APPENDIX Q -- Steel Spread Boxes Girders

Approach

A separate study was conducted that was specific to steel spread box girder bridges. The typical tub configuration as shown in Figure 1 was used. Two sources were used for the geometry: A recent study by Samaan et al (2005) and bridges provided by several DOTs. Samaan et al performed an extensive parametric study considering 240 bridges with various geometries and four curvature ratios, including straight. Distribution factors for dead and live loads for positive and negative moment and deflection were proposed. The equations for stress in the positive and negative moment regions are:

$$D_{\sigma p} = \left(\frac{4}{N_L}\right)^{0.2}\left[1+\left(\frac{\kappa}{10}\right)^2\left(\frac{N_b}{N_L}\right)^{0.8}\left(L\right)^{0.75}\right] \quad \text{(Q1)}$$

$$D_{\sigma n} = \left(\frac{4}{N_L}\right)^{0.2}\left[1+\left(\frac{\kappa}{10}\right)^2\left(\frac{N_b}{N_L}\right)^{1.8}\left(L\right)^{0.8}\right] \quad \text{(Q2)}$$

where κ is the curvature ratio that is zero for a straight bridge, L is the span length in meters, N_b is the number of boxes, and N_L is the number of lanes. Therefore, these distribution factors reduce to only a function of number of lanes, which appears unlikely to be appropriate for the present work. However, the geometry of these bridges is considered to be reasonable and 60 bridges were used in aggregate for calibration. Three of these bridges were studied in detail and analyzed rigorously with shell-element models. Additional bridges were obtained from DOTs, including Tennessee, Kansas, Texas, Georgia, and Illinois. The typical geometry was obtained from the plans and the longest span was used for each bridge. The mid-span cross section was used in most cases. Some bridges were modestly curved and were analyzed as straight bridges. These bridges have varied characteristics, with box widths ranging from 6.25 to 11.67 ft, span lengths ranging from 49 to 328 ft, and with bridge widths accommodating two to 11 lanes of traffic. The bridge name is denoted, for example, 3L-66-3B (Tennessee) where this Tennessee bridge has three traffic lanes, is approximately 66 m long (216 ft), and has three boxes. As the Samaan bridges were originally metric and this naming convention was used, it was continued herein. US units are also provided.

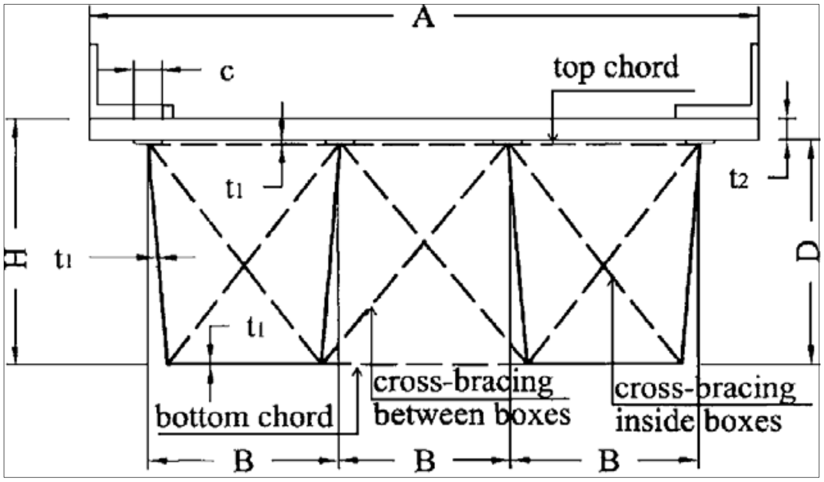


Figure 1. Typical Cross Section (after Samaan et al, 2005)

Using SAP 2000 (Version 10) three-dimensional shell-element models were created. Simple supports (pin-roller) at the webs were used with diaphragms located at the supports. The diaphragms behave rigid in plane and flexible out of plane. The wheel weights were modeled as joint loads and the deck was meshed to provide joint locations necessary for locating these loads. The design truck was used with axles spaced at 14 ft with a gage of 6 ft. Adjacent trucks were spaced at approximately 4-ft. Three load cases were used for each bridge:

1. A single truck positioned near the end of the bridge (near the 1.10 point)
2. Two trucks positioned near the end of the bridge (near the 1.10 point)
3. Three trucks positioned near the end of the bridge (near the 1.10 point)

4. A truck positioned near the middle of the bridge (near the 1.40 point)
5. Two trucks positioned near the middle of the bridge (near the 1.40 point)
6. Three trucks positioned near the middle of the bridge (near the at 1.40 point)

Figure 2 and Figure 3 illustrate typical loads for moment and shear, respectively. The bridges were modeled using quadrilateral shell elements with in-plane and out-of-plane stiffness properties considering the thickness of the deck and steel. The modular ratio was assumed to be eight.

