ELASTIC EXPERIMENTAL AND ANALYTICAL STUDIES OF CURVED STEEL BRIDGE BEHAVIOR UNDER SELF-WEIGHT (STR28)

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ABSTRACT: An extensive series of tests of a full-scale curved steel bridge system have been completed for the Federal Highway Administration (FHWA). These tests are being used to study the behavior of curved I-girders under realistic load and support conditions. An early phase of the testing involved examining various framing plans of the bridge system under self-weight. These tests occurred during erection and examined the behavior of six different framing plans elastically as intermediate shoring supports were removed and replaced. They were used to validate instrumentation placement, establish data reduction schemes and verify analytical models. An overview of the tests is given and samples of data that was produced and comparisons that were made are presented.

1. INTRODUCTION

The use of curved steel girder bridges has increased dramatically over the past 30 years. In the United States, curved steel bridges currently constitute one-quarter to one-third of all bridges being constructed. For complicated bridge geometries, steel girders offer many advantages over other materials with regards to fabrication, erection, and serviceability.

The need for further research into the behavior of curved steel bridges in the U.S. led to the initiation of an extensive project by the Federal Highway Administration (FHWA). The goal of this project is to conduct fundamental research into the behavior of curved steel members and to develop rational design procedures for curved steel bridge structures though examination of a large-scale experimental system (Zureick et al. 1994).

The initial group of tests for the project studied the experimental curved bridge system as it was being erected. Six different framing plans were examined using nine tests. These six framing plans were variations of the final experimental structure, a simply-supported three-girder system. The tests studied each framing plan elastically under self-weight with differing degrees of shoring support.

A comprehensive test methodology was developed to insure that reliable data was produced. This methodology involved careful selection of instrumentation and validation of data reduction methods along with detailed geometry and material property measurements. Equilibrium investigations of free-body diagrams of each test were used extensively during data reduction. It was felt that if equilibrium could be obtained with a reasonable amount of accuracy then proposed instrumentation schemes would be considered acceptable. Data produced from the tests was also used to evaluate the accuracy of a number of finite element models. These models helped predict behavior of the curved bridge during its erection. This paper contains brief summaries of the erection studies and discusses information documented both prior to and during the tests. Data reduction schemes are presented and representative results are given. Sample comparisons between experimental and analytical data are shown and conclusions from those comparisons are made.

2. PREVIOUS RESEARCH

Major research focusing on the use of curved steel bridges did not occur in the United States until the late 1960's when the Consortium of University Research Teams (CURT) was formed. This team consisted of five universities whose research efforts resulted in initial development of working stress design criteria and tentative design specifications. The work eventually led to publication of the Guide Specifications for Horizontally Curved Highway Bridges (AASHTO 1980, 1993).

The other large body of curved steel bridge research was produced in Japan in the late 1970's and early 1980's. Much of the research occurred prior to publication of the Hanshin Expressway Public Corporation's Guidelines for the Design of Horizontally Curved Girder Bridges (Hanshin Expressway Public Co. 1988).

Extensive laboratory testing was an integral part of both bodies of research. Tests of scale model bridge systems and medium-scale bridge components provided data against which theoretical and analytical predictions were measured. Both curved I- and box girders were tested, although only I-girder research is mentioned here. The curved I-girder scale model tests examined both twin (Culver and Christiano 1969, Mozer et al. 1973, Nakai and Kotoguchi 1983) and multi-girder systems (Brennan 1970, 1971, Brennan et al. 1970, Brennan 1974, Brennan and Mandel 1979). They looked at I-girders with various radii of curvature, span lengths and unbraced lengths under a number of simulated dead and live load scenarios.

Component tests of curved I-girders were used to study specific failure modes and to examine the ramifications of varying certain design parameters on behavior. These tests typically examined single I-girders with imposed support and loading conditions (Heins and Spates 1970, Mozer and Culver 1970, Mozer et al. 1971, Fukumoto and Nishida 1981, Nakai et al. 1983, 1984a, 1984b).

