Examination of Level of Analysis Accuracy for Curved I-Girder Bridges through Comparisons to Field Data

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Abstract: To evaluate the accuracy of different levels of analysis used to predict horizontally curved steel I-girder bridge response, a field test was performed on a three-span structure. Collected strain data were reduced to determine girder vertical and bottom flange lateral bending moments. Experimental moments were compared to numerical moments obtained from three commonly employed levels of analysis. Level 1 analysis includes two manual calculation methods: a line girder analysis method described in the AASHTO *Guide Specification for Horizontally Curved Highway Bridges*, and the V-load method. Grillage models represent Level 2 and were created using three commercially available computer programs: SAP2000, MDX, and DESCUS. Level 3 consists of three-dimensional (3D) finite element models created using SAP2000 and the BSDI 3D system. Responses obtained from each level are compared and discussed for a single radial cross section of the structure, and the compared results involve truck loads and placement schemes that do not represent those used for bridge design. The field test and numerical data presented are used solely to determine the accuracy of each level of analysis for predicting structure response to a specific live load at a specific cross section. Results showed that Level 2 and Level 3 analyses predict girder vertical bending moment distributions more accurately than Level 1 analyses throughout the tested cross section. The comparisons indicate that Level 3 girder vertical bending moment distributions offered no appreciable increase in accuracy over Level 2 analyses. The study also indicates that both Level 1 and Level 3 analyses provide bottom flange lateral bending moment distributions that do not correlate well with field test results for the studied bridge cross section.

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Introduction

Currently the AASHTO (2003) *Guide Specification for Horizontally Curved Steel Girder Highway Bridges* is the only generally accepted specification or code in the United States that attempts to incorporate the accuracy of varying levels of analysis during the design of horizontally curved steel I-girder bridges. Most curved bridge analyses are performed using commercially available computer software packages and/or manual calculation methods. Analysis recommendations made in the 2003 AASHTO *Guide Specifications* are limited and qualitative in nature. The 2003 AASHTO *Guide Specifications* recommend an approximate analysis method (V-load) for bridges that have slight skews and curvatures and more refined analysis methods for other, more complicated, curved structures. The development and incorporation of more refined analysis considerations into the curved bridge design process could eventually lead to benefits for engineers that choose to complete more sophisticated and theoretically more accurate analyses (e.g., less restrictive resistance factors).

The current study evaluated the accuracy of different levels of analysis, listed in Table 1, by comparing predicted results to the measured response of a single in-service horizontally curved steel I-girder bridge. Computer programs used in this study were selected based on their ability to represent these different levels of analysis. Girder vertical and lateral bending moments from the field test were compared to moments obtained from the computer programs and manual calculation methods listed in Table 1. Comparisons discussed herein were made at a single radial cross section and were used to assess the validity and accuracy of the different levels of analysis. The comparisons served as a first step in the process of incorporating analysis accuracy into the design process for curved steel bridges.

Background

Within the last 50 years, a limited number of horizontally curved steel bridge field tests and full-scale laboratory tests have been conducted. However, these past studies have not examined various numerical predictions of curved steel I-girder bridge response by thoroughly comparing those predictions to field data. Field studies conducted by Beal and Kissane (1971a,b, 1972) stated that theoretical predictions from a planar grid analysis proved reliable for predicting vertical bending moments. Galambos et al. (1996) and Hajjar and Boyer (1997) showed a good correlation between measured and computer results for girder locations in the positive

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Table 1. Levels of Analysis

Level	Description	Analysis tool
1	Manual	AASHTO guide specification V-load method
2	2D grillage	SAP2000 MDX DESCUS
3	3D FEM	SAP2000 BSDI

Note: FEM=finite element method.

moment region but indicated a need for further research into how to model negative moment regions. McElwain and Laman (2000) concluded that grillage model results compared well to curved steel girder bending distribution factors determined from field testing. Linzell (1999) and White et al. (2001) documented a number of tests of a prototype full-scale horizontally curved I-girder bridge under construction loads and loads that simulated high bending, shear, and combined bending and shear actions on the girders but did not compare test results to different analysis levels. Modjeski and Masters (1989) published a level of analysis study focusing on horizontally curved bridges. The report reviewed a number of commercially available computer programs but did not include any comparisons to field data.

Objectives

The objectives of this research project were to (1) compare field response parameters to predictions from three different level of analysis techniques; (2) establish the accuracy of the different level of analysis techniques based on these comparisons; and (3) determine the level of increased or decreased accuracy between the different analysis levels. The scope of this study is limited to a single curved multispan bridge, and as such, recommendations made herein are correspondingly limited. However, it is believed that the results are of interest to the bridge engineering community. Results presented herein are also limited in that they are for a single representative cross section of the structure. The reader is referred to Nevling (2003) for more information on the study and results from other cross sections. Programs and techniques selected for this study were chosen based on their utilization by the engineering community and their ability to represent different levels of analysis. It was not the intent of the writers to include all commercially available programs that can be used to complete bridge analysis.

Bridge Description

The bridge that was field tested is a three-span continuous structure composed of five ASTM A572 Grade 50 steel plate girders (Fig. 1, Table 2) spaced at 2.39 m center to center. All of the girders have 1,219 mm×13 mm webs with 356 mm wide top and bottom flanges of varying thickness. The radius of curvature is 178.5 m to the exterior girder, and the abutment skew varies between 60° and 35° (south to north). Girders are braced using two different K-shaped cross-frame configurations: Type A, with top and bottom chords composed of 89×89×9.5 double angles and diagonals composed of 89×89×9.5 angles; and Type B, with top chords composed of WT380×73.5 s, bottom chords composed of 89×89×9.5 double angles, and diagonals composed of 89×89×9.5 angles. The cross frames along Girders 1 and 5 are spaced at 4.76 and 5.03 m, respectively, except for the cross frames near the abutments. Bridge support conditions are shown in Fig. 1.

