Appendix E. Executive Summary of Study Bridges

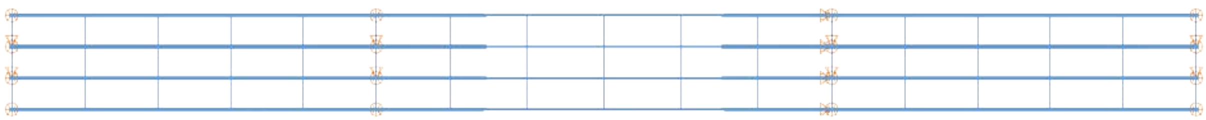
This appendix provides an executive summary of the bridges that are studied in the NCHRP 12-79 research. The bridges are presented in alphabetical and numerical order within the following bridge categories:

(1) ICSN: I-girder, Continuous-span, Straight, No-skew,
(2) ISSS: I-girder, Simple-span, Straight, Skewed supports,
(3) ICSS: I-girder, Continuous-span, Straight, Skewed supports,
(4) ISCR: I-girder, Simple-span, Curved, Radial supports,
(5) ICCR: I-girder, Continuous-span, Curved, Radial supports,
(6) ISCS: I-girder, Simple-span, Curved, Skewed supports,
(7) ICCS: I-girder, Continuous-span, Curved, Skewed supports,
(8) TCSN: Tub-girder, Continuous-span, Straight, No-skew,
(9) TSSS: Tub-girder, Simple-span, Straight, Skewed supports,
(10) TSCR: Tub-girder, Simple-span, Curved, Radial supports,
(11) TCCR: Tub-girder, Continuous-span, Curved, Radial supports,
(12) TSCS: Tub-girder, Simple-span, Curved, Skewed supports,
(13) TCCS: Tub-girder, Continuous-span, Curved, Skewed supports.

The basic geometry information, key indices, and a summary of important observations are provided for each bridge. For the Existing bridges (indicated by an "E" in front of the above designations), the location information and key information about the physical structure are listed. For the eXample bridges, designated by an "X" in front of the above designations, the reference citation for the example calculations is provided.

(E1) ICSN (I-girder, Continuous-span, Straight, No skew)

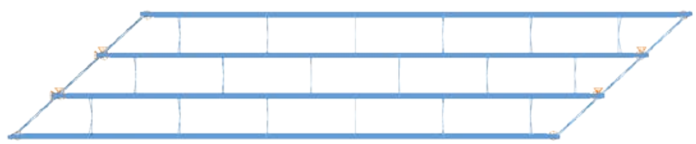
E1.1 XICSN1 (L_1 = 140 ft, L_2 = 175 ft, L_3 = 140 ft / w = 43 ft, 4 girders)



- Reference: (Eaton, et al. 1997).
- I_{S1} = 0, I_{S2} = 0, I_{S3} = 0 / I_{L1} = 1.0, I_{L2} = 1.0, I_{L3} = 1.0 / I_{T1} = 0.5, I_{T2} = 0.5, I_{T3} = 0.5
- Differences in the fascia and interior girder responses due to different applied loadings.

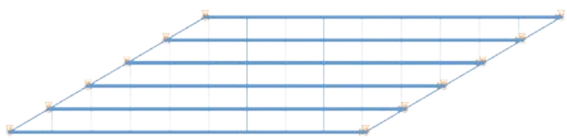
(E2) ISSS (I-girder, Simple-span, Straight, Skewed supports)

E2.1 EISSS3 (L_1 = 133 ft / w = 30.1 ft / θ_1 = -46.2°, θ_2 = -46.2° / 4 girders)



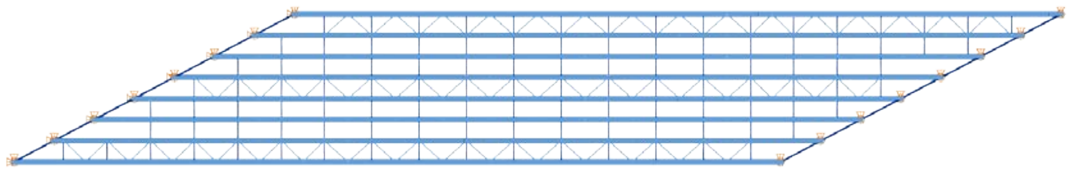
- Bridge on SR 1003 (Chicken Road) over US 74 between SR 1155 & SR 1161, Robeson Co., NC
- Undesirable girder layover and bowing of the girder webs occurred during construction.
- $I_{S1} = 0.24$, $I_{L1} = 1.0$, $I_{T1} = 0.50$
- Significant second-order amplification due to the absence of the top chord in the interior V-type cross-frames.
- Neither the 1D line girder nor the 2D-grid analysis captures the second-order amplification.
- Failure due to lateral torsional buckling of the interior girder occurs at 1.2 times the total dead load (TDL).