Experimental studies of curved steel girders have continued since publication of the AASHTO and Hanshin documents. Single curved I-girder tests have been used to validate computer analyses and to examine specific aspects of curved system behavior (Yoo and Carbine 1985, Shanmugam et al. 1995, Thevendran et al. 1998).

One item that the laboratory studies did not explicitly examine was the behavior of curved steel bridge systems during erection. In addition, limited field studies of curved bridge erection behavior have been conducted. The most extensive study focused on a two-span continuous horizontally curved and superelevated I-girder structure (Galambos et al. 1996, Pulver 1996, Hajjar and Boyer 1997). The superstructure was instrumented with strain gages and readings were taken at critical points during construction (e.g. girder placement, deck placement, etc.). Field results were compared to values produced from two computer analysis packages (Huang, 1996).

Therefore, it was hoped that the research described herein would help expand the knowledge base of curved steel I-girder bridge behavior, especially during construction.

3. TESTING

3.1. Experimental Structure

Figure 1 indicates that the experimental curved bridge consisted of three simply-supported and radially braced I-girders without a deck. The system was designed so that under flexural loads the mid-span portion of the exterior girder (G3) failed under realistic loading and boundary conditions while the remainder of the bridge remained elastic. This permitted reusing the structure for a number of tests.

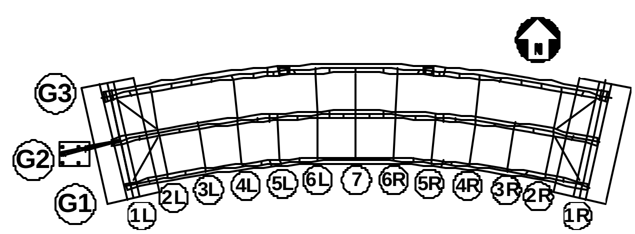

Figure 1. Bridge plan (courtesy FHWA/HDR).

The design stipulation that required that the mid-span portion of G3 fail before any other portions of the bridge yielded greatly affected the sizes, types and positions of members in the structure. Girder spans ranged between 26.2 m for G1 to 28.6 m for G3 along the arc with radii of curvature between 58.3 m and 63.6 m. Girder dimensions varied between 121.9 cm x 0.8 cm and

121.9 cm x 1.3 cm for the webs and between 40.6 cm x 1.7 cm and 61.0 cm x 5.7 cm for the flanges.

Another by-product of the aforementioned design stipulation was the cross frame placement scheme shown in Figure 1. Extra lines of cross frames were placed between G1 and G2 to stiffen and stabilize the inner girder pair and to provide a load transfer path that placed the highest forces at mid-span of G3. To achieve this load distribution path, a unique cross frame design scheme was utilized to simplify instrumentation while providing the required strength and stability. The design consisted of five 413 MPa tubular steel members arranged in a “K”-type frame.

Intermediate transverse girder stiffeners were provided in between cross frame connection plates with additional stiffeners placed at the bearings and beneath the load points. The stiffeners were typically full-height and welded to one side of the girder web. Bearing and load stiffeners were also full-height and were placed in back-to-back pairs.

The girders were supported with radially oriented abutments consisting of steel W-sections and channels tied to the strong floor with DYWIDAG bars. The abutments elevated the system to a height of approximately 2 m off the laboratory floor. A combination of spherical bearings and Teflon pads were used to minimize frictional forces and allow translation and rotation in any direction except downward at the ends of G1 and G3. Girder G2’s movement was restricted using guided bearings at both ends and a tangential support frame at its west end as shown in Figure 1. The guided bearings prevented radial translation and the tangential frame, consisting of W-sections and pinned to G2 at its neutral axis, helped stabilize the system. Differential radial displacement between adjacent girders was minimized through the use of lower lateral bracing mounted diagonally between adjacent girders in the exterior cross frame bays.