At each girder location, the stresses were integrated to obtain the actions associated with each girder,

$$Moment = \int_{AREA} \sigma_{longitudinal}\, y\, dA \tag{Q3}$$

Tributary widths were used to define the girder boundaries. The total bridge moment was determined in the same manner. The individual girder actions were ratioed to determine the distribution factor for each girder for each load case,

$$Distribution\ factor = \frac{M_i}{\sum_{i=1}^{NGirders} M_i}\left(No.of\ Lanes\,Loaded\right) \qquad \text{(Q4)}$$

where M_i is the moment to a girder of interest. The elastic neutral axis for the entire bridge cross section was used as the moment center, i.e., y in Eq. Q3. The results are given in Table 2. The integration was aided by the SAP 2000 postprocessor that computes the girder actions, i.e., Eq. Q3. Typical results are illustrated in Figure 6. The distribution factors, Eq. Q4, were computed separately by hand and with a spreadsheet.

Additional checks, including distribution factor computations, were made on the basis of the flexural stress at the same locations with each girder. The summation of all stresses and individual stresses were ratioed (Eq. Q4). The particular transverse location was not critical as shear lag effects were minimal. See Figure 4 and Figure 5 as examples. The results were typically within 10 percent of the integrated values. Global equilibrium was checked for all load cases.

For shears and reactions, the shears based upon integrated stress and reactions recovered from the system stiffness were compared. The standard reactions were used for the distribution factors reported herein because of more consistency (shear stresses are more difficult to accurately compute than are global reactions).

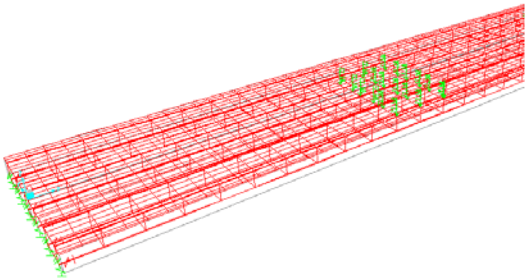


Figure 2. Load Positions for Three Lanes Moment

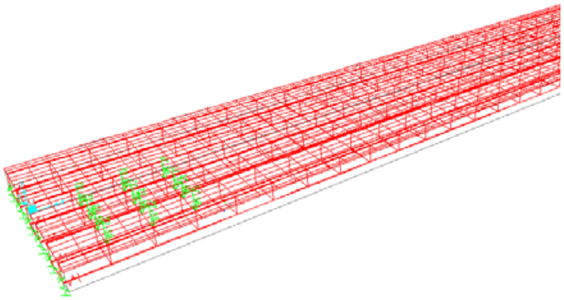


Figure 3. Load Positions for Two Lanes for Shear

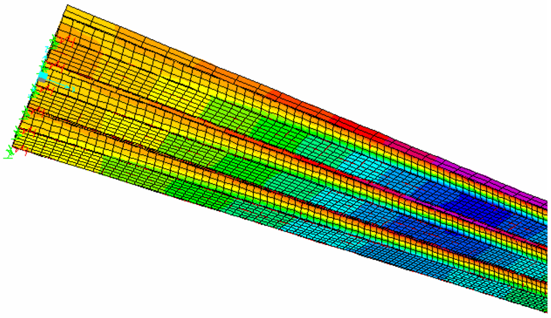


Figure 4. Typical Bottom Longitudinal Stress Plot (three lanes loaded for moment)