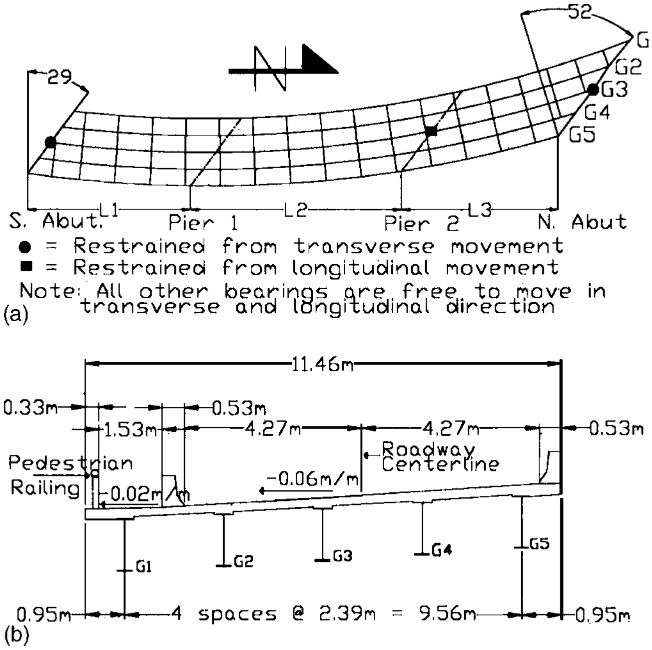

Fig. 1. Tested bridge: (a) Plan view and (b) cross section looking North

Field Testing

To determine the location of the instruments for the field test, preliminary analyses of the bridge were conducted using a grillage model created in SAP2000 (2000). The structure was analyzed for live load only. The live load consisted of an AASHTO HS20 truck, which was selected because of its wide use for bridge design and because of the uncertainty regarding actual truck loads that would be used during testing. A number of different load cases were analyzed by placing one and two trucks at different locations on the bridge. After completing the analyses in SAP2000, girder vertical bending moments were used to estimate locations of maximum positive and negative moments acting on the structure. Instrumented sections for the field tests were placed along each girder at locations that represented a majority of the maximum positive and negative moments. This paper presents results for only the instrumented girders in

Table 2. Bridge Geometry

Girder	L1 (m)	L2 (m)	L3 (m)	Top flange (mm)	Web (mm)	Bottom flange (mm)
1	23.83	31.56	24.84	356×16	1219×13	356×25
2	23.67	31.15	24.23	356×16	1219×13	356×25
3	23.52	30.77	23.67	356×16	1219×13	356×32
4	23.38	30.42	23.17	356×16	1219×13	356×32
5	23.25	30.10	22.72	356×16	1219×13	356×32

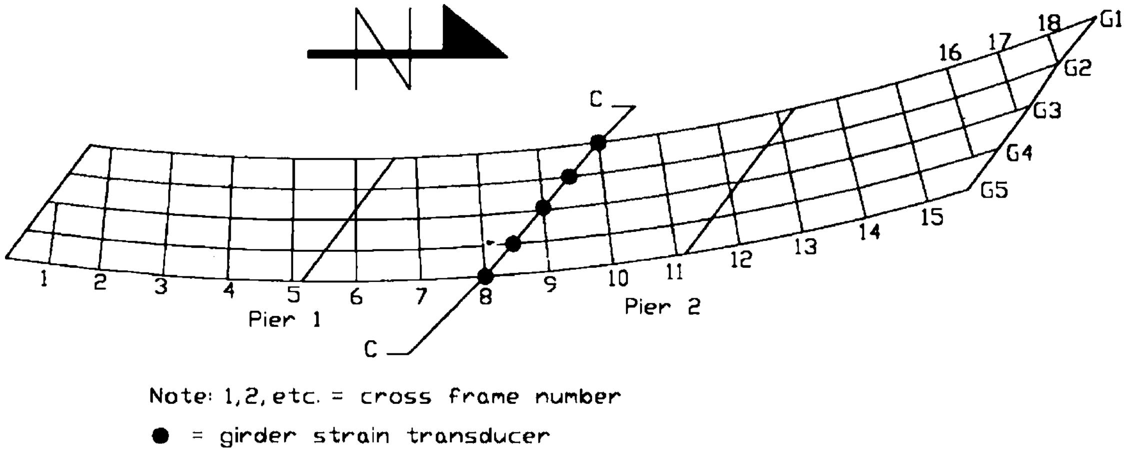

Fig. 2. Instrumentation plan

the positive moment region. Fig. 2 shows the locations of the instruments discussed in this paper, and Table 3 lists the instrument locations.

Selected girder locations were instrumented with Bridge Diagnostics, Inc., aluminum strain transducers. Four instruments were used per cross section. Each of these locations had an instrument placed on each of the top flange tips and each of the bottom flange tips (Fig. 3). The distance from the middle of the strain gauges to the edge of the beam was 29 mm. Girder instrument locations were selected to ensure adequate capture of the vertical and lateral bending response of the girders to the truck loads.

Bridge response data were collected under static load supplied by two test trucks of known weight (Fig. 4). For each of the 17 different test truck locations investigated during field testing (Table 4), both trucks were placed side by side (0.79 m clear distance) on the structure. Truck positions were selected to develop maximum vertical and lateral bending effects on the interior and exterior girders at the instrumented sections. A majority of the static test positions were tested twice to ensure repeatability of the data.

The bridge response data were used to calculate mean strain values for all 17 static test positions. Girder strain values were converted into static vertical and lateral bending stresses, and the static bending stress for both the top and bottom flanges was determined using the member size, gauge location, and calculated mean strain values. A linear stress distribution along the width of the flange was assumed to determine the total stress at the flange tips. Vertical bending stresses at both the top and bottom flanges were calculated using the average of the interior and exterior flange tip stresses. Lateral bending stresses for each flange tip were then calculated by subtracting the vertical bending (average) stresses from each calculated tip stress.