Inducing failure at mid-span of G3 while the rest of the system remained elastic forced an increase in steel strength for G2 from ASTM A572 Grade 50 to AASHTO M270 Grade 70W. Grade 70W steel plate was not available in lengths necessary to complete G2 and butt welds were used to splice the girder together 7.6 m from each abutment.

3.2. Instrumentation

Insuring equilibrium of all or portions of the bridge during testing was crucial for accurate evaluation of the data. Therefore, load cells and strain gages were placed at numerous locations on the superstructure so that a number of free body diagrams could be examined. Load cells were positioned at girder support points at the abutments and intermediate shoring locations. Strain gages were affixed to the girders, cross frames and lower lateral bracing. Figure 2 indicates where girder strain gages were positioned. Vibrating wire gages, which provided dependable long-term strain measurements while saving data acquisition space for other instruments, were affixed to the girder flanges and web at the locations shown the figure.

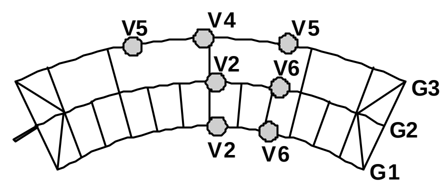

Figure 2. Girder Strain Gage Locations

Resistance strain gages were placed at mid-span of each cross frame member. They were arranged as shown in Figure 3.

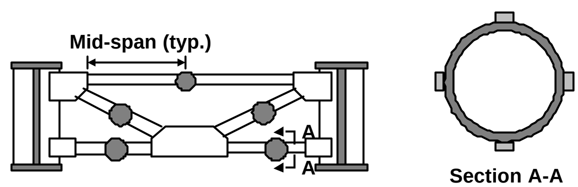

Figure 3. Typical Cross Frame Strain Gage Locations

The deformed shape of the structure was recorded using standard displacement and rotation measurement transducers, a laser measurement system and a total station. The transducers (potentiometers, LVDT’s and tiltmeters) were placed at mid-span and at the supports of each girder. The laser and total station systems acquired targets affixed to the girder flanges.

Instrument quantities increased with each test as more structural components were added to the bridge. Over 1050 data points were recorded for ES3-1.

3.3. Property Measurements

Material property measurements were obtained from 200 coupon and 3 stub column tests. Tests were performed in accordance with ASTM E8-96a (ASTM 1996) and SSRC Technical Memorandum No. 8 from the Guide to Stability Design Criteria for Metal Structures (SSRC 1998). Geometric properties were determined from measurements of the plate girders, transverse stiffeners, cross frame members, gusset plates, lower lateral bracing, splice plates and the tangential support frame attached to G2. Over 1600 measurements were recorded.

3.4. Procedure

A total of nine tests were completed which involved six different framing plans. Framing plans that were tested are variations of the final structure shown in Figure 1 and involve either girders G1 and G2 or all three girders. The framing plans are shown in Figure 4.

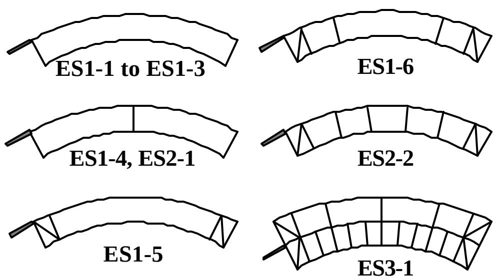

Figure 4. Erection Study Framing Plans

3.4.1. Single Girder Studies (ES1 Series)

Those tests in which shoring was removed from beneath the interior girder (G1) in a twin-girder system were termed ES1 studies. Six ES1 series tests were performed and for the first three (ES1-1 to ES1-3), restraint was provided at the ends of the span by cross frames 1L and 1R. Each of the ES1 tests began with both girders shored to their theoretical "no-load" positions. Shoring was incrementally removed from beneath G1 until either the limits of the girder support fixtures (shoring screw jacks or supports utilizing an overhead crane) or the maximum predicted elastic deformation had been reached. ES1-3 achieved the largest G1 mid-span elastic deformations, with 25.4 cm of vertical displacement and 13° of radial rotation.

