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## **BENCHMARK PROBLEMS**

TASK 7 REPORT

Prepared for NCHRP Transportation Research Board of The National Academies

Donald W. White, Georgia Institute of Technology, Atlanta, GA Andres Sanchez, HDR Engineering, Inc., Pittsburgh, PA Cagri Ozgur, Paul C. Rizzo Associates, Inc., Pittsburgh, PA Juan Manuel Jimenez Chong, Paul C. Rizzo Associates, Inc. Pittsburgh, PA

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Project No. NCHRP 12-79

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### **Executive Summary**

The engineer generally should understand the broad aspects of the assumptions and limitations of the modeling strategies, to ensure their proper application, and generally, he or she should conduct testing and validation studies with the software to ensure that the methods work as intended and that they provide correct answers for relevant benchmark problems.

This document provides a series of formal benchmark cases that can be used to evaluate several analytical methods. The benchmark cases are presented in a combined drawing/report/data file format. The drawings indicate the characteristics of the structure, with all key structural element sizes and dimensions, material properties, bearing conditions, design loads, etc.

This task indicate modeling assumptions (load and displacement boundary conditions, stiffness modeling assumptions, etc.) and bridge descriptions and benchmark results in a data format easily accessed for comparison to the results of alternate proposed analysis methods.

### **1. Introduction**

In this report, two I-girder bridges and one tub girder bridge studied in Task 7 of the NCHRP 12-79 research are presented as a set of benchmark cases that can be used to evaluate other analytical methods. These models are presented in a combined drawing/report/data file format. The drawings indicate the characteristics of the structure, with all key structural element sizes and dimensions, material properties, bearing conditions, design loads, etc. Also, the modeling assumptions, which include boundary conditions, loading assumptions, stiffness modeling assumptions, etc., are included. The data shown in this report in graphical format is provided also in electronic form as spreadsheets and other data files. In this way, designers and software developers should be able to identify all key parameters of the benchmark solutions, run their analysis using consistent parameters, and compare the results.

### 2. I-Girder Bridges

### 2.1 Bridge XICSS5

XICSS5 is a three span continuous straight I-girder bridge with the span lengths of 140ft, 175ft and 140ft with parallel abutments skewed at 60°. This structure is an example bridge studied in "Load and Resistance Factored Design for Highway Bridge Superstructures" (FHWA-NHI, 2007a & 2007b). Figure 2.1 shows the perspective and plan views of XICSS5 with key dimensions. The girders are labeled from bottom to top as Girder 1 to Girder 4 (G1-G4).



Figure 2.1. XICSS5, perspective and plan views.

The assumed bearing restraints for 3DFEA models are tabulated in Table 2.1. Moreover, Figure 2.2 shows the framing plan of XICSS5. Girder plate dimensions are illustrated in Figure 2.3. The intermediate cross-frames are V-type, and inverted V-type cross-frames are used at abutments and at the interior bents. The cross-frame member sizes are summarized in Table 2.2. Also, typical bridge cross-section is shown in Figure 2.4. The weight of the formwork (10 psf), and the slab reinforcing steel plus the wet concrete (150 psf) is applied to the top flanges as uniformly distributed line loads based on the tributary width of each girder across the cross-section of the bridge. In addition, the overhang brackets used for resisting the weight of wet concrete and formwork at the fascia girders are considered. In the model, the steel properties are  $E_s = 29000$  ksi and  $F_y = 50$  ksi. Similarly, the concrete properties are  $E_c = 3600$  ksi and  $f'_c = 4$  ksi. Additionally, Figure 2.5 provides the deck placement sequence of the bridge.

Girder #	Abutment 1	Pier 1	Pier 2	Abutment 2
1	Free	Free	12000 kip/ft Longitudinally	Free
2	Guided Longitudinally	24000 kip/ft Transversely	12000 kip/ft Longitudinally and 24000 kip/ft Transversely	Guided Longitudinally
3	Guided Longitudinally	24000 kip/ft Transversely	12000 kip/ft Longitudinally and 24000 kip/ft Transversely	Guided Longitudinally
4	Free	Free	12000 kip/ft Longitudinally	Free

Table 2.1. XICSS5, assumed bearing restraints in 3D FEA models.



Figure 2.2. XICSS5, framing plan.



Figure 2.3. XICSS5, girder plate dimensions.

Table 2.2. XICSS5, cross-frame member sizes.

Cross-Frame Type	Top Chord	Diagonals	Bottom Chord		
Interior (V)	L6x6x1/2	L6x6x5/8	L6x6x5/8		
End (Inverted V)	L6x6x1/2	L6x6x5/8	L6x6x5/8		



Figure 2.4. XICSS5, typical bridge cross-section.