E2.2 EISSS5 (L_1 = 123 ft / w = 43.8 ft /θ_1 = -59.7°, θ_2 = -59.7° / 5 girders)



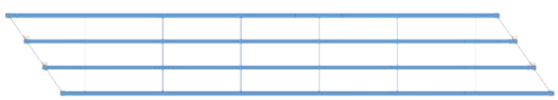
- SR 0581 Section A01, Cumberland Co., PA
- One unit of a phased construction project. Difficulty was encountered with the concrete cover during the deck replacement.
- $I_{S1} = 0.54$, $I_{L1} = 1.0$, $I_{T1} = 0.50$
- The approximate analysis methods accurately capture the responses of the bridge during the steel erection.
- At the total dead load (TDL) level, the bridge experiences second-order amplification that is not captured by the 1D and 2D models. This nonlinear behavior is associated with the limited bracing provided by the V-type cross-frame without top chords.

E2.3 EISSS6 (L_1 = 267 ft / w = 58 ft /θ_1 = -62.3°, θ_2 = -62.3°, 8 girders)



- I-87 / I-287, Westchester Co., NY
- Successful implementation of TDLF detailing. The steel dead load deflections were used to alleviate fit-up problems during the steel erection.
- I_{S1} = 0.43, I_{L1} = 1.0, I_{T1} = 0.50
- Importance of erection sequence for the methods of detailing.
- Estimation of the required layovers during construction.
- Influence of methods of detailing on girder responses and cross-frame forces.

E2.4 NISSS2 (L_1 = 150 ft / w = 30 ft /θ_1 = 35°, θ_2 = 35°, 4 girders)

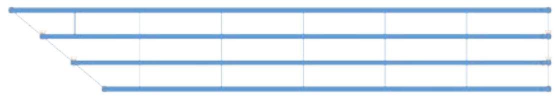


- I_{S1} = 0.11, I_{L1} = 1.0, I_{T1} = 0.50
- The influence of the skew is minor on the behavior of this structure (I_S < 0.30). The girder responses are accurately predicted by1D line girder and the 2D-grid analyses for the different erection stages.
- Minor variation in the flange lateral bending stresses between cross-frames due to second-order effects.

E2.5 NISSS4 (L_1 = 150 ft / w = 30 ft /θ_1 = 70°, θ_2 = 70°, 4 girders)

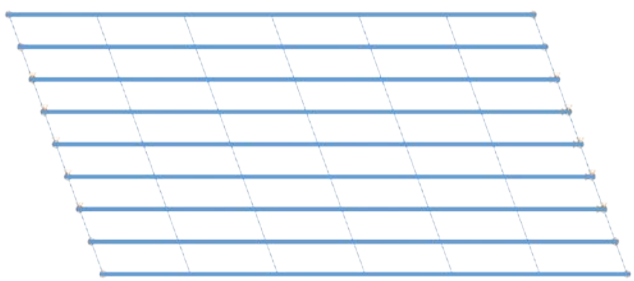
- I_{S1} = 0.44, I_{L1} = 1.0, I_{T1} = 0.50
- Slight variation in the vertical displacement and girder major-axis bending stress predictions of by1D line girder and the 2D-grid analyses, since I_S is approaching 0.65.
- Significant flange lateral bending due to small offset distance of the first intermediate cross-frame from the skewed bearing

E2.6 NISSS6 (L_1 = 150 ft / w = 30 ft /θ_1 = 50^o, θ_2 = 0^o / 4 girders)



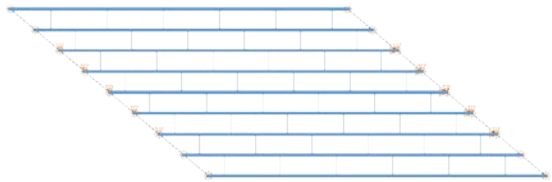
- I_{S1} = 0.19, I_{L1} = 1.21, I_{T1} = 0.53
- The influence of the skew is minor on the behavior of this structure. The girder responses are accurately predicted by the approximate methods for the different erection stages.