Static vertical bending stresses for the top and bottom flanges were used to calculate the level of composite action in each girder. The location of the neutral axis was determined for each girder, assuming a linear variation in the strain through the girder depth. Basic beam theory was then employed to calculate girder vertical bending moments. Girder lateral bending moments were calculated using the lateral bending stresses and the bottom flange weak axis section modulus.

Table 3. Locations of Girder Instruments

Girder	Section (Fig. 2)	Cross-frame number	Location from cross frame (m)	Instrument quantity
1	C-C	10	0.3	4
2	C-C	9	2.3	4
3	C-C	8	4.1	4
4	C-C	8	2.5	4
5	C-C	8	0.3	4

Numerical Analyses

Level 1

Two manual calculation methods were used to analyze the field-tested structure: (1) a line girder method from the AASHTO (1993) *Guide Specification for Horizontally Curved Highway Bridges*, and (2) the V-load method (NSBA 1996). One could state that analysis criteria from the 2003 AASHTO *Guide Specifications* were not directly incorporated into this study as they were not published until after completion of the work. However, the 2003 AASHTO *Guide Specifications* recommend using the V-load method as an approximate method of analysis.

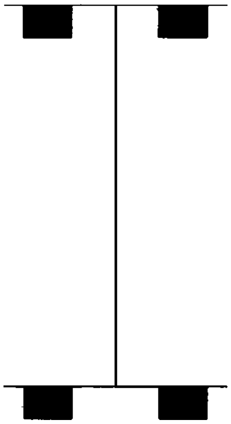

Fig. 3. Strain gauge locations

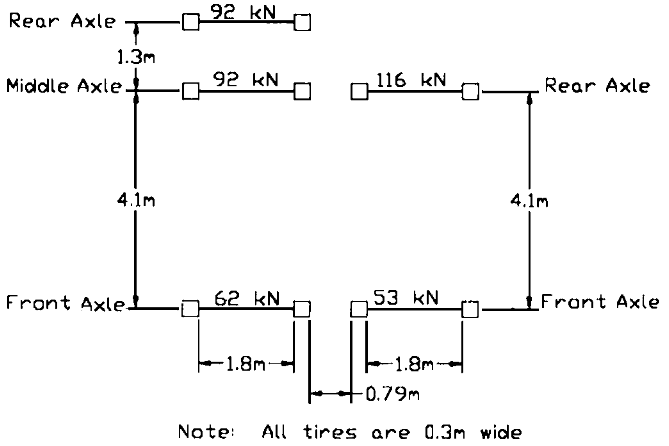

Fig. 4. Test truck parameters

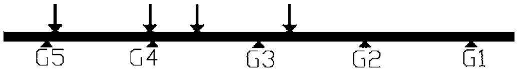

Fig. 5. Calculation of distribution factors

Even though it is not available in the 2003 AASHTO *Guide Specifications*, the line girder method from the 1993 AASHTO *Guide Specifications* was still incorporated into the study as another Level 1 analysis technique because it had been a widely used approximate method.

All 17 vehicle positions (Table 4) were analyzed using these two methods. Distribution factors for both methods were calculated by analyzing the entire bridge cross section as a continuous beam with supports located at each girder location (Fig. 5). Six sets of distribution factors were calculated based on the transverse location of the test trucks used for the field tests. Point loads were placed on the continuous beam in locations that corresponded to test truck transverse positions, and reactions were determined at each of the supports that represented the girders. Distribution factors for each girder were then calculated by dividing the support reaction value by the total load.

Table 4. Static Tests

Static test number	Transverse position three-axle truck (m)	Transverse position two-axle truck (m)	Truck longitudinal position from south end of bridge (m)[a]
1	0.6 from east parapet	3.8 from east parapet	64.3
2	0.6 from east parapet	3.8 from east parapet	41.8
3	0.6 from east parapet	3.8 from east parapet	33.5
4	0.6 from west parapet	3.8 from west parapet	46.3
5	0.6 from west parapet	3.8 from west parapet	34.7
6	0.6 from west parapet	3.8 from west parapet	29.3
7	1.2 from east parapet	4.4 from east parapet	64.3
8	1.2 from east parapet	4.4 from east parapet	42.1
9	1.2 from east parapet	4.4 from east parapet	32.9
10	1.2 from west parapet	4.4 from west parapet	59.7
11	1.2 from west parapet	4.4 from west parapet	36.6
12	1.2 from west parapet	4.4 from west parapet	30.8
13	1.8 from east parapet	5.0 from east parapet	41.5
14	1.8 from east parapet	5.0 from east parapet	33.5
15	1.8 from west parapet	5.0 from west parapet	60.4
16	1.8 from west parapet	5.0 from west parapet	36.3
17	1.8 from west parapet	5.0 from west parapet	30.2

[a] Refers to position of front axle of three-axle truck.

Girder vertical bending moments were calculated by analyzing the girders as equivalent straight girders and then multiplying resulting straight girder moments by the distribution factors. The straight girder vertical bending moments were then modified again, depending on the Level 1 method of analysis being examined. Vertical bending moments from the V-load method were calculated by reanalyzing the straight girders under the V-loads and adding resulting moments to the original straight girder moments. Vertical bending moments from the 1993 AASHTO *Guide Specifications* method were calculated by multiplying straight girder moments by a modification factor that accounted for curvature as presented in the 1993 AASHTO *Guide Specifications*.