Single girder tests ES1-4 to ES1-6 looked at the twin girder system with 3, 4, and 6 cross frames in-place between G1 and G2 (see Figure 4). All three of the tests proceeded in a similar manner to ES1-3, with each system beginning in its theoretical "no-load" position. Shoring was incrementally removed from beneath G1 until it reached its predicted maximum elastic deformation. ES1-4 involved cross frames 1L, 1R and 7 and the maximum mid-span displacement for G1 was 0.8 cm. This displacement was accompanied by minimal mid-span radial rotation (less that 0.2°). ES1-5 involved cross frames 1L, 1R, 2L and 2R. G1 mid-span displacement was 4.6 cm with 0.65° of rotation. ES1-6 involved cross frames 1L, 1R, 2L, 2R, 4L and 4R. G1 displaced 1.1 cm vertically and rotated 1.25° at mid-span.

3.4.2. Twin-Girder Studies (ES2 Series)

Tests that incrementally removed shoring from beneath G1 and G2 in a twin-girder system were termed ES2 studies. Two ES2 tests were completed. ES2-1 examined the same framing plan as ES1-4. Once the predicted "no-load" position was established, the test proceeded by incrementally lowering G1 into its deformed shape. G2 was then incrementally lowered to its deformed shape. Observed mid-span displacements were 1.8 cm for G1 and 6.3 cm for G2 with accompanying mid-span radial rotations near 1° for both girders. ES2-2 was completed with the lower lateral bracing and cross frames 1L, 2L, 4L, 6L, 4R, 2R, and 1R in-place. The testing procedure was similar to that used for ES2-1. Maximum mid-span displacements were 1.0 cm for G1 and 3.6 cm for G2 with mid-span radial rotations of 0.5°.

3.4.3. Three-Girder Study (ES3-1)

The single test in which intermediate supports were removed from beneath a three-girder system was termed ES3-1. Thirteen cross frames were in-place between G1 and G2 and seven between G2 and G3. The test began with the system shored in its "no-load" position (Figure 5). Shoring was incrementally removed from beneath the entire system. Resulting mid-span displacements and rotations were 0.5 cm and 0.2° for G1, 1.5 cm and 0.2° for G2, and 2.5 cm and 0.3° for G3. A series of investigations of each girder using a single mid-span shore were then performed. G3 was raised and lowered in equal load increments. Similar examinations of G2 and G1 followed the G3 study.

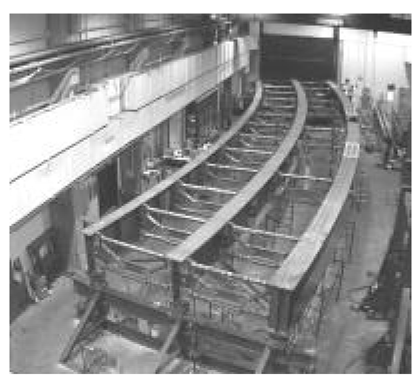

Figure 5. Test ES3-1

3.5. Data Reduction

The main focus of the data reduction process was numerous attempts at studying equilibrium. The studies not only examined the validity of the results, they helped to determine if instrumentation specified during the planning phase was adequate for future tests.

3.5.1. Equilibrium

Equilibrium calculations were performed vectorally for each test, using unit vectors and position vectors to identify resultant dead load directions and locations. Results were decomposed into components relative to a global right-handed coordinate system so that contributions to overall equilibrium could be examined independently. In this system, the x-axis was oriented in the north-south direction, the y-axis oriented vertically, and the z-axis from east to west, (see Figure 1). It should be noted that construction sequence effects and imperfections introduced during fabrication and construction influenced the highly indeterminate structures that were tested so that equilibrium in a theoretical sense (all force and moment components summing to zero) could not be achieved experimentally.