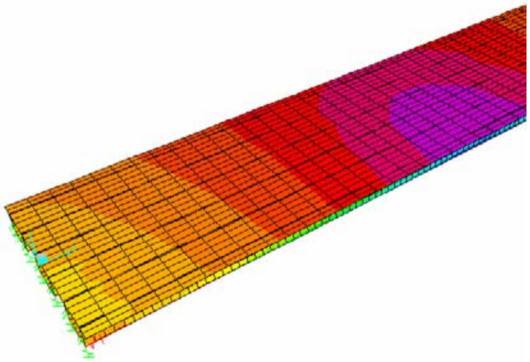


Figure 5. Typical Top Longitudinal Stress Plot (three lanes loaded for moment)

Table 1. Tub Girder Geometries

			Span			Cross-section dimensions (m)							Cross-section dimensions (ft)						
Bridge Name (source)	Max Number of lanes loaded, N_L	Lanes Possible	(m)	(ft)	Number of boxes, N_b	A	B	C	D	H	Nominal thickness (equiv concrete), t_1	Deck thickness, t_2	A	B	C	D	H	t_1	t_2
3l-100-3b (wide) (via web) (Samaan)	3	4	100.00	328.08	3	16.80	2.100	0.30	4.00	4.225	0.016	0.225	55.118	6.890	0.984	13.123	13.862	0.052	0.738
3l-60-3b via beam (Samaan)	3	4	63.64	328.08	3	16.80	2.100	0.30	4.00	4.225	0.016	0.225	55.118	6.890	0.984	13.123	13.862	0.052	0.738
2l-100-2b (to web) (Samaan)	2	2	100.00	328.00	2	9.30	2.325	0.30	4.00	4.225	0.016	0.225	30.512	7.628	0.984	13.123	13.862	0.052	0.738
11L-103-6B (Georgia)	3	11	100.00	328.00	6	41.768	3.557	0.000	2.642	3.049	0.407	0.415	137.00	11.67		8.67	10.00	1.33	1.36
3L-66-3B (Tennessee)	3	4	66.06	216.67	3	15.854	2.744	0.405	1.499	1.715	0.128	0.203	52.00	9.00	1.33	4.92	5.63	0.42	0.67
4L-15-4B (Texas)	3	3	15.00	49.20	4	14.024	1.905	0.457	0.915	1.118	0.203	0.134	46.00	6.25	1.50	3.00	3.67	0.67	0.44
2L-50-2B (Illinois)	2	2	50.00	164.00	2	9.146	2.439	0.457	1.524	1.829	0.203	0.305	30.00	8.00	1.50	5.00	6.00	0.67	1.00
4L-33-6B (Kansas)	3	4	33.00	110.00	6	15.448	1.905	0.305	0.991	1.194	0.244	0.203	50.67	6.25	1.00	3.25	3.92	0.80	0.67