Level 2

Three programs were used to create two-dimensional (2D), Level 2 grillage models of the tested bridge. The three grillage models were created to ensure consistency when comparing results to field data and were constructed using frame elements placed along the centerline of each girder. Small straight sections simulated the curvature of the girders, and frame elements were used to model the cross frames. The cross-frame top chords were modeled as noncomposite. The models contained six to nine segments per span, depending on the span length. Composite member properties were used for girder frame elements to reflect the composite action between the slab and girder in the positive moment regions. The deck was not treated as a transverse member because it was included in the composite girder member properties.

An initial SAP2000 model was examined that included the deck as a transverse member and incorporated composite girder properties. The results showed that the model was overstiffened when compared to the field test results. Composite action was not modeled in the negative moment regions. Following typical grillage model procedures, parapets and railings were not included in the models. Support conditions were modeled to correlate with design support conditions. Each of the three grillage models used slightly different methods for determining girder vertical bending moments, and lateral bending moments could not be obtained without additional hand calculations. These additional calculations to determine the lateral bending moments were not performed, since this study focused on examining output provided directly from the computer program with minimal postprocessing.

SAP2000

Vertical bending moment influence lines were used to determine moments from SAP2000. Models were run with a unit load traveling in specified lane locations that corresponded with transverse truck positions from the field tests. Truck wheel loads were then multiplied by influence line ordinates that corresponded to the wheel position on the bridge for each static test. Total vertical bending moments were determined by summing each of the individual wheel moments for each static case.

MDX

MDX (2000) develops influence line ordinates for a unit load moving along each girder rather than in a lane. In addition, influence lines were limited to the tenth points of each girder span. Therefore, to determine vertical bending moment influence line ordinates that corresponded to instrumented sections and lane locations used during the field tests, linear interpolation was used twice to create an influence surface.

The first set of interpolations involved linearly interpolating along each girder arc. Influence line ordinates for tenth-span points along each girder were used to estimate ordinates at each instrument location. After completing the first set of interpolations, ordinates for all instrumented points were known for a unit load moving along each girder.

The second set of interpolations involved linearly interpolating between each girder. Ordinates at the instrumented points were used to determine influence line values for specific lane locations for each static test. After completing both sets of linear interpolations, ordinates were known for each instrumented point for a unit load moving along a lane that corresponded to the field test lanes. Once these ordinates were established, the same procedure discussed for SAP2000 was used to determine vertical bending moments.

DESCUS

DESCUS (2002) is unable to produce influence line ordinates for a unit load moving along a specified longitudinal path on the bridge. Therefore, each static case needed to be analyzed separately and concentrated loads were placed along a girder line. Prior to completing the analysis, test truck wheel loads needed to be distributed to the girders based on their distances from adjacent girders. Girder vertical bending moments were obtained for locations along each girder that corresponded to cross-frame locations. A single linear interpolation step was used to obtain girder vertical bending moments at the instrumented locations.

Level 3

SAP2000 and BSDI (2000) were used to create three-dimensional (3D) finite element models of the tested structure. Locations and numbers of nodes used were based on coarse discretization required for the BSDI model. It is recognized by the writers that more sophisticated 3D finite element models could be developed that would produce accurate results if correctly calibrated. However, this study attempted to use 3D models that were of similar construction. Therefore levels of discretization described were dictated by the BSDI models and are similar to levels used during the analysis and design of many curved bridges.

Nodes were placed along the bottom and top of each girder web and were also placed at the center of the slab along each girder and at locations that corresponded to the center of the bottom diagonal of each cross-frame member. Frame elements were used to model the top and bottom flanges. Webs were modeled using a single four-noded shell element through the depth. Four-noded shell elements were also used to model the slab. The parapets were included in the model by increasing the stiffness of the shell elements at the parapet locations. Shell elements representing the slab were connected to the top of the girder webs using rigid links. Cross frames were modeled using frame elements. Support conditions matched structure support conditions. See Fig. 6 for a diagram of the 3D models.

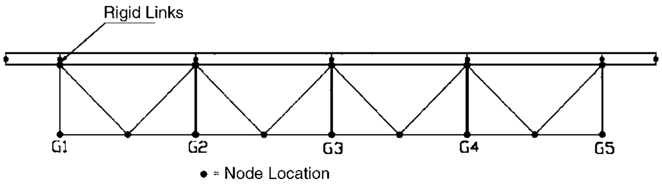

Fig. 6. Three-dimensional finite element model cross section

SAP2000 and BSDI calculated girder vertical bending moments differently. SAP2000 girder vertical bending moments were calculated using influence line values for the axial force in the top and bottom flanges. These axial forces were used to determine stress distributions through the girder depth and girder vertical bending moments. Girder lateral bending moments were calculated using influence line values for weak axis moments in the bottom flanges.

BSDI reported the maximum vertical bending stresses near the instrumented sections for 6 of the 17 test truck positions, and these stresses were then used to calculate vertical bending moments. Output from the model was provided directly from the vendor to the researchers and did not include lateral bending stresses and moments. Since additional calculations and assumptions would be required to calculate this information from the output provided, the researchers decided not to include it.

Discussion of Results

Results for 2 of the 17 static test cases; Static 3 and Static 5, will be presented herein; results for all 17 test cases are found elsewhere (Nevling 2003). The numerical predictions presented were based on the location of the trucks during field testing, and the field test and numerical data presented are used solely to determine the accuracy of each level of analysis for predicting structure response to a specific live load at a specific radial cross section through the structure. Analysis results that would be of interest to designers (moments near the center of gravity of the truck load) will be discussed, and results at other girder locations in the cross section will also be examined. Some of the results are presented as a percentage of the observed filed test values. Percentage values that are negative indicate that the level of analysis technique predicted results that had a sign opposite to that observed in the field.

Girder Vertical Bending Moment

Girder vertical bending moments observed in the field range from 21 to 325 kN·m. Girder vertical bending moment distribution results from two representative field tests, termed Static 3 and Static 5 (Table 4), at midspan of Span 2 (Section C-C, Fig. 2) are compared to values from each level of analysis in Figs. 7–11. Each figure contains a schematic indicating location of test truck wheel lines and their center of gravity (C.G.). Vertical bending moment distribution for each girder at a cross section was calculated by dividing individual girder vertical bending moments by the sum of the vertical bending moments for all five girders.