E2.7 NISSS11 (L_1 = 150 ft / w = 80 ft /θ_1 = 20^o, θ_2 = 20^o / 9 girders)



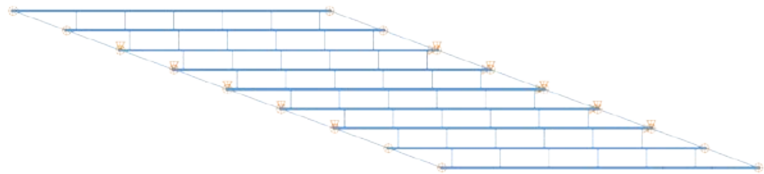
- I_{S1} = 0.18, I_{L1} = 1.0, I_{T1} = 0.50
- Due to the relatively simple geometry of this bridge, its behavior is accurately captured by the approximate methods of analysis.
- The use of inclined cross-frames helps reduce the flange lateral bending stresses to a negligible level.

E2.8 NISSS13 (L_1 = 150 ft / w = 80 ft /θ_1 = 50^o, θ_2 = 50^o, 9 girders)



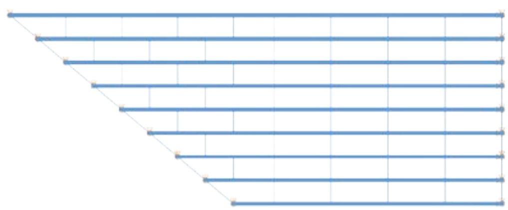
- I_{S1} = 0.60, I_{L1} = 1.0, I_{T1} = 0.50
- Girder responses are accurately predicted by the approximate methods.

E2.9 NISSS14 (L_1 = 150 ft / w = 80 ft /θ_1 = 70°, θ_2 = 70° / 9 girders)



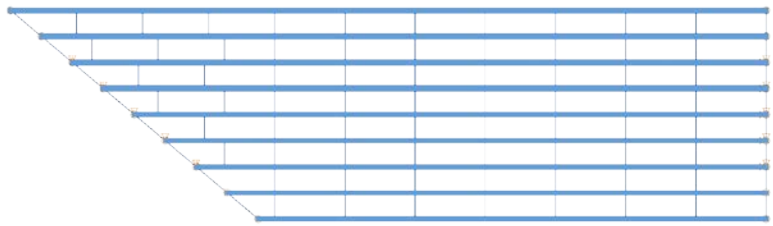
- I_{S1} = 1.36, I_{L1} = 1.0, I_{T1} = 0.50
- The skew effects are particularly important in this bridge. Very large cross-frame forces and levels of flange lateral bending stress are observed at the TDL level.
- Similarly, the skew effects have a considerable participation on the system response during the steel erection.
- The 1D and 2D analyses do not adequately predict the behavior of the bridge both during the steel erection and during the placement of the deck.

E2.10 NISSS16 (L_1 = 150 ft / w = 80 ft /θ_1 = 50°, θ_2 = 0° / 9 girders)



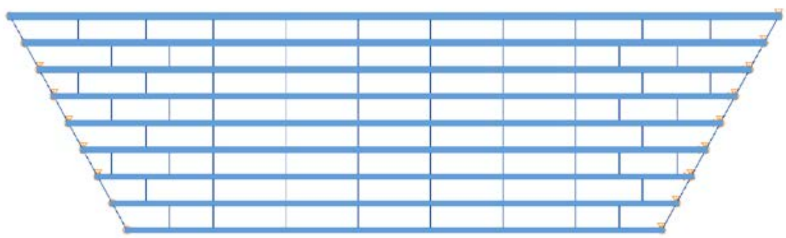
- I_{S1} = 0.59, I_{L1} = 1.83, I_{T1} = 0.58
- The use of staggered cross-frames relaxes the "nuisance stiffness" problem, but results in considerable levels of flange lateral bending stresses.
- At the TDL level, the cross-frame element forces are between 64 kips in compression and 153 kips in tension. Due to these large forces, the dimensions of the cross-frames and their connections can become impractical.

E2.11 NISSS36 (L_1 = 225 ft / w = 80 ft /θ_1 = 50°, θ_2 = 0°, 9 girders)



- I_{S1} = 0.40, I_{L1} = 1.49, I_{T1} = 0.55
- Significant flange lateral bending stresses at the girder ends since intermediate cross-frames enforce the same layovers between adjacent girders at the cross-frame locations.
- Illustration of the coupling between major-axis bending rotations and torsional rotations at the skewed bearings.