Prior to the equilibrium studies, a number of additional investigations were performed to: (1) determine the optimal scheme for positioning dead load resultants on the structure, (2) establish an optimal location for the origin of the global Cartesian coordinate system and (3) determine what inputs were required to produce acceptable equilibrium results. Two plots were used to examine the accuracy of the equilibrium evaluations. The first tracked the variation in equilibrium for each change in shoring conditions, termed a "testing step". In this plot, the first step, Step 1, was corrected so that initial force and moment sums equaled zero. Force sums represented differences between dead loads and the measured reactions and internal strains while moment sums represented differences between moments causing clockwise and counterclockwise rotation about one of the axes. A representative plot for ES1-3 is shown in Figure 6. The plot examines external equilibrium of the twin girder system and indicates that, in general, forces and moments summed to near zero throughout test. However, moment equilibrium about the global x-axis (M_x) deviated from zero and may be considered too high of an imbalance.

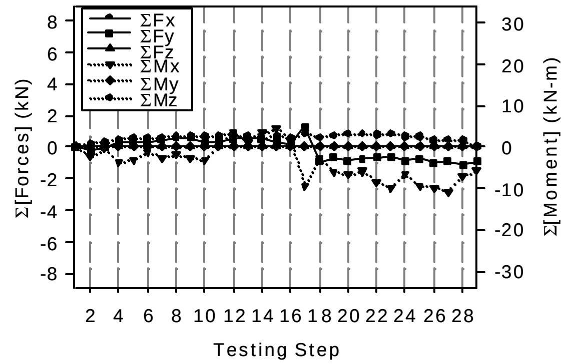

Figure 6. External Equilibrium vs. Testing Step, ES1-3

To explain this apparent imbalance, a second plot, in which the equilibrium sums in Figure 6 were normalized, was also used. The quantities were normalized against total positive contributions to the equilibrium equations from all loads on the free-body diagram, as shown in Figure 7. So that comparisons would be made to a consistent total, the testing step that produced the largest forces onto the free-body was used for the total positive contribution values. For example, values for M_x were normalized against the positive total for M_x from Step 17 and the resulting ratio converted to a percentage. Figure 6 indicates that error magnitudes for M_x approached 10 kN-m. Normalization percentages for external equilibrium of ES1-3 in Figure 7 show that this imbalance was never greater than 1% of the Step 17 positive total for M_x. Therefore, a 10 kN-m imbalance was considered acceptable.

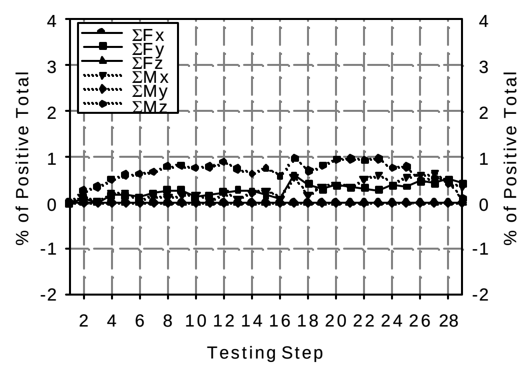

Figure 7. External Equilibrium as % of Positive Total vs. Testing Step, ES1-3

Two additional free body diagrams of ES1-3 had equilibrium studied. They examined the entire span of G1 and half the span of G1. These evaluations utilized readings from strain gages affixed to the cross frames and/or flanges of G1 to determine internal forces. Using plots similar to those shown in Figures 6 and 7, errors were considered acceptable, with magnitudes that appeared excessive (>44.5 kN, >54.4 kN-m) having normalization percentages less than 20%.

The three free body diagrams examined for ES1-3 were also studied for the remaining single girder tests, ES1-4 to ES1-6 and for the two twin-girder studies, ES2-1 and ES2-2. However, for these tests additional instrumentation at mid-span of G2 permitted performing another equilibrium study, that of half the span of the twin-girder system. The addition of G3 for ES3-1 and its corresponding instrumentation permitted performing yet another equilibrium evaluation, that of half the span of the three girder system. Results obtained from the equilibrium studies indicated that error magnitudes obtained throughout the duration of the tests were generally acceptable.