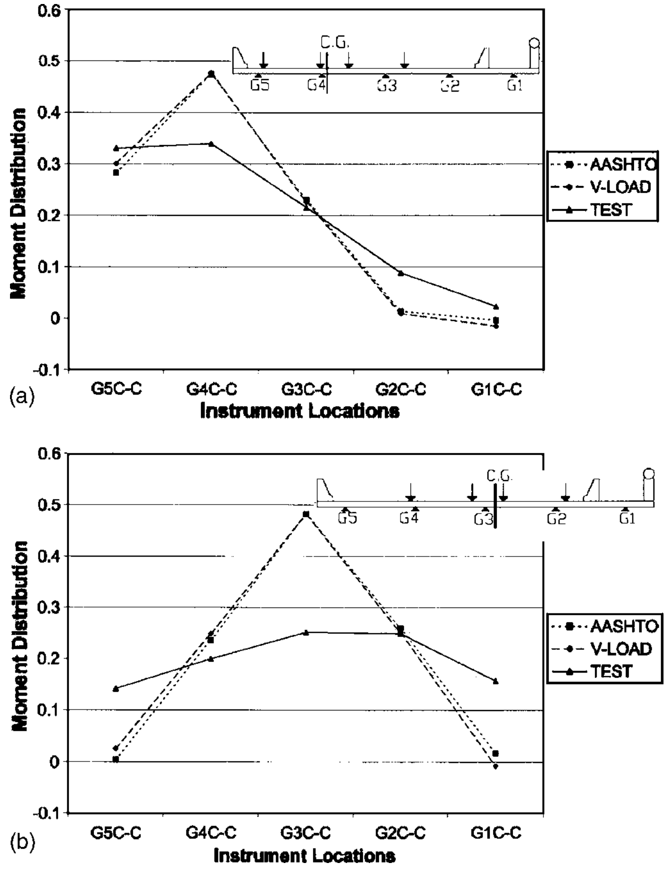

Fig. 7. Vertical moment transverse distribution, midspan Span 2, Level 1: (a) Static 3 and (b) Static 5

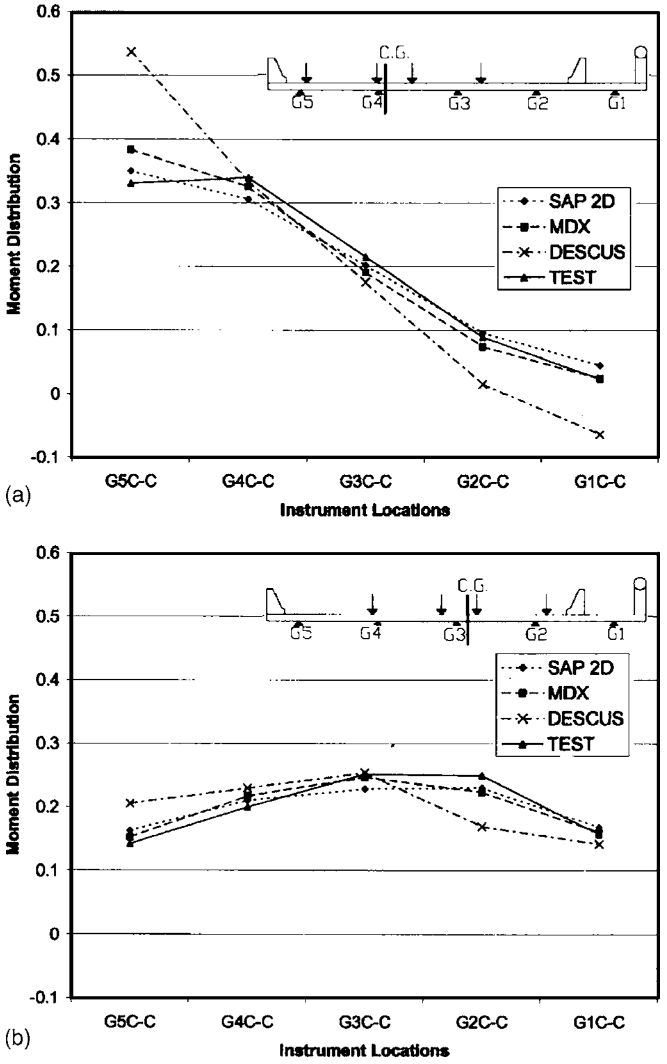

Fig. 8. Vertical moment transverse distribution, midspan Span 2, Level 2: (a) Static 3 and (b) Static 5

Level 1

At midspan of Span 2, the V-load and 1993 AASHTO *Guide Specification* analyses predicted higher vertical bending moment distribution factors for girders closest to the center of gravity of the two test trucks than those observed in the field and smaller distribution factors for girders furthest from the truck load (Fig. 7). Fig. 7(a) shows transverse moment distribution for the Level 1 analyses and field test results for Static 3. The majority of the total bridge moment is distributed to Girder 4, the girder closest to the center of gravity. Distribution factors for the V-load and 1993 AASHTO *Guide Specification* methods for Girder 4 are conservative, as expected, being 140% times the field values. Transverse distribution factors for Girders 3 and 5 obtained from the V-load and 1993 AASHTO *Guide Specification* methods are nearly identical to those obtained from the field. Vertical bending distribution factors predicted by the V-load and the 1993 AASHTO *Guide Specification* methods are unconservative for Girders 1 and 2, which are located furthest from the truck loads and subsequently experience the lowest vertical bending moments at the instrumented sections. These values are 11 to −62% of the field values. This is an expected result since Level 1 methods are approximate methods that predict conservative results for girders closest to the truck load.