E2.12 NISSS37 (L_1 = 225 ft / w = 80 ft /θ_1 = 28.6°, θ_2 = -28.6°, 9 girders)

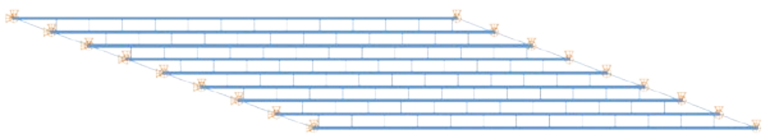


- I_{S1} = 0.18, I_{L1} = 1.44, I_{T1} = 0.54
- The influence of the skew is minor on the behavior of this structure (I_S < 0.30). The girder responses are accurately predicted by1D line girder and the 2D-grid analyses for the different erection stages.
- Illustration of the coupling between major-axis bending rotations and torsional rotations at the skewed bearings.

E2.13 NISSS53 (L_1 = 300 ft / w = 80 ft /θ_1 = 50°, θ_2 = 50°, 9 girders)

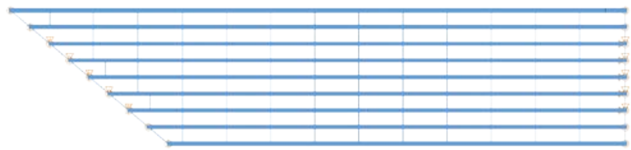
- I_{S1} = 0.29, I_{L1} = 1.0, I_{T1} = 0.50
- The influence of the skew is minor on the behavior of this structure (I_S < 0.30). The girder responses are accurately predicted by1D line girder and the 2D-grid analyses for the different erection stages.
- Illustration of the coupling between major-axis bending rotations and torsional rotations at the skewed bearings.
- Significant second-order amplification in the global flange lateral bending stresses since flange-level lateral bracing is not provided.

E2.14 NISSS54 (L_1 = 300 ft / w = 80 ft /θ_1 = 70°, θ_2 = 70° / 9 girders)



- I_{S1} = 0.68, I_{L1} = 1.0, I_{T1} = 0.50
- In this bridge, the flange lateral bending stress levels reach very high values (e.g., 65 ksi) at the TDL loading level.
- Similarly, the forces in the cross-frames are in the order of 324 kips in compression and 467 kips in tension.
- The approximate analysis methods are not able to properly predict the behavior of the structure either during the steel erection or in the completed configuration.

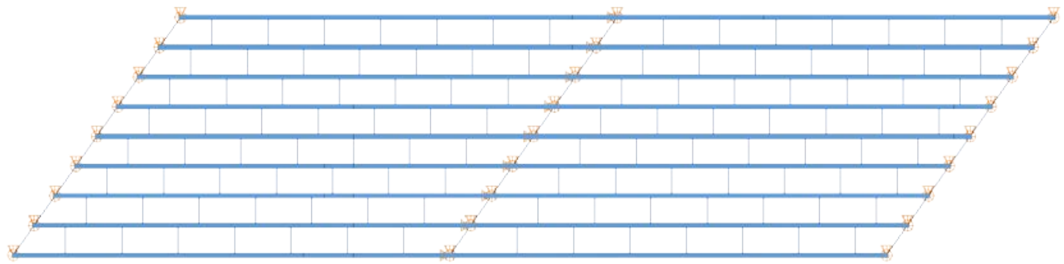
E2.15 NISSS56 (L_1 = 300 ft / w = 80 ft /θ_1 = 50°, θ_2 = 0° / 9 girders)



- I_{S1} = 0.30, I_{L1} = 1.34, I_{T1} = 0.53
- The girder responses throughout the construction process are properly captured for this bridge by the 1D and 2D methods of analysis. However, the forces in some of the cross-frames are considerable large (above 100 kips) at the TDL level. These forces cannot be predicted by the approximate methods.

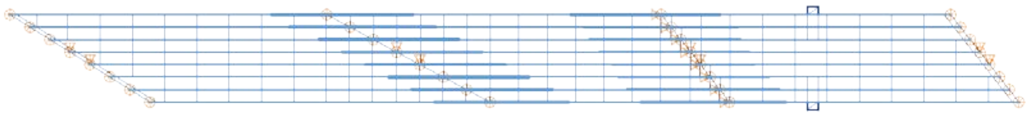
(E3) ICSS (I-girder, Continuous-span, Straight, Skewed supports)

E3.1 EICSS1 (*L_1* = 160 ft, *L_2* = 160 ft / *w* = 95.2 ft / θ = -35.2º (all bearing lines), 9 girders)