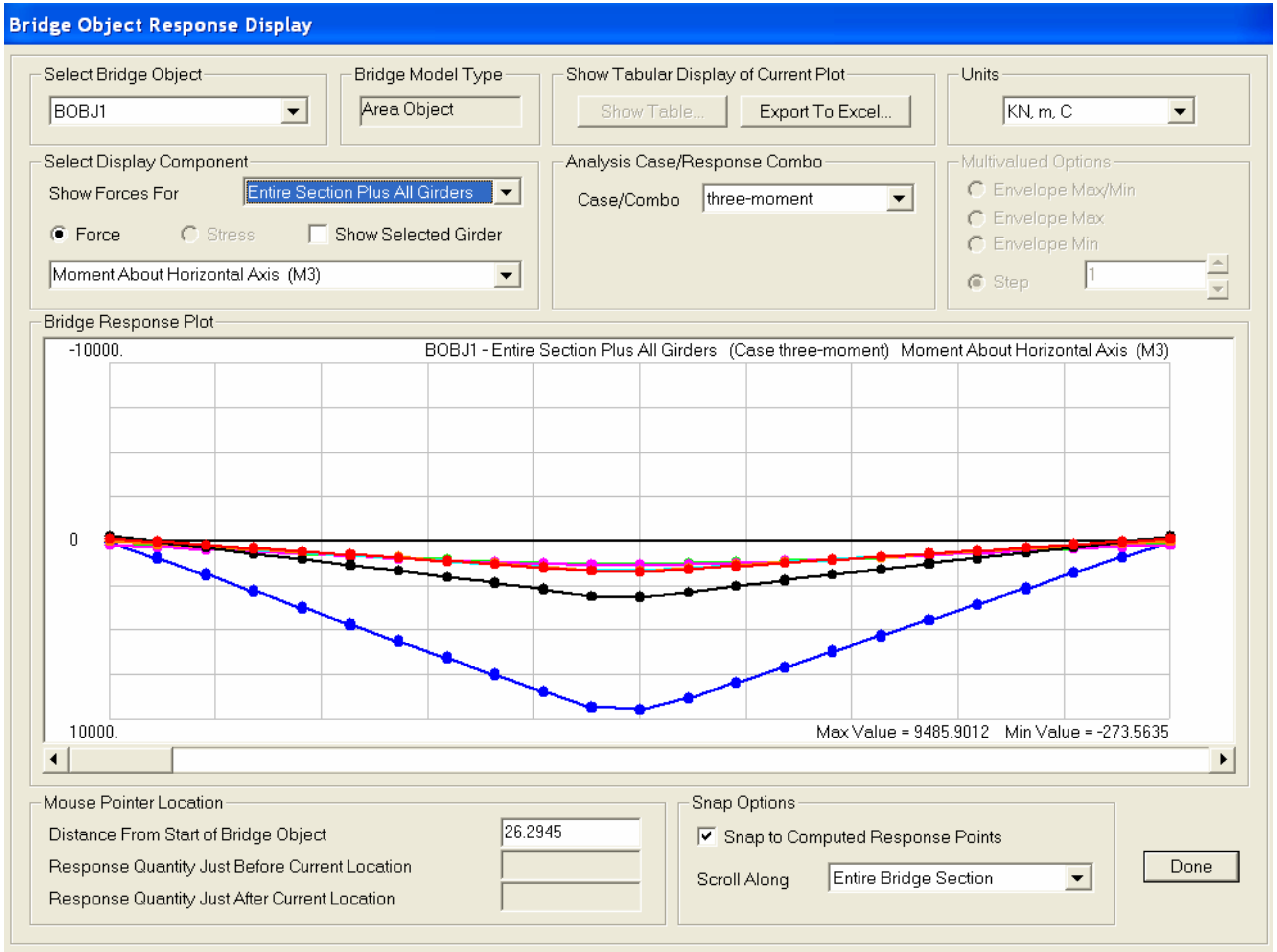
Table 2. Rigorous Distribution Factor Results

		SAP 2000 Shell Analysis											
		Shear/Reaction						Moment					
	Spacing (m)	Exterior			Interior			Exterior			Interior		
		1	2	3	1	2	3	1	2	3	1	2	3
3L-100-3B (Samaan et al)	2.100	0.38	0.64	0.76	0.23	0.53	0.65	0.19	0.32	0.44	0.20	0.34	0.45
3L-60-3B (Samaan et al)	2.100	0.39	0.65	0.77	0.31	0.42	0.54	0.15	0.37	0.47	0.12	0.30	0.46
2L-100-2B (Samaan)	2.325	0.57	0.63		0.36	0.54		0.28	0.52		0.27	0.52	
11L-103-6B (Georgia)	3.56	0.64	0.92	1.04	0.36	0.82	1.12	0.23	0.40	0.52	0.22	0.44	0.60
3L-66-3B (Tennessee)	2.74	0.48	0.77	0.88	0.35	0.60	0.73	0.24	0.41	0.53	0.42	0.76	0.98
4L-15-4B (Texas)	1.91	0.37	0.61	0.99	0.23	0.40	0.58	0.21	0.32	0.41	0.41	0.64	0.89
2L-50-2B (Illinois)	2.44	0.60	0.77		0.36	0.59		0.27	0.52		0.35	0.66	
4L-33-6B (Kansas)	1.91	0.28	0.47	0.59	0.25	0.42	0.53	0.18	0.28	0.34	0.16	0.26	0.32

Table 3. Shell Analysis Results SAP Integration (with multiple presence)