Fig. 7(b) shows the similar trends for Static 5. As expected, the V-load and 1993 AASHTO *Guide Specification* methods distribute the majority of the total bridge moment to Girder 3, the girder closest to the center of gravity of the total truck load. The distribution factors are 192% of those observed in the field. Distribution factors for Girders 2 and 4 are nearly identical to those obtained from the field test data. The girders furthest from the truck, Girders 1 and 5, have Level 1 moment distribution factors that are −5 to 11% of those observed in the field.

Level 2

At midspan of Span 2, girder vertical bending moment distribution values from Level 2 analyses are also typically higher than those observed in the field for girders closest to the center of gravity of the truck loads, with smaller predicted distribution factors being obtained at girders furthest from the center of gravity of the loads. However, in general, agreement with field data is measurably improved over the Level 1 analyses. Fig. 8 illustrates these trends. Fig. 8(a) shows results for Static 3. The programs distribute more moment to Girder 5, near where the truck center of gravity is located, than the field test results. DESCUS tends to distribute a higher portion of total girder vertical bending moment to Girder 5 than SAP2000 and MDX, but these discrepancies are largely attributed to the method used to distribute applied truck wheel loads to the DESCUS model. The DESCUS model predicts a distribution factor for Girder 5 that is 162% of the value observed in the field where the SAP2000 and MDX models predict factors that are 106 and 116% of those observed in the field, respectively.

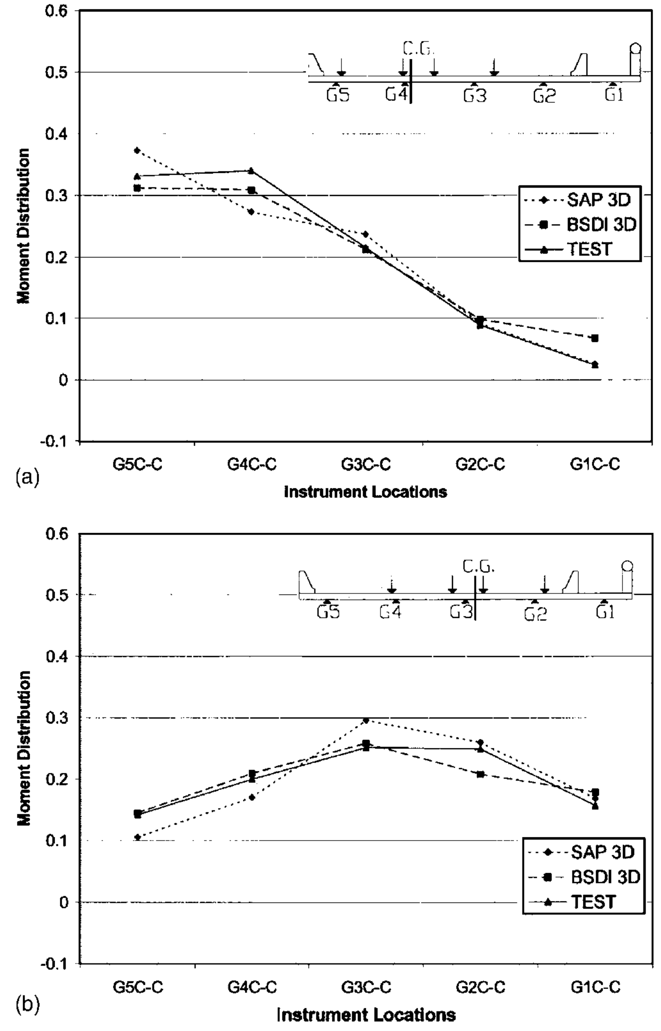

Fig. 9. Vertical moment transverse distribution, midspan Span 2, Level 3: (a) Static 3 and (b) Static 5

Fig. 8(b) presents similar results for Static 5, although the trends are not nearly as pronounced. SAP2000 and MDX predict nearly identical girder distribution factors when compared to those obtained from the field (90 to 115% of those observed in the field). DESCUS predicts the distribution factors for Static 5 more accurately than for Static 3, with any discrepancies again possibly being caused by the approach used to distribute the applied truck loads to the model. The DESCUS results for Static 5 are 68 to 145% of those observed in the field.

Level 3

Girder vertical bending moment distribution factors obtained from the Level 3 analyses for midspan of Span 2 produced somewhat contradictory results, although agreement is generally good. Vertical bending moment distribution factors from the SAP2000 3D finite element model are 104 to 117% of those observed in the field for the instrumented sections closest to the truck loads than those observed in the field. In addition, SAP2000 tends to predict smaller distribution factors (74 to 85% of field values) than the field values for girders furthest from the loads. Fig. 9 illustrates these trends for Static 3 and Static 5. However, the BSDI 3D-System model predicts distribution factors lower (91 to 94%) than those observed in the field for Girders 4 and 5 for Static 3 [Fig. 9(a)] and for Girder 2 (84%) for Static 5 [Fig. 9(b)].