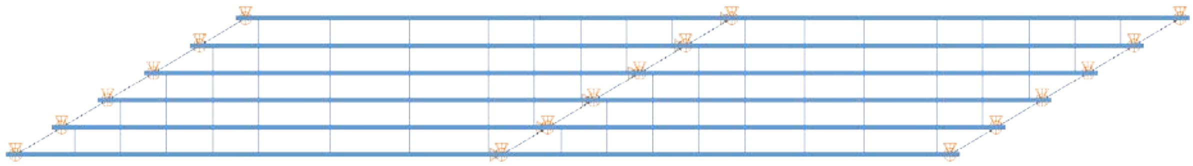
- Steel Overpass, Sunnyside Road I.C. (I-15B) over I-15, Bonneville Co., ID
- Successful implementation of total dead load fit detailing.
- I_{S1} = 0.42, I_{S2} = 0.42 / I_{L1} = 1.0, I_{L2} = 1.0 / I_{T1} = 0.50, I_{T2} = 0.50
- Comparison of the results associated with the staged deck placement.
- Differences in the girder stresses and vertical displacements of 3D-FEA solutions due to staged deck placement.
- Influence of cross-frame detailing methods on the girder responses

E3.2 EICSS2 (*L_1* = 239 ft, *L_2* = 257 ft, *L_3* = 220 ft / *w* = 74.3 ft / θ_1 = 58º, θ_2 = 61.8º, θ_3 = 38º, θ_4 = 38º, 8 girders)



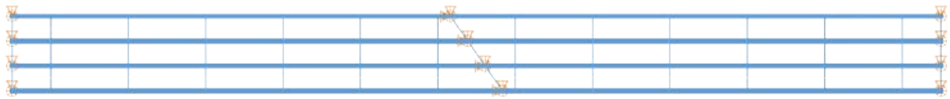
- I-235 EB over E. University Ave., Polk Co., IA
- Difficulty installing cross-frames during erection.
- I_{S1} = 0.50, I_{S2} = 0.46, I_{S3} = 0.26 / I_{L1} = 1.0, I_{L2} = 1.35, I_{L3} = 1.0 / I_{T1} = 0.48, I_{T2} = 0.55, I_{T3} = 0.50.
- Tracking nuisance stiffness issues.
- Large cross-frame forces along stiff transverse load paths.
- Overall deflection behavior due to the different cross-frame detailing methods.
- Influence of method of detailing on girder responses and cross-frame forces

E3.3 EICSS12 *(L_1 =150* ft, L_2 = 139 ft, w = 47 ft, θ = 59.6°, 6 girders lean-on cross-frame system)



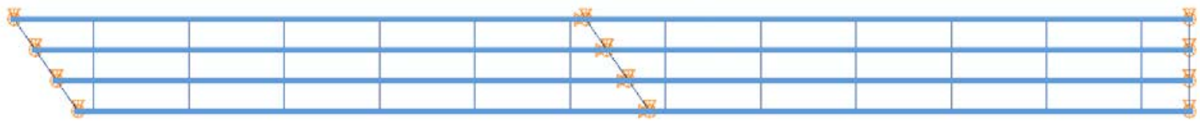
- US 82 Mainlane Underpass at 19th Street WB, Lubbock Co., TX
- Lean-on cross-frame system.
- I_{S1} = 0.53, I_{S2} = 0.58 / I_{L1} = 1.0, I_{L2} = 1.0 / I_{T1} = 0.50, I_{T2} = 0.50
- Girder responses are accurately predicted by1D line girder and the 2D-grid analyses.

E3.4 NICSS1 (L_1 = 150 ft, L_2 = 150 ft / w = 30 ft / θ_1 = 0°, θ_2 = 35°, θ_3 = 0° / 9 girders)



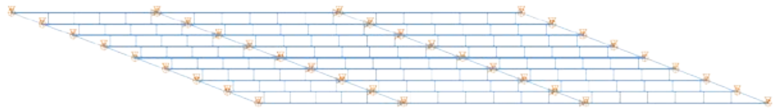
- I_{S1} = 0.11, I_{S2} = 0.11 / I_{L1} = 1.25, I_{L2} = 1.25 / I_{T1} = 0.48, I_{T2} = 0.52
- The 1D and 2D models accurately represent the behavior of this structure. The girder responses are captured properly for all the erection stages and in the final configuration.

