoring support for the interior girder. Therefore, these tests examined behavior as shoring was sequentially removed and replaced from the interior girder in the system (G1 from Figure 1) while the exterior girder (G2) remained shored.

The ES2 series tests studied deformation and load redistribution in twin curved girder systems as levels of shoring restraint were varied for both the interior and exterior girder. A total of two ES2 series tests were completed and shoring was sequentially removed and replaced from beneath G1 and G2.

One ES3 series test was completed and it studied levels of deformation and load redistribution in a three-girder system as shoring conditions changed. Therefore, data was recorded as shoring was sequentially removed and replaced from beneath all of the girders shown in Figure 1.

ANALYTICAL MODELS

Detailed finite element models were used during design and construction testing to predict behavior of the curved bridge systems that were examined. Since framing plans that were tested differed in size and complexity, their finite element models had varying numbers of elements and degrees of freedom. The largest model for the final construction tests, that for the single ES3 series test, contained over 8400 elements and 50000 degrees of freedom. All of the models were assembled and analyzed using ABAQUS/Aqua Versions 5.4 to 5.8 (Hibbitt, Karlsson & Sorenson, Inc., 1998a, 1998b, 1998c).

Finite element and experimental results were compared for five of the nine tests. The tests that were selected were ES1-4, ES1-6, ES2-1, ES2-2, and ES3-1. These tests were chosen because they examined curved bridge framing plans similar to framing plans that may be erected in the field. Comparisons that were performed were conducted to: (1) validate the accuracy of the models; (2) refine the instrumentation plan before initiating the flexural tests; and (3) study the effects of shoring conditions, fabrication and construction on the behavior of curved steel bridges during construction.

Finite element models were run using support lowering and removal sequences that matched testing procedures followed in the laboratory. The analyses were initially completed using nominal geometric dimensions and then the models were re-analyzed using geometric dimensions taken from an extensive set of measurements recorded during the construction process (Linzell, 1999).

Comparisons between finite element and experimental results centered on comparing girder support reactions, vertical displacements, and strains and on comparing cross frame internal forces. Sample comparisons girder support reactions and mid-span displacements are shown in Figure 6 for ES1-4 and Figure 7 for ES3-1. Figure 6 plots the variation in support reactions for G1 at the abutments (cross frames 1L and 1R) and at a shoring frame located at mid-span (cross frame 7) verses the mid-span displacement of G1. Figure 7 studies variations in support reactions at the same three locations for G3 as a function of its mid-span displacement. Nine testing “steps” are plotted in Figure 6 and three in Figure 7. A testing “step” involved the removal or replacement of one or a group of shoring supports.

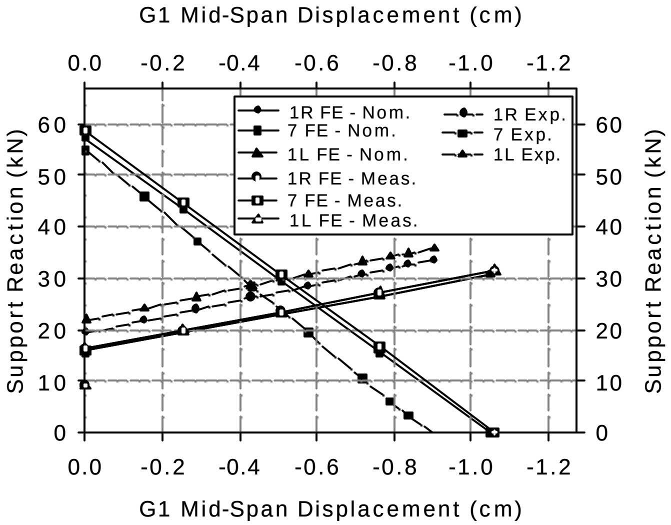


Figure 6. Finite Element and Experimental G1 Support Reactions vs. Mid-Span Displacement, ES1-4.

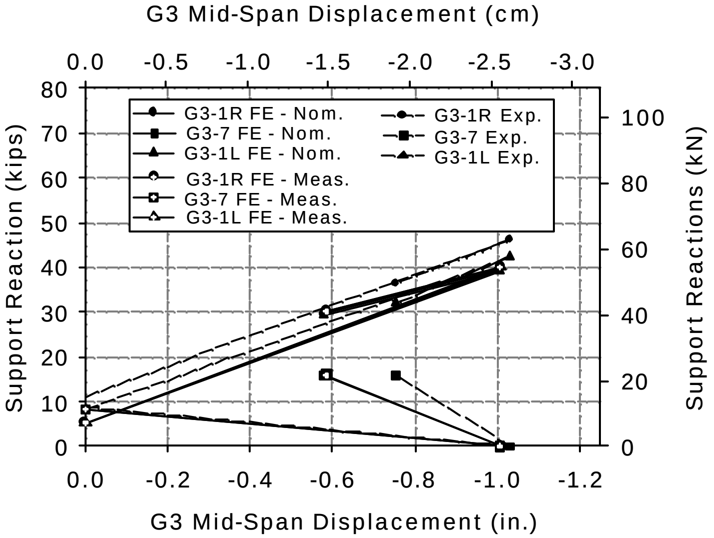


Figure 7. Finite Element and Experimental G3 Support Reactions vs. Mid-Span Displacement, ES3-1.