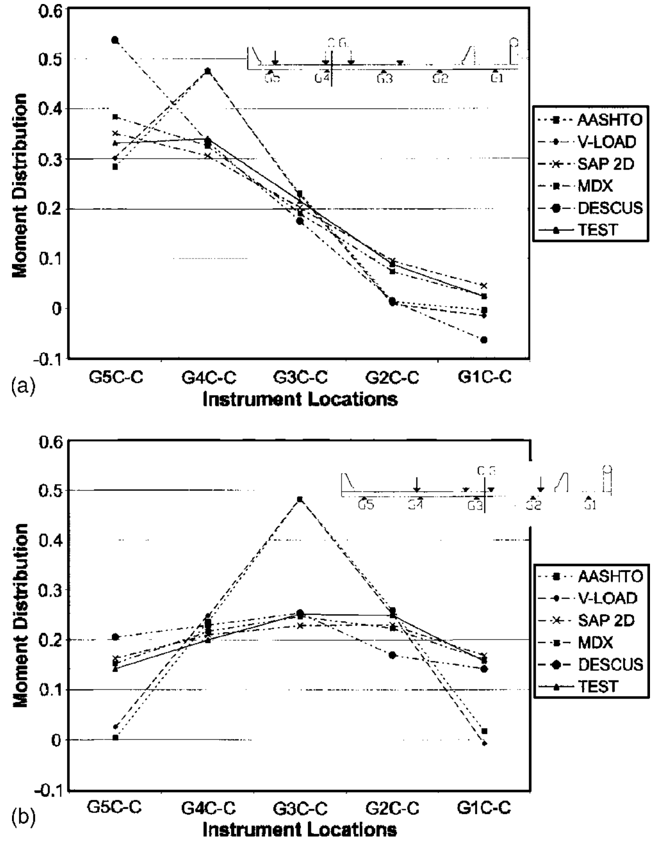

Fig. 10. Vertical moment transverse distribution, midspan Span 2, Level 1 versus Level 2: (a) Static 3 and (b) Static 5

Comparisons—Level 1 versus Level 2

As stated earlier, the intent of this study was to examine if measurable improvements in accuracy could be observed using different levels of analysis to examine the tested structure. While it could be argued that this information may not be of direct interest to the bridge engineering community due to the lack of a direct link to the design process, information from these comparisons could lead to future changes in the curved bridge design and analysis process (e.g., refined resistance factors for more sophisticated analyses) that would be of interest.

Fig. 10 details Level 1, Level 2, and field test results for vertical moment distribution at midspan of Span 2 for Static 3 and Static 5 and shows that the Level 2 analyses more accurately predict the measured vertical bending moment distribution than the Level 1 analyses. The Level 1 analyses predict considerably higher, and subsequently more conservative, moment distribution values for girders located closest to the truck loads. Both Level 1 and Level 2 analyses predict smaller vertical bending moment distribution factors than those observed in the field for some of the instrumented locations, generally furthest from the location of the load.

Comparisons—Level 2 versus Level 3

Girder vertical bending moment distribution values obtain from the Level 2 and Level 3 analyses are compared to field test distributions at midspan of Span 2 in Fig. 11. The figure shows there is generally no significant increase in accuracy of vertical moment predictions between Level 2 and Level 3 analyses for the levels of discretization and model construction used. Both Levels 2 and 3 predict distribution values that are both slightly higher and lower

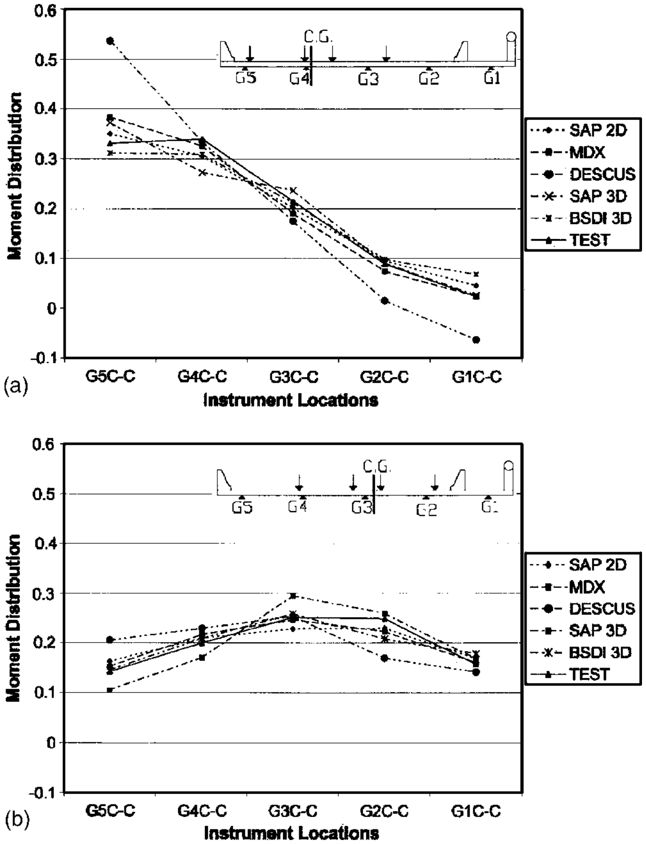

Fig. 11. Vertical moment transverse distribution, midspan Span 2, Level 2 versus Level 3: (a) Static 3 and (b) Static 5

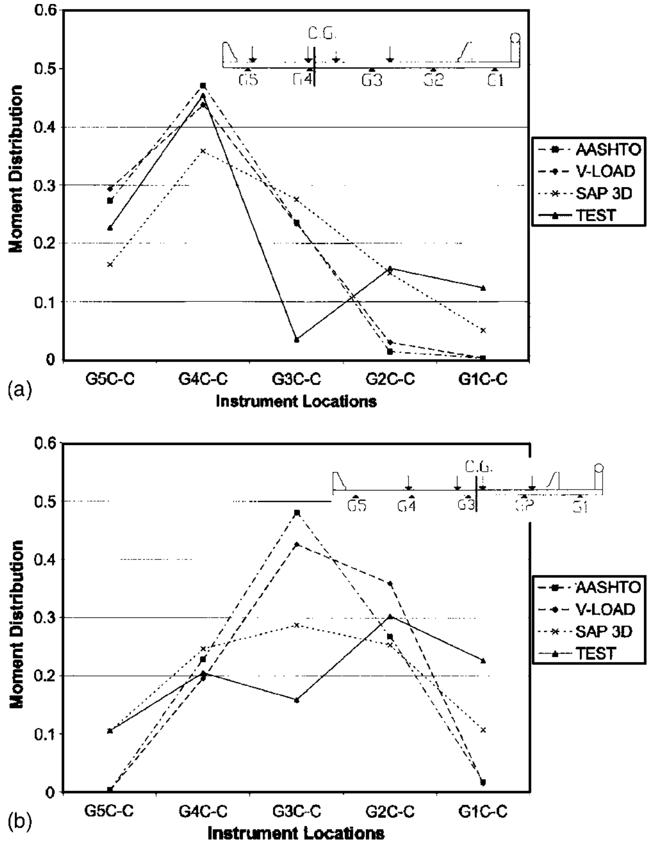

Fig. 12. Lateral moment distribution, midspan Span 2, Level 1 versus Level 3: (a) Static 3 and (b) Static 5

than the field test results, depending upon girder location relative to the truck loads. In some cases Level 2 analyses were shown to predict distribution factors more accurately than Level 3 analyses.