		SAP 2000 Shell Analysis											
		Shear						Moment					
with multiple presence	Spacing (m)	Exterior			Interior			Exterior			Interior		
		1	2	3	1	2	3	1	2	3	1	2	3
3L-100-3B (Samaan et al)	2.100	0.46	0.64	0.65	0.28	0.53	0.55	0.23	0.32	0.37	0.24	0.34	0.38
3L-60-3B (Samaan et al)	2.100	0.47	0.65	0.65	0.37	0.42	0.46	0.18	0.37	0.40	0.14	0.30	0.39
2L-100-2B (Samaan)	2.325	0.68	0.63		0.43	0.54		0.34	0.52		0.32	0.52	
11L-103-6B (Georgia)	3.56	0.77	0.92	0.88	0.43	0.82	0.95	0.28	0.40	0.44	0.26	0.44	0.51
3L-66-3B (Tennessee)	2.74	0.58	0.77	0.75	0.42	0.60	0.62	0.29	0.41	0.45	0.50	0.76	0.83
4L-15-4B (Texas)	1.91	0.44	0.61	0.84	0.28	0.40	0.49	0.25	0.32	0.35	0.49	0.64	0.76
2L-50-2B (Illinois)	2.44	0.72	0.77		0.43	0.59		0.32	0.52		0.42	0.66	
4L-33-6B (Kansas)	1.91	0.34	0.47	0.50	0.30	0.42	0.45	0.22	0.28	0.29	0.19	0.26	0.27

Critical values between two and three-lanes loaded are highlighted. $m_2 = 1.0$, $m_3 = 0.85$


Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: KN, m, C

Select Display Component

Show Forces For: Entire Section Plus All Girders

● Force ○ Stress ☐ Show Selected Girder

Moment About Horizontal Axis (M3)

Analysis Case/Response Combo

Case/Combo: three-moment

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - Entire Section Plus All Girders (Case three-moment) Moment About Horizontal Axis (M3)

Max Value = 9485.9012 Min Value = -273.5635

Mouse Pointer Location

Distance From Start of Bridge Object: 26.2945

Response Quantity Just Before Current Location:

Response Quantity Just After Current Location:

Snap Options

☑ Snap to Computed Response Points

Scroll Along: Entire Bridge Section

Figure 6. Post Processing Shell Stresses for Actions (bending moments are shown)

Table 4 illustrates three simple approaches:

1a. Present LRFD computation (per AASHTO 2005) (distribution to boxes) and
1b. No. 1a divided by two for distribution to a web

2a. Lever rule using webs and
2b. Lever rule calibrated to AASHTO 2005.

3a. Uniform method calibrated to AASHTO 2005 (distribution to boxes) and
3b. Uniform method calibrated to AASHTO 2005 (distribution to webs).

Calibrations (using no. 2b and 3b) were performed using the Samaan et al bridges. The DOT bridges were used for validation independent of the calibration. Note that the engineering time required for the 3-D shell analysis of a bridge and to post process the results is significant. Therefore, the number of analyses can not nearly approach the automated methods used for the other bridge types.

Table 4. Possible Simple Approaches

	N_L/N_b	Shear & Moment Interior & Exterior AASHTO 4.6.2 (to box) (2005)	Moment Interior & Exterior AASHTO 4.6.2 (to web (2005)	Lever Rule (to web)	Calibrated Lever Rule (calibrated to LRFD 2005)	Calibrated Uniform (to beam)	Calibrated Uniform (to web)
3l-100-3b (Samaan et al)	1.333	1.29	0.64	0.56	0.504	1.323	0.661
3l-60-3b (Samaan et al)	1.333	1.29	0.64	0.56	0.504	1.323	0.661
2l-100-2b (Samaan)	1.000	1.11	0.56	0.61	0.556	1.044	0.522
11L-103-6B (Georgia)	1.833	1.65	0.82	0.75	0.734	1.741	0.870
3L-66-3B (Tennessee)	1.333	1.29	0.64	0.67	0.634	1.323	0.661
4L-15-4B (Texas)	0.750	0.83	0.41	0.52	0.449	0.835	0.418
2L-50-2B (Illinois)	1.000	1.11	0.56	0.63	0.579	1.044	0.522
4L-33-6B (Kansas)	0.667	0.72	0.36	0.52	0.449	0.765	0.383

Results

The proposed simplified methods for all other bridge types, i.e., calibrated lever rule and uniform method, may be cast to yield the same distribution factors as the present LRFD approach, i.e.,

$$mg_{box} = 0.05 + .85\left(\frac{N_L}{N_b}\right) + \frac{0.425}{N_L} \qquad \text{(Q5)}$$

limited to

$$0.5 \le \frac{N_L}{N_b} \le 1.5$$

This approach could provide a unified and simple method for steel tub girders as well. Figure 7 and Figure 8 illustrate the correlation (with calibration) to the present AASHTO approach. The reason for calibration to the existing is the limited sample of bridges upon which to base a recalibration.