Good agreement is shown for predicted support reactions and displacements for each of the girders in the figures, but some discrepancies do exist. They were attributed to: (1) fit-up problems during construction caused by imperfections introduced during fabrication; and (2) heating of the instrumentation and data acquisition circuitry prior to testing causing zero shifts of the data.

The fabrication imperfections predominantly resulted from incorrect cambering of G2. The camber was incorrectly induced after transverse stiffeners had been attached and after the girder was re-heated and the camber corrected many of the stiffeners were out-of-plumb. This resulted in fit-up problems for the cross frames during construction. Forces that were induced into the experimental structure when cross frames were put into place were not measured but the effects of those “locked-in” forces are demonstrated in the support reaction discrepancies shown in the figures. However, these discrepancies are small when compared against the total self-weight of the systems that were tested. For ES3-1, a maximum discrepancy of 18 kN (4 kip) existed in Figure 7. This value was less than 5% of the total self-weight of the structure, which was 521 kN (117 kips). Replacing nominal geometric properties with measured properties had little effect on the accuracy of the analytical predictions in Figures 6 and 7.

A typical girder strain comparison is shown in Figure 8 and cross frame axial force comparisons are shown in Figure 9. The girder strain comparisons are for ES3-1 for the top and bottom flanges of G3 for one testing "step". Cross frame force comparisons are also for ES3-1 and are for three testing "steps" for lower chord members in cross frame 7 between G2 and G3.

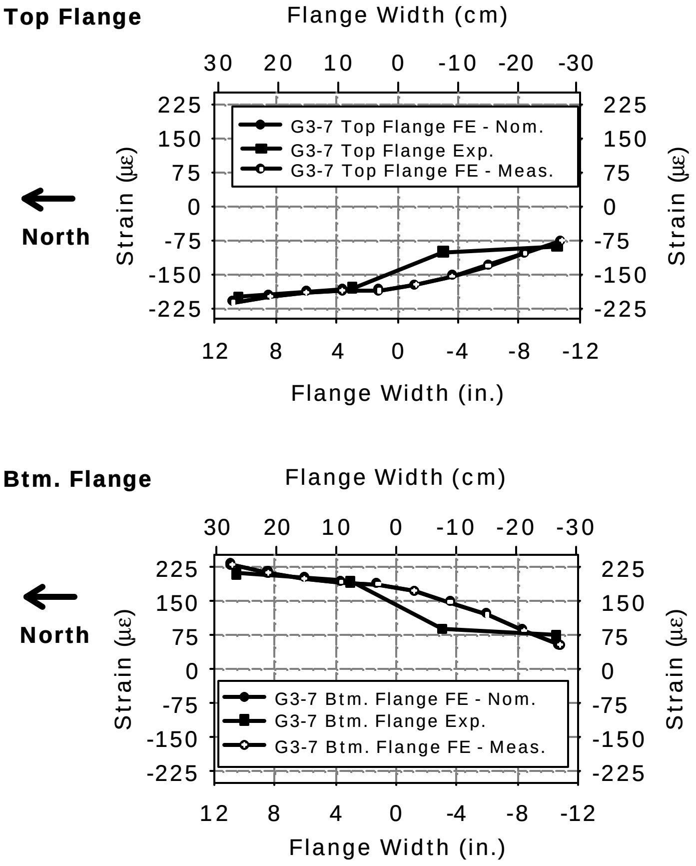


Figure 8. Finite Element and Experimental G3 Flange Strains at Mid-Span, G3 Mid-Span Displacement = 2.5 cm (1"), ES3-1.