Figure 2.5. XICSS5, deck placement sequence.

#### 2.1.1 Summary of Results

The following plots show the results obtained from the geometrically nonlinear 3D FEA, which represents the benchmark model, and from the approximate methods. The other curves illustrate the nature of the approximations by the simplified models. One can observe that the discrepancy between the simplified model predictions and the benchmark 3D FEA solutions is large at certain locations. Figures 2.6 and 2.7 illustrate the vertical displacements and girder layovers respectively. Figures 2.8 and 2.9 show total dead load girder major-axis bending and flange lateral bending stresses respectively. All the responses are shown at the total noncomposite dead load (TDL). The data used to generate the plots is available in electronic format.



Figure 2.6. XICSS5, vertical displacements under nominal total dead load.



Figure 2.7. XICSS5, lateral displacements under nominal total dead load.



Figure 2.8. XICSS5, top flange major-axis bending stresses under nominal total dead load.



Figure 2.9. XICSS5, top flange minor-axis bending stresses under nominal total dead load.

#### 2.2 Bridge XICCS7

This structure is an example bridge studied in "Load and Resistance Factored Design and Analysis of Skewed and Curved Steel Bridges" (FHWA-NHI, 2010a & 2010b). It is a three-span four-girder bridge with the interior supports skewed 60 degrees. The span lengths are 160 ft, 210 ft, and 160 ft. The radius of curvature is 700 ft, and the girders are spaced 11 ft apart. This structure is selected as a benchmark problem since it has a complex geometry that includes horizontal curvature and support skew. Figure 2.10 shows the plan view of the bridge. Figure 2.11 depicts the bridge cross-section with the slab information and the dimensions of the cross-frame elements. Figure 2.12 illustrates the girder elevations. The material properties and loading conditions are the same as in Bridge XISSS5.



Figure 2.10. XICCS7, framing plan.



TYPICAL CROSS SECTION

Figure 2.11. XICCS7, bridge cross-section.



Figure 2.12. XICCS7, girder elevations.



Figure 2.12. XICCS7, girder elevations (continued).

#### 2.2.1 Summary of Results

The following plots show the results obtained from the nonlinear 3D FEA, which represents the benchmark model, as well as the characteristics of the approximations from the simplified methods. One can observe that the discrepancy between the simplified model predictions and the benchmark 3D FEA solutions is large at certain locations. Figures 2.13 and 2.14 illustrate the vertical displacements and girder layovers respectively. Figure 2.15 shows total dead load girder major-axis bending stresses. Similarly, Figure 2.16 shows the flange lateral bending stresses in the girders, predicted by the refined geometric nonlinear FEA. All the responses are shown at the total noncomposite dead load (TDL). The data used to generate the plots is available in electronic format.



Figure 2.13. XICCS7, girder vertical displacements under total dead load.







Figure 2.15. XICCS7, girder major-axis bending stresses under total dead load.



Figure 2.16. XICCS7, lateral bending stresses in the top flanges under total dead load.

### **3. Tub-Girder Bridges**

#### 3.1 Bridge XTCCR8

XTCCR8 is a three span continuous curved twin tub-girder bridge. It has spans of 160 ft, 210 ft and 160 ft measured along the centerline of the bridge and radius of 700 ft. Supports are radial with respect to the bridge centerline, the bridge deck is 40.5ft wide and 9.5 in thick. This structure is a design example studied in "AASHTO-LRFD Design Example Horizontally Curved Steel Box Girder Bridge" from the NCHRP Project 12-52 (Kulicki et al, 2005).

To illustrate the bridge geometry, Figure 3.1 shows the framing plan with span dimensions with respect to the centerline. In the plan view shown the girders are labeled from bottom to top as girder G1 to girder G2. Figure 3.2 illustrates the typical bridge cross-section. The assumed bearing restraints for 3D-FEA models are tabulated in Table 3.1, the original design uses twin-bearing configuration but it was modified to use single bearings since the double bearing configuration reported a torsional constraint that is not possible to accomplish in a real bridge.

The internal cross-frames are spaced at 16 ft for Spans 1 and 3 and 15 ft for Span 2, the cross-fames use an inverted-V configuration with cross-section area of 5 in<sup>2</sup> for chords and diagonals. The top flange lateral bracing system uses a Warren-type truss with constant panel size defined by the internal cross-frame spacing, the diagonals are WT9x48.5 and the struts are defined by the internal cross-frame top chords. Internal and external support diaphragms are solid plate diaphragms 1/2 in thick, the internal diaphragm has four vertical stiffeners of 5.5 in by 1/2 in and the external diaphragm has top and bottom flanges of 8 in by 1 in.