E3.5 NICSS3 *(L_1* = 150 ft, L_2 = 150 ft / w = 30 ft /θ_1 = 35°, θ_2 = 35°, θ_3 = 0°, 4 girders)



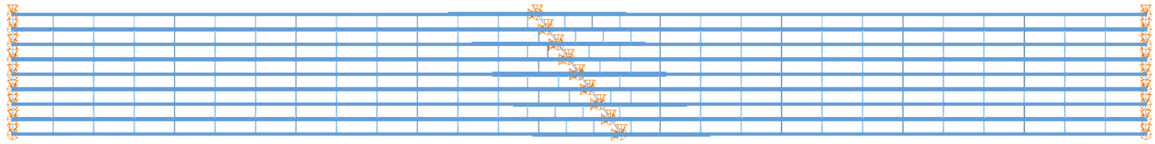
- I_{S1} = 0.11, I_{S2} = 0.11 / I_{L1} = 1.0, I_{L2} = 1.25 / I_{T1} = 0.50, I_{T2} = 0.52
- Uplift during erection Stages 1 and 3 at the piers.
- The influence of the skew is minor on the behavior of this structure (I_S < 0.30). The girder responses are accurately predicted by1D line girder and the 2D-grid analyses for the different erection stages.

E3.6 NICSS16 (L_1 = 350 ft, L_2 = 350 ft / w = 80 ft / $\theta_1 = 0^o$, $\theta_2 = 35^o$, $\theta_3 = 0^o$/ 4 girders)



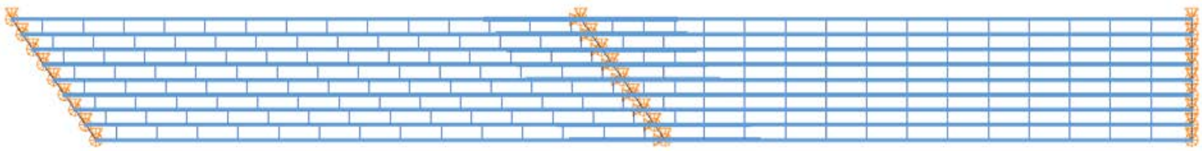
- I_{S1} = 1.69, I_{S2} = 1.36, I_{S3} = 1.36 / I_{L1} = 1.0, I_{L2} = 1.0, I_{L3} = 1.0 / I_{T1} = 0.50, I_{T2} = 0.50, I_{T3} = 0.50
- The cross-frame forces in this structure reach values that are between 62 kips in compression and 74 kips in tension at the TDL level.
- The flange lateral bending stresses reach values of 25 kips at the same load level.
- The approximate analysis methods are not able to properly predict the behavior of the structure neither during the steel erection nor in the completed configuration.

E3.7 NICSS25 (L_1 = 350 ft, L_2 = 350 ft / w = 80 ft / $\theta_1 = 0^o$, $\theta_2 = 35^o$, $\theta_3 = 0^o$/ 4 girders)



- I_{S1} = 0.15, I_{S2} = 0.15 / I_{L1} = 1.16, I_{L2} = 1.16 / I_{T1} = 0.48, I_{T2} = 0.52
- The major-axis bending responses in the girders are accurately captured by the approximate models. However, near the middle support, there are large forces in the cross-frames, in the order of 120 kips, that cannot be captured by the 1D and 2D models.

E3.8 NICSS27 (L_1 = 350 ft, L_2 = 350 ft / w = 80 ft /$\theta_1 = 35^o$, $\theta_2 = 35^o$, $\theta_3 = 0^o$, 9 girders)



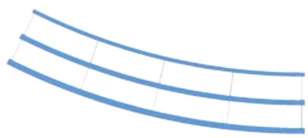
- I_{S1} = 0.15, I_{S2} = 0.15 / I_{L1} = 1.0, I_{L2} = 1.16 / I_{T1} = 0.50, I_{T2} = 0.52
- Influence of large span lengths on girder responses.
- Significant second-order amplification of the global flange lateral bending stresses since flange-level lateral bracing is not provided.

E3.9 XICSS5 (L_1 = 140 ft, L_2 = 175 ft, L_3 = 145 ft / w = 43 ft / θ_1 = -60 °, θ_2 = -60 °, θ_3 = -60 ° / 4 girders)

- I_{S1} = 0.53, I_{S2} = 0.43, I_{S3} = 0.53 / I_{L1} = 1.0, I_{L2} = 1.0, I_{L3} = 1.0 / I_{T1} = 0.50, I_{T2} = 0.50, I_{T3} = 0.50
- The effects of the skew in this bridge are moderate. The cross-frame forces are around 45 kips, and the flange lateral bending stresses are in the order of 4 ksi.
- The approximate analysis methods capture the response of the structure as predicted by the 3D FEA.