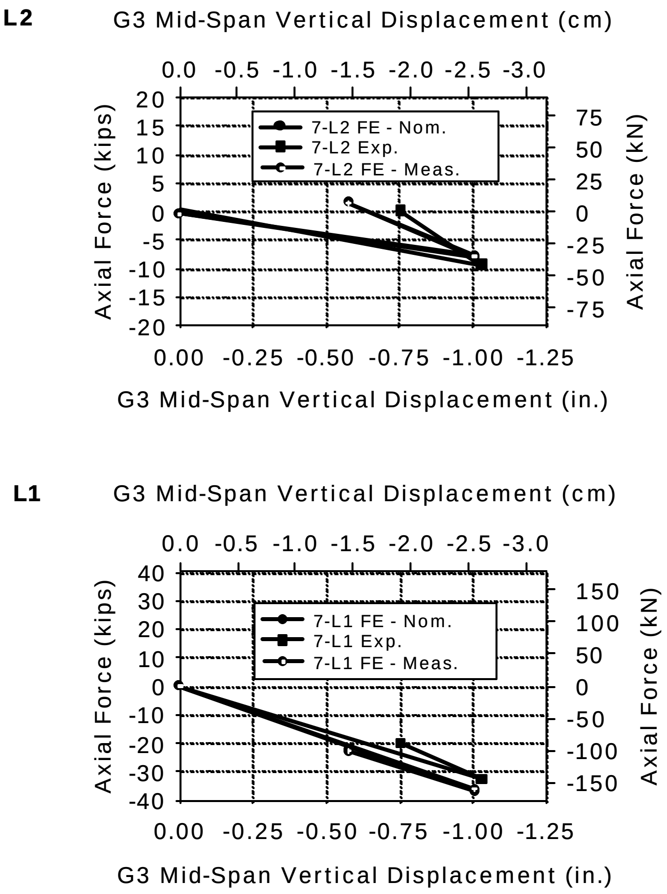


Figure 9. Finite Element and Experimental Axial Forces, Cross Frame 7 Between G2 and G3, ES3-1.

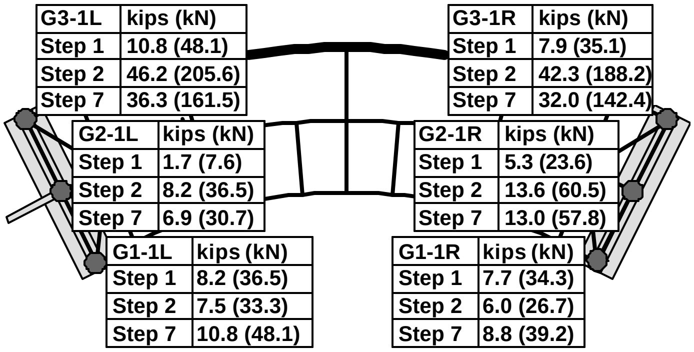
Good agreement is again demonstrated, with discrepancies being attributed to fabrication and zero-shifts of the data.

The accuracy with which another analytical methods, the V-Load method (AISC, 1986), predicted the system's behavior was also studied. Predicted girder mid-span moments from the V-Load method were compared to moments obtained from ABAQUS results and to experimental mid-span moments. Comparisons were completed for ES3-1 for mid-span moments in G1 and G3 with intermediate shoring removed. Table 1 shows that the V-Load method and the ABAQUS model provided good estimates of G3 mid-span moments. However, V-Load estimations for G1 mid-span moments were nonconservative, with -50 kN-m (-37 k-ft) being predicted at mid-span of G1 while the experimental magnitude was +41 kN-m (+30 k-ft). Good prediction of mid-span moment for G1 was obtained using the ABAQUS model. The underestimation of G1 mid-span moments using the V-Load method, even though moment magnitudes were quite small, showed that interior girder moment predictions using this method might not be as accurate as those for an exterior girder. These results correspond to previously published findings from a study of the V-Load method (Fiechtl et al., 1987).

Table 1. G1 and G3 Mid-Span Moments, Unshored Condition.

Girder	Mid-Span Moment (kN-m)			Difference from Experiment (%)	
	Exp.	FEM	V-Load	FEM	V-Load
G1	41	39	-50	-3	-220
G3	1306	1395	1333	7	2

An additional indication of the effects of fabrication errors on load distribution is shown in Figure 10. The figure summarizes abutment load cell readings for three testing "steps" during ES3-1. Step 1 is when the structure was shored to its “no-load” geometric configuration, Step 2 is the unshored condition where the structure has deformed under self-weight and Step 7 is a condition where G3 was shored to a reaction of 71.2 kN (16 kips) at mid-span. For Step 2, a lack of symmetry for the support reactions is shown. One of the main causes for this lack of symmetry was related to the changes in geometry that occurred when G2 was re-cambered. The figure also provides some indication of the level of load redistribution that occurs in curved girder systems as shoring conditions change.