The results tend to indicate that additional time and effort needed to create a simplified 3D model instead of a 2D model did not appear to provide any appreciable increase in accuracy of calculation of positive vertical bending moments for the tested bridge. However, the writers recognize that more sophisticated 3D models would certainly provide more accurate results than those shown herein. Again, the intent was to use models of similar construction to those implemented during bridge design and analysis using commonly available commercial programs.

Bottom Flange Lateral Bending Moments

Bottom flange lateral bending moment distributions from the field tests were also compared to distribution values from the numerical models. Bottom flange lateral bending moments observed in the field varied in magnitude between 2.7 and 63.8 kN·m. Since Level 2 models could not explicitly determine bottom flange lateral bending moments because they were created in a 2D plane with a single member representing each girder, comparisons are limited to Level 1 and Level 3 analyses. Level 3 analyses were restricted to the SAP2000 model, as BSDI 3D System output as provided to the researchers did not explicitly provide lateral bending moments for reasons discussed earlier. As was done for vertical bending, bottom flange lateral bending distribution factors for each girder were calculated by dividing the provided flange lateral bending moment by the sum of the bottom flange lateral bending moments in the girders at a given cross section.

Comparisons—Level 1 versus Level 3

Field test bottom flange lateral bending moment results showed smaller magnitudes near cross-frame locations than locations near midspan of a girder unbraced length. Instruments on Girders 1, 3, and 5 were relatively close to a cross-frame location and had smaller bottom flange lateral bending moments and distribution factors than those for Girders 2 and 4, located closer to the center of the unbraced length.

Bottom flange lateral bending moment distributions from the Level 1 analyses, obtained at the same locations as the girder instruments, were quite erratic and both larger and smaller when compared to those observed in the field. Adequate correlation was generally linked to (1) distance from girder bracing points, with Girders 2 and 4, near the middle of an unbraced length, showing improved agreement between all analysis levels and field data than the other girders; and (2) location of the truck wheel lines' center of gravity relative to the girders. Fig. 12 shows that Level 1 analysis techniques predict similar distribution factors for the girder (Girder 3) closest to the center of gravity of the load for Static 3 when compared to the field test results.

However, for Static 5, the Level 1 analysis techniques predict significantly larger distribution factor values for Girder 3 when compared to the field results. Fig. 12 shows that Level 1 analysis methods predicted significantly smaller bottom flange lateral bending moment distributions for girders located furthest from the wheel load center of gravity for Static 3 and Static 5 (Girders 1 and 5), which were also at sections located near cross-frame connection points. Fig. 12 shows that the Level 3 analysis predicts a smaller distribution factor for Girder 5 for Static 3, while the Level 3 analysis predicts a higher distribution factor for Girder 3 for Static 5. One item shown in Fig. 12 is that no significant increase in accuracy existed between Level 1 and Level 3 bottom flange lateral bending moment predictions.

Conclusions

Several conclusions can be drawn from this study:

1. Level 1 analyses predicted larger girder vertical bending moment distribution factors for girders located closest to the center of gravity of the test loads when compared to the field test distribution. Conversely, Level 1 analyses predicted lower distribution factors for the girders located furthest from the load when compared to the field test values. These results were expected because of the simplified analysis methods employed by the Level 1 analysis techniques.
2. Both Level 1 analysis techniques predicted some bottom flange lateral bending moment distribution factors that were similar to those observed in the field. These locations were generally either (1) at a girder cross section located away from a bracing point, or (2) near the center of gravity of the truck wheel lines. However, there were no clearly visible trends observed from the Level 1 bottom flange lateral bending moment distribution results.
3. Both Level 2 and Level 3 analyses produce girder vertical bending moment distributions that generally correlated well with the field test distributions.
4. As was observed for Level 1, the Level 3 analysis used herein provided erratic bottom flange lateral bending moment distribution results when compared to the field test distribution. Again, better correlation existed away from girder bracing points or near the wheel lines' center of gravity.
5. Level 2 analysis techniques provided more accurate girder vertical bending moment distributions that the Level 1 analysis techniques when compared to field test distribution results.
6. Level 3 analyses of the structure using the models constructed herein provided no significant increase in accuracy over the Level 2 analyses for the calculation of girder vertical bending moments.

As discussed above, the study indicated that, for the structure examined, the coarse Level 3 analyses performed herein did not offer significant improvement over Level 2 analyses for predicting vertical bending moments. Both Levels 2 and 3 provided improved vertical bending moment accuracy over the Level 1 analyses. Therefore, it appears that Level 2 analyses would be recommended as an acceptable and reasonable approach when compared to coarse 3D models for practicing engineers when vertical bending moment predictions are required for a horizontally curved steel I-girder bridge. It was also apparent that neither the Level 1 nor Level 3 analyses adequately predicted the lateral bending moments within the tested structure, with accuracy worsening near bracing points or away from the wheel lines center of gravity. The writers recognize that these results incorporate coarse 3D models for a single curved I-girder structure, and as such, field tests of additional curved steel I-girder bridges are recommended to augment findings reported herein.

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