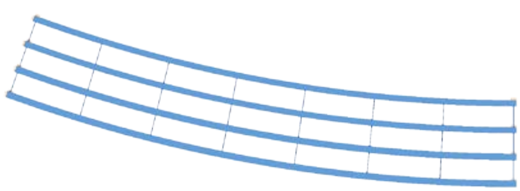
(E4) ISCR (I-girder, Simple-span, Curved, Radial supports)

E4.1 EISCR1 (L_1 = 90 ft / R = 200 ft / w = 23.5 ft / 3 girders)



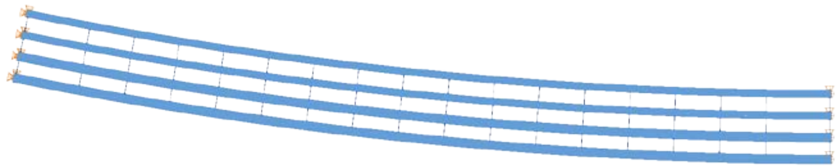
- FHWA Test Bridge.
- Bridge designed to a number of limits of the AASHTO LRFD Specifications. Extensive test date available (Jung, 2006; Jung and White, 2008).
- $I_{S1} = 0$, $I_{L1} = 1.09$, $I_{T1} = 0.71$, $I_{C1} = 18.8$
- The influence of the poor torsion model implemented in the 2D-grid analysis is notorious in this bridge when more than one element is used to model the girders between the cross-frames. The grid model over estimates the vertical deflections during the steel erection and when the structure is completed.
- The 1D line girder analysis based on the V-load method provides a good estimate of the girder responses.

E4.2 NISCR2 *(L_1 = 150 ft/ R_1 = 438 ft / w = 30 ft, 4 girders)*



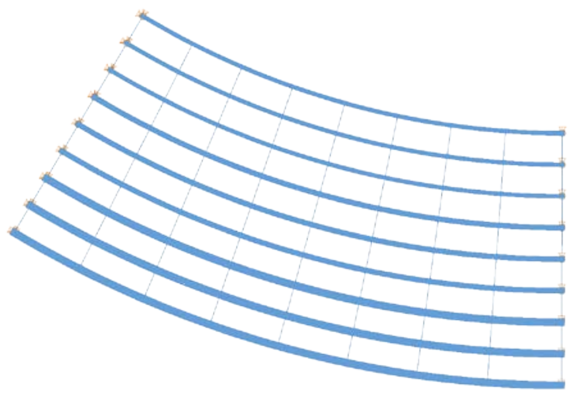
- $I_{S1} = 0$, $I_{L1} = 1.06$, $I_{T1} = 0.69$, $I_{C1} = 4.89$
- Illustration of the coupling between major-axis bending and torsional rotations due to curvature effects.
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames.
- Nonlinearity in the flange lateral bending stresses due global flange lateral bending effects.

E4.3 NISCR5 (L_1 = 300 ft/ R_1 = 1530 ft / w = 30 ft, 4 girders)



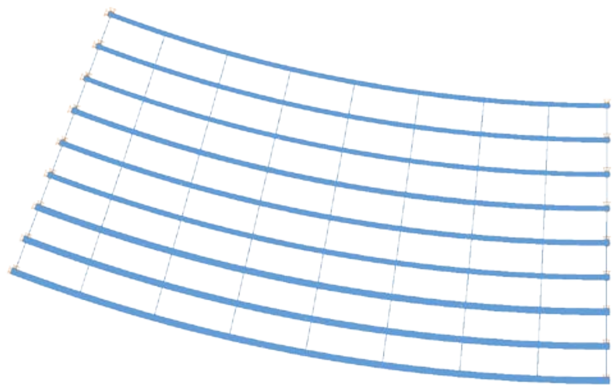
- $I_{S1} = 0$, $I_{L1} = 1.02$, $I_{T1} = 0.71$, $I_{C1} = 0.58$
- Importance of using temporary supports during construction.
- Poor prediction of the layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Second-order amplification of the flange lateral bending stresses due global flange lateral bending effects since the bridge has large length-to-width ratio.