The tub-girder plate dimensions are illustrated in Figure 3.3 and plate lengths are tabulated in Table 3.2. The bottom flange is longitudinally stiffened by a WT8x28.5 at the negative moment regions (64 ft to the left and 45 ft to the right of Support 2 and similarly for Support 3), at these locations the bottom chord of the cross-frame was raised to prevent interference with the longitudinal stiffener. The webs are stiffened transversally by 5.5 in by 1/2 in plates that serve as the internal cross-frame connection plates.

The weight of the formwork (10 psf), and the slab reinforcing steel plus the wet concrete (150 psf) is applied to the top flanges as uniformly distributed line loads based on the tributary width of each girder across the cross-section of the bridge. In addition, the overhang brackets used for resisting the weight of wet concrete and formwork at the fascia webs are considered. In the model, the steel properties are  $E_s = 29000$  ksi and  $F_y = 50$  ksi. Similarly, the concrete properties are  $E_c = 3600$  ksi and  $f''_c = 4$  ksi.



Figure 3.1. XTCCR8, framing plan and general dimensions.





Girder #	Support 1	Support 2	Support 3	Support 4
1	Fixed single support at center of bottom flange	Free single support at center of bottom flange	Free single support at center of bottom flange	Single support at center of bottom flange Guided Longitudinally
2	Free single support at center of bottom flange	Free single support at center of bottom flange	Free single support at center of bottom flange	Free single support at center of bottom flange

Table 3.1. XTCCR8, assumed bearing restraints in 3D FEA models.





Length @ Bridge CL		Тор	Girder 1		Girder 2		Bottom	Girder 1		Girder 2	
Section	Dim (ft)	Flange	b <sub>f</sub> (in)	t <sub>f</sub> (in)	b <sub>f</sub> (in)	t <sub>f</sub> (in)	Flange	b <sub>f</sub> (in)	t <sub>f</sub> (in)	b <sub>f</sub> (in)	t <sub>f</sub> (in)
А	120	TF1	16	1	16	1	BF1	83	0.625	83	0.625
В	24	TF2	18	1.5	18	1.5	BF2	83	1	83	1
С	16	TF3	18	3	18	3	BF3	83	1.5	83	1.5
D	15	TF4	18	3	18	3	BF4	83	1.5	83	1.5
Е	30	TF5	18	1.5	18	1.5	BF5	83	1	83	1
F	120	TF6	16	1	16	1	BF6	83	0.75	83	0.75
G	30	TF7	18	1.5	18	1.5	BF7	83	1	83	1
Н	15	TF8	18	3	18	3	BF8	83	1.5	83	1.5
Ι	16	TF9	18	3	18	3	BF9	83	1.5	83	1.5
J	24	TF10	18	1.5	18	1.5	BF10	83	1	83	1
K	120	TF11	16	1	16	1	BF11	83	0.625	83	0.625

Table 3.2. XTCCR8 plate dimensions.

#### 3.1.1 Summary of Results

The following plots show the results obtained from the geometric nonlinear 3D FEA, which represents the benchmark model, and from the simplified methods. One can observe that the discrepancy between the simplified model predictions and the benchmark 3D FEA solutions is large at certain locations. All the responses are shown at the total noncomposite dead load (TDL). The data used to generate the plots is available in electronic format.

The following figures show the results for the vertical displacements (Figure 3.4), the top flange and bottom flange relative lateral displacements (Figure 3.5), top flange major axis bending stresses (Figure 3.6), top flange lateral bending stresses (Figure 3.7), top flange lateral bracing diagonals axial forces (Figure 3.8), internal cross-frame top chord axial forces (Figure 3.9) and internal cross-frame diagonal axial forces (Figure 3.10).

Results for vertical displacements and major axis stresses are reported for the 3D FEA, 2D Grid and 1D Line Girder methods. The other results are reported only for the 3D FEA and 2D Grid methods.



Figure 3.4. XTCCR8, vertical displacements under nominal total dead load.



Figure 3.5. XTCCR8, lateral displacements under nominal total dead load.



Figure 3.6. XTCCR8, top flange major-axis bending stresses under nominal total dead load.



Figure 3.7. XTCCR8, top flange minor-axis bending stresses under nominal total dead load.



Figure 3.8. XTCCR8, top flange lateral bracing diagonals axial forces under nominal total dead load.



Figure 3.9. XTCCR8, internal cross-frame top chords axial forces under nominal total dead load.



Figure 3.10. XTCCR8, internal cross-frame diagonals axial forces under nominal total dead load.

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