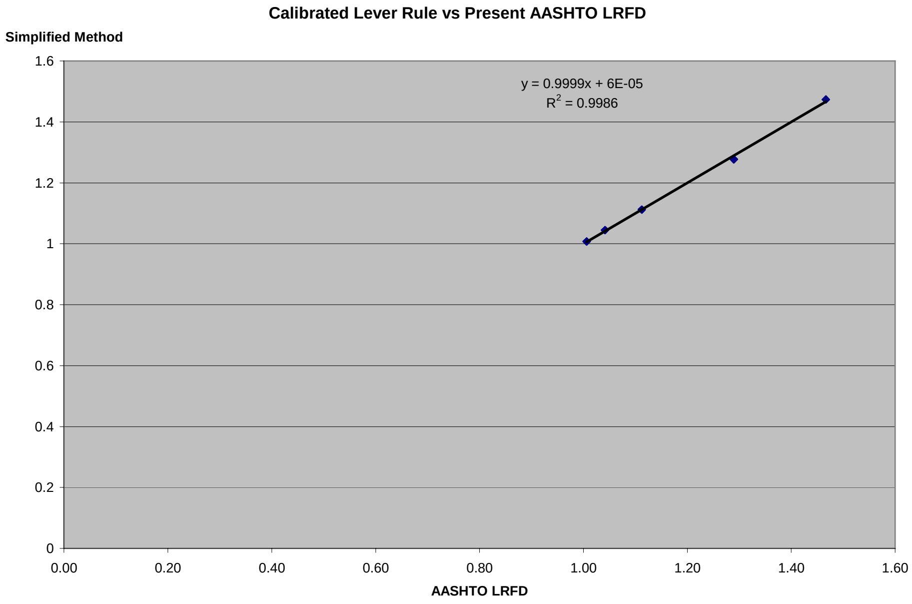


Figure 7. Calibrated Lever Rule (Simplified to Present AASHTO) (distribution to box)

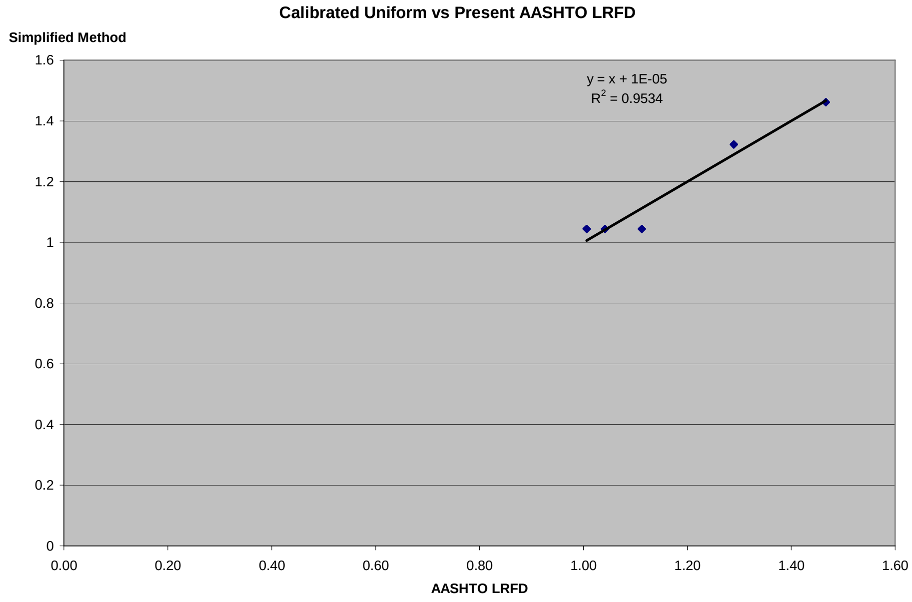


Figure 8. Calibrated Uniform Method (Simplified to Present AASHTO) (distribution to box)