3.6. Analytical Models

A detailed finite element model with 8400 elements and over 50000 degrees of freedom was assembled using ABAQUS/Aqua Versions 5.4 to 5.8 (Hibbitt, Karlsson & Sorenson, Inc. 1998a, 1998b, 1998c). This model was used to predict behavior of the experimental curved bridge during design and testing (Zureick et al. 1997). Detailed comparisons between analytical and experimental results were completed for five tests: ES1-1, ES1-6, ES2-1, ES2-2, and ES3-1.

Finite element simulations were initially run using nominal geometric dimensions. The models were then re-analyzed with revised dimensions, which were found from averages of measurements taken during construction. Loads consisted of self-weights of the bridge components, calculated using a steel density of 77 kN/m^3, and additional point loads that accounted for cross frame connection details that were not modeled.

Support reactions, vertical displacements and girder and cross frame internal forces from the ABAQUS models were compared against experimental results for various testing steps. A representative plot, which examines G1 support reactions and mid-span displacements for ES1-4, is shown in Figure 8. The figure examines the changes in support reactions at cross frames 1L, 1R (located at the abutments) and 7 (located at the mid-span) as a function mid-span displacement. It indicates that the detailed finite element model predicted actual behavior quite well, although some discrepancies were apparent. These discrepancies were caused by zero shifts in the data and by imperfections unintentionally introduced into the structure during fabrication that could not be incorporated into the ABAQUS model. The imperfections led to fit-up problems in the laboratory, particularly for the cross frames, which introduced unwanted forces and displacements into the system. The figure also indicates that replacing nominal geometric properties with measured properties had little bearing on analytical results. Similar discrepancies to those shown in Figure 8 were observed when girder strains and cross frame member forces were compared.

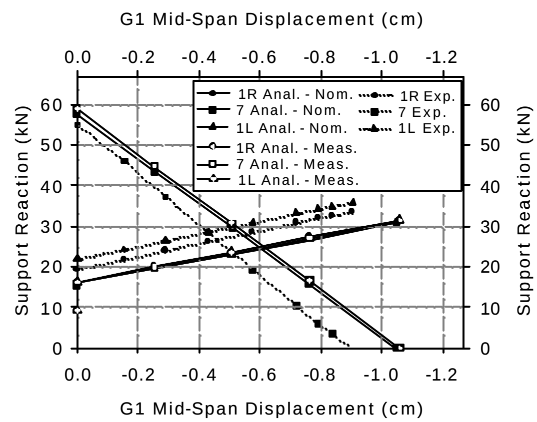

Figure 8. Analytical and Experimental G1 Support Reactions vs. Mid-Span Displacement, ES1-4

Comparative plots for the remaining erection study tests modeled in ABAQUS showed similar results to those shown in Figure 8. The addition of cross frames caused further redistribution of dead loads and reaction magnitude discrepancies approached 18 kN for ES3-1. While this level of error appears alarming, it was small compared to the total self-weight of the system, which was 521 kN for ES3-1.

4. CONCLUSIONS

Summaries of a series of elastic tests of a full-scale horizontally curved steel bridge system are presented. Descriptions of the bridge are given and levels of instrumentation and documentation are discussed.

A methodology that utilized a series of equilibrium studies to assess the robustness of data generated during each test was discussed. A semi-empirical approach was used to assess the data since inputs from sensors and data acquisition systems with different resolutions had to be reconciled. Representative equilibrium studies were presented and discussed and they indicated that data produced from the instrumentation was valid.

Comparisons between experimental results and predictions from ABAQUS finite element models were presented. These comparisons indicated that the models provided acceptable predictions of erection behavior. Discrepancies were attributed to zero shifts of the data and to fabrication of imperfections into the structure that could not be reproduced in the models. In addition, it was shown that replacing nominal geometric and material properties with measured properties did not significantly improve analytical results.

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