G3-1L	kips (kN)
Step 1	10.8 (48.1)
Step 2	46.2 (205.6)
Step 7	36.3 (161.5)

G3-1R	kips (kN)
Step 1	7.9 (35.1)
Step 2	42.3 (188.2)
Step 7	32.0 (142.4)

G2-1L	kips (kN)
Step 1	1.7 (7.6)
Step 2	8.2 (36.5)
Step 7	6.9 (30.7)

G2-1R	kips (kN)
Step 1	5.3 (23.6)
Step 2	13.6 (60.5)
Step 7	13.0 (57.8)

G1-1L	kips (kN)
Step 1	8.2 (36.5)
Step 2	7.5 (33.3)
Step 7	10.8 (48.1)

G1-1R	kips (kN)
Step 1	7.7 (34.3)
Step 2	6.0 (26.7)
Step 7	8.8 (39.2)

Figure 10. Abutment Load Cell Readings, ES3-1.

CONCLUSIONS

A series of construction tests of an experimental curved steel bridge structure completed for the CSBRP are summarized. The structure is described and instruments used for the tests are summarized. Analytical models of the construction tests are described and results are compared to experimental data. Representative comparisons between girder support reactions, mid-span displacements and strains and cross frame axial forces are presented. An examination of the accuracy of the V-Load Method is also presented. The studies indicated that:

- analytical models used to predict behavior of the construction tests produced accurate results,
- discrepancies between analytical and experimental results were largely attributed to forces and deformations induced into the structure during construction,
- fabrication errors can lead to load redistribution in curved bridges,
- replacing nominal geometric properties with measured properties did not result in appreciable change in analytical results
- the V-Load Method may provide nonconservative predictions of interior girder moments.

ACKNOWLEDGEMENTS

HDR, Inc. through FHWA Contract No. DTFH61-92-C-00136 supported this research for the Georgia Institute of Technology. Sheila Duwadi serves as the Contracting Officer’s Technical Representative for FHWA. Advisement provided by Dr. Abdul-Hamid Zureick and Dr. Roberto Leon of The Georgia Institute of Technology and technical input from Dann Hall and Mike Grubb of BSDI and John Yadlosky of HDR is gratefully acknowledged. The author would also like to thank Bill Wright of FHWA, Joey Hartmann of Professional Service Industries, Inc., and James Burrell of Qualcomm, Inc. for their assistance.

REFERENCES

American Association of State Highway and Transportation Officials (1980, 1993), *Guide Specifications for Horizontally Curved Bridges*, USA.
American Institute of Steel Construction (1986), *Highway Structures Design Handbook, Volume I, Ch.12 - V-Load Analysis*, USA.

Brennan, P.J. (1970), Horizontally Curved Bridges First Annual Report: Analysis of Horizontally Curved Bridges through Three-Dimensional Mathematical Model and Small Scale Structural Testing, *Syracuse University, First Annual Report, Research Project HPR-2(111)*, USA.

Brennan, P.J. (1971), Horizontally Curved Bridges Second Annual Report: Analysis of Seekonk River Bridge Small Scale Structure through Three-Dimensional Mathematical Model and Small Scale Structural Testing, *Syracuse University, Second Annual Report, Research Project HPR-2(111)*, USA.

Brennan, P.J. (1974), Analysis and Structural Testing of a Multiple Configuration Small Scale Horizontally Curved Highway Bridge, *Syracuse University, Research Project HPR-2(111),* USA.

Brennan, P.J. and Mandel, J.A. (1979), Multiple Configuration Curved Bridge Model Studies, *Journal of the Structural Division, ASCE*, 105(ST5), 875-890, USA.

Brennan, P.J., Antoni, C.M., Leininger, R. and Mandel, J.A. (1970), Analysis for Stress and Deformation of a Horizontally Curved Bridge Through a Geometric Structural Model, *Syracuse University Dept. of Civil Eng., Special Research Report No. SR-3*, USA.

Culver, C.G. and Christiano, P.P. (1969), Static Model Tests of Curved Girder Bridge, *Journal of the Structural Division, ASCE,* 95(ST8), 1599-1614, USA.

Fiechtl, A.L., Fenves, G.L. and Frank, K.H. (1987), Approximate Analysis of Horizontally Curved Girder Bridges, *Texas University, Austin, Center for Transportation Research, Final Report No. FHWA-TX-91-360-2F*, November. USA.