Table 5. Summary

			Possible Simple Approaches						SAP 2000 Shell Analysis											
									Shear						Moment					
	Spacing (m)	N_L/N_b	Shear & Moment Interior & Exterior AASHTO 4.6.2 (to box) (2005)	Shear & Moment Interior & Exterior AASHTO 4.6.2 (to web (2005)	Lever Rule (to web)	Calibrated Lever Rule (calibrated to LRFD 2005)	Calibrated Uniform (to beam)	Calibrated Uniform (to web)	Exterior			Interior			Exterior			Interior		
									1	2	3	1	2	3	1	2	3	1	2	3
3l-100-3b (wide) (via web) (Samaan)	2.100	1.333	1.29	0.64	0.56	0.50	1.32	0.66	0.46	0.64	0.65	0.28	0.53	0.55	0.23	0.32	0.37	0.24	0.34	0.38
3l-60-3b via web (Samaan)	2.100	1.333	1.29	0.64	0.56	0.50	1.32	0.66	0.47	0.65	0.65	0.37	0.42	0.46	0.18	0.37	0.40	0.14	0.30	0.39
2l-100-2b (to web) (Samaan)	2.325	1.000	1.11	0.56	0.61	0.56	1.04	0.52	0.68	0.63		0.43	0.54		0.34	0.52		0.32	0.52	
11L-103-6B (Georgia)	3.56	1.833	1.65	0.82	0.75	0.73	1.74	0.87	0.77	0.92	0.88	0.43	0.82	0.95	0.28	0.40	0.44	0.26	0.44	0.51
3L-66-3B (Tennessee)	2.74	1.333	1.29	0.64	0.67	0.63	1.32	0.66	0.58	0.77	0.75	0.42	0.60	0.62	0.29	0.41	0.45	0.50	0.76	0.83
4L-15-4B (Texas)	1.91	0.750	0.83	0.41	0.52	0.45	0.84	0.42	0.44	0.61	0.84	0.28	0.40	0.49	0.25	0.32	0.35	0.49	0.64	0.76
2L-50-2B (Illinois)	2.44	1.000	1.11	0.56	0.63	0.58	1.04	0.52	0.72	0.77		0.43	0.59		0.32	0.52		0.42	0.66	
4L-33-6B (Kansas)	1.91	0.667	0.72	0.36	0.52	0.45	0.77	0.38	0.34	0.47	0.50	0.30	0.42	0.45	0.22	0.28	0.29	0.19	0.26	0.27

Critical values between two- and three-lanes loaded are highlighted. $m_2 = 1.0$, $m_3 = 0.85$

Table 6. Summary Using Average of Exterior & Interior Webs

			Possible Simple Approaches						SAP 2000 Shell Analysis (with multiple presence)					
									Shear			Moment		
	Spacing (m)	N_L/N_b	Shear & Moment Interior & Exterior AASHTO 4.6.2 (to box) (2005)	Shear & Moment Interior & Exterior AASHTO 4.6.2 (to web (2005)	Lever Rule (to web)	Calibrated Lever Rule (calibrated to LRFD 2005)	Calibrated Uniform (to beam)	Calibrated Uniform (to web)	Average (Exterior & Interior)			Average (Exterior & Interior)		
									1	2	3	1	2	3
3l-100-3b (wide) (via web) (Samaan)	2.100	1.333	1.29	0.64	0.56	0.50	1.32	0.66	0.37	0.59	0.60	0.23	0.33	0.38
3l-60-3b via web (Samaan)	2.100	1.333	1.29	0.64	0.56	0.50	1.32	0.66	0.42	0.54	0.56	0.16	0.34	0.39
2l-100-2b (to web) (Samaan)	2.325	1.000	1.11	0.56	0.61	0.56	1.04	0.52	0.56	0.59		0.33	0.52	
11L-103-6B (Georgia)	3.56	1.833	1.65	0.82	0.75	0.73	1.74	0.87	0.60	0.87	0.92	0.27	0.42	0.48
3L-66-3B (Tennessee)	2.74	1.333	1.29	0.64	0.67	0.63	1.32	0.66	0.50	0.69	0.68	0.40	0.59	0.64
4L-15-4B (Texas)	1.91	0.750	0.83	0.41	0.52	0.45	0.84	0.42	0.36	0.51	0.67	0.37	0.48	0.55
2L-50-2B (Illinois)	2.44	1.000	1.11	0.56	0.63	0.58	1.04	0.52	0.58	0.68		0.37	0.59	
4L-33-6B (Kansas)	1.91	0.667	0.72	0.36	0.52	0.45	0.77	0.38	0.32	0.45	0.48	0.20	0.27	0.28

A summary is presented in Table 5 for exterior and interior webs. The exterior and interior web (box) results are averaged in Table 6. It was hoped that the results might improve and compare better with the present AASHTO method. Clearly the results vary with few trends. Some miscellaneous observations are:

1. For longer spans the results for the interior and exterior web are similar and the load distributes more uniformly. For short spans, the longitudinal direction is stiffer and the load is more concentrated and differs between the webs.
2. The Georgia bridge exceeds the present limit of application on NL/NB of 1.5.
3. The box size for the Georgia bridge is 11.67 ft (3.56 m) and the shear distributions are approximately one lane per web. However, the distribution factor for moment is approximately 0.6.
4. The Tennessee bridge has a spacing of 9 ft and a shear distribution of 0.88 and 0.73 lanes per web for exterior and interior, respectively. But the span length of 216 ft is shorter than that of the Georgia bridge (328 ft) and the distribution was 0.98 for the interior web.
5. The Samaan et al bridges behave in a similar manner with spans ranging between 60 and 100 m (197 and 328, ft) and spacing between 2.1 and 2.325 m (6.9 and 7.6, ft). The overall depths were 4 m (13 ft). The bridges have lower span-to-depth ratio than the DOT bridges.
6. The Texas bridge is a relatively short span for a steel box girder bridge with a span of 15m (49 ft) and the distribution factors to the web were 0.99 and 0.89. The differences between the interior and exterior web were significant.
7. The lever rule works reasonably well for shear distribution factors.

Note that these results do not trend well within this limited sample, nor illustrate a truly simple approach for steel tub-girder bridges. The structural analysis models have been checked to determine if any systematic problems exist. Similar results are obtained with direct comparison of stresses reasonably compare with SAP integrated methods. It may be that this sample has a couple odd bridges, e.g., Georgia bridge with the wide beam spacing and width and the Texas bridge with the short span.

Skew and curvature further complicate the distribution of dead and live loads, required cross frame forces, etc.

Analysis

Considering the limitations illustrated within the present study, several options for moment exist:

1. Cast the tub-girder method in the form of the proposed, i.e., calibrated uniform and lever rules. This will yield the results the same as the present methods.
2. Use the present LRFD method.
3. Adopt either no. 1 or no. 2 and recommend rigorous analysis for this bridge type.
4. Based upon judgment, use the approach for steel I girders. (I girder section is not as torsionally stiff)

5. Require rigorous analysis.

Options for shear include:

1. Use the present LRFD method.
2. Use lever rule.

For option no. 1, the affine transformation coefficients are provided in Table 7 (calibrated to the present LRFD method, Eq. 5 divided by two.

Table 7. Calibration Constants

Shear and Moment	Lever Rule Method	Uniform Method
$a_{(v\ or\ m)}$	1.24	0.84
$b_{(v\ or\ m)}$	-0.20	0.21

Lever rule is computed in the usual manner. Uniform method is computed using the maximum number of lanes loaded divided by the number of beams. The minimum multiple presence factor is $m = 0.85$. Because of simplicity and consistency with the other bridge types, the calibrated lever rule is recommended for shear and one-lane loaded for moment; the uniform method is recommended for the multiple-lanes loaded. These coefficients are for distribution to the girder webs (not entire box). Double for distribution to the box. This can be written either way in the specification language (box or web).

Recommendation

The recommendation is to use the present AASHTO method without further the simplification, use Eq. 5. A recast within the new method could lead the user to think that there was a significant finding in support of the change. This is not the case. If the AASHTO Subcommittee wants to unify the procedure, and then it should reference the possible deficiencies within the commentary. Without changing (or recasting), the present method stands on the basis of the previous work in this area. The lever rule could be used for shear distribution.

Summary

The bridges modeled were a challenging group with widely varying geometry, but typical of US construction. The steel tub-girder work was performed without providing a trustworthy finding regarding simplification. (At least nothing nearly as complete and statistically reliable as the other bridge types.) This bridge type presents small portion of present designs, and in many cases, these bridges are curved and should require a rigorous analysis for dead as well as live loads. In short, the goals of this project are not significantly compromised by this result in the overall scope.