Fukumoto, Y. and Nishida, S. (1981), Ultimate Load Behavior of Curved I-Beams, *Journal of the Engineering Mechanics Division, ASCE*, 107(EM2), 367-384, USA

Galambos, T.V., Hajjar, J.F., Leon, R.T., Huang, W., Pulver, B.E., and Rudie, B.J. (1996), Stresses in Steel Curved Girder Bridges, *Minnesota Dept. of Trans. Report No. MN/RC-96/28*, USA

Hajjar, J.F. and Boyer, T.A. (1997), Live Load Stresses in Steel Curved Girder Bridges, *Progress Report on Task 1 for Minnesota Dept. of Trans. Project 74708*, USA.

Hanshin Expressway Public Corporation (1988), *Guidelines for the Design of Horizontally Curved Girder Bridges (Draft)*, Japan.

Heins, C.P. and Spates, K.R. (1970), Behavior of Single Horizontally Curved Girder, *Journal of the Structural Division, ASCE,* 96(ST7), 1511-1529, USA.

Hibbitt, Karlsson & Sorenson, Inc. (1998a), *Introduction to ABAQUS/Pre, Version 5.8,* USA.

Hibbitt, Karlsson & Sorenson, Inc. (1998b), *ABAQUS/Post Manual, Version 5.8,* USA.

Hibbitt, Karlsson & Sorenson, Inc. (1998c), *ABAQUS/Standard User's Manual, Version 5.8*, USA.

Huang, W.H. (1996), Curved I-Girder Systems, *Ph.D. Dissertation, Department of Civil Engineering, University of Minnesota*, USA.

Linzell, D.G. (1999), Studies of a Full-Scale Horizontally Curved Steel I-Girder Bridge System Under Self-Weight, *Ph.D. Dissertation, School of Civil and Environmental Engineering, Georgia Institute of Technology,* USA.

Mozer, J., Culver, C. (1970), Horizontally Curved Highway Bridges – Stability of Curved Plate Girders, *Carnegie Mellon University, Report No. P1, Research Project HPR – 2(111),* USA.

Mozer, J., Ohlson, R. and Culver, C. (1971), Horizontally Curved Highway Bridges – Stability of Curved Plate Girders, *Carnegie Mellon University, Report No. P2, Research Project HPR – 2(111),* USA.

Mozer, J., Cook, J., and Culver, C. (1973), Horizontally Curved Highway Bridges – Stability of Curved Plate Girders, *Carnegie Mellon University Report No. P3, Research Project HPR-2(111),* USA.

Nakai, H. and Kotoguchi, H. (1983), A Study on Lateral Buckling Strength and Design Aid for Horizontally Curved I-Girder Bridges, *Transactions of the Japanese Society of Civil Engineers*, 339, 195-205, Japan (in Japanese).

Nakai, H., Kitada, T., and Ohminami, R. (1983), Experimental Study on Bending Strength of Web Plate of Horizontally Curved Girder Bridges, *Proceedings of the Japanese Society of Civil Engineers*, 340, 19-28, Japan (in Japanese).

Nakai, H., Kitada, T., and Ohminami, R. (1984a), Experimental Study on Ultimate Strength of Web Panels in Horizontally Curved Girder Bridges Subjected to Bending, Shear, and Their Combinations, Proceedings, *Annual Technical Session – Structural Stability Research Council: Stability Under Seismic Loading*, 91-102, USA.

Nakai, H., Kitada, T., Ohminami, R. and Fukumoto, K. (1984b), Experimental Study on Shear Strength of Horizontally Curved Plate Girders, *Transactions of the Japanese society of Civil Engineers*, October, 350, 291-290, Japan (in Japanese).

Pulver, B.E. (1996), Measured Stresses in a Steel Curved Bridge System, *M.C.E. Report, Department of Civil Engineering, University of Minnesota*, USA.

Shanmugam, N.E., Thevendran, J.Y., Liew, R., Tan, L.O. (1995), Experimental Study on Steel Beams Curved in Plan, *Journal of Structural Engineering, ASCE*, 121(2), 249-259, USA.

Structural Stability Research Council (1998), Guide to Stability Design Criteria for Metal Structures, 5th Ed., T.V. Galambos, Editor, USA.

Thevendran, J.Y., Shanmugam, N.E., Liew, R. (1998), Flexural Torsional Behavior of Steel I-Beams Curved in Plan, *Journal of Constructional Steel Research*, 46 (1-3), 79-80, UK.

Yoo, C.H. and Carbine, R.L. (1985), Experimental Investigation of Horizontally Curved Steel Wide Flange Beams, *Proceedings Annual Technical Session: Stability Aspects of Industrial Buildings, SSRC*, Cleveland, OH, USA, 183-191.

Zureick, A., Naqib, R., and Yadlosky, J.M. (1994), *Curved Steel Bridge Research Project, Interim Report I: Synthesis*, HDR Engineering, Inc., Publication Number FHWA-RD-93-129, USA.