E4.4 NISCR7 (L_1 = 150 ft / R = 280 ft / w = 80 ft / 9 girders)



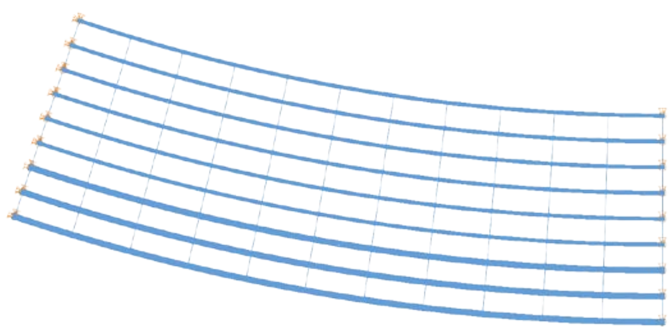
- $I_{S1} = 0$, $I_{L1} = 1.30$, $I_{T1} = 0.62$, $I_{C1} = 6.70$
- The torsion model that neglects the warping contributions used in the 2D analysis results in a significant mis-prediction of the girder responses. Due to this limitation, the vertical displacements and girder layovers are not accurately captured by the 2D model.
- Since this structure satisfies the assumptions used in the formulation of the V-load method, the simplified line girder analysis is able to predict the bridge behavior as described by the 3D model.

E4.5 NISCR8 (L_1 = 150 ft / R = 420 ft / w = 80 ft / 9 girders)



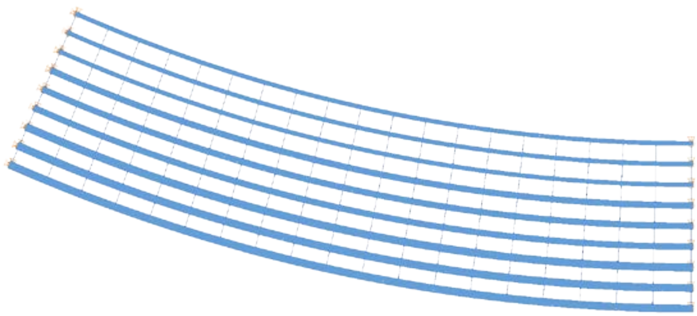
- $I_{S1} = 0$, $I_{L1} = 1.19$, $I_{T1} = 0.58$, $I_{C1} = 4.46$
- The bridge behavior is misrepresented by the 2D model. The line girder analysis yields better result predictions than the grid model.
- The lack of a term that represents the flange warping contributions to the girder torsion stiffness has a very important influence in the response prediction of this structure.

E4.6 NISCR10 (L_1 = 225 ft / R = 705 ft / w = 80 ft / 9 girders)



- $I_{S1} = 0$, $I_{L1} = 1.11$, $I_{T1} = 0.59$, $I_{C1} = 1.93$
- The effects of the curvature are not accurately captured by the 2D model. There is a significant over prediction of the vertical displacements and the girder layovers.
- The 1D model is a closer representation of the structure's behavior. The major-axis bending responses are properly predicted by the model based on the V-load method. Similarly, the flange lateral bending stress responses are well predicted by this analysis method.

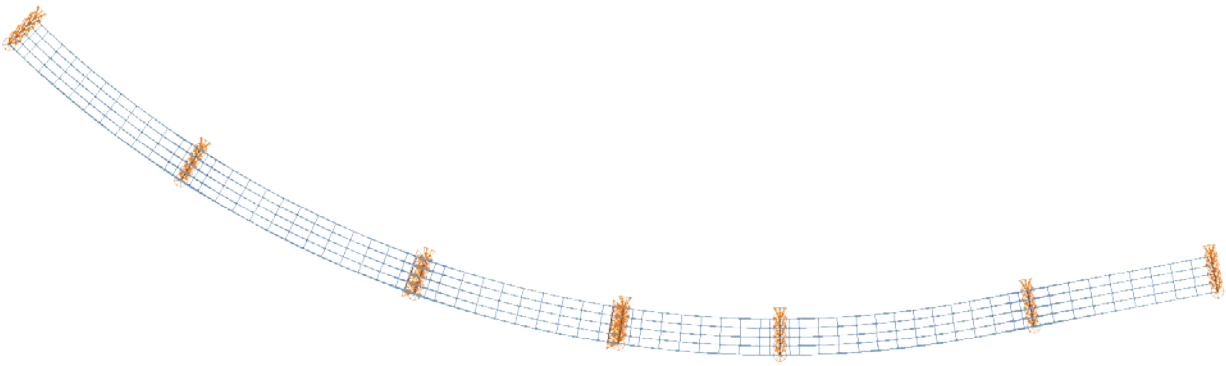
E4.7 NISCR11 (L_1 = 300 ft/ R_1 = 730 ft / w = 80 ft, 9 girders)



- $I_{S1} = 0$, $I_{L1} = 1.11$, $I_{T1} = 0.65$, $I_{C1} = 1.08$
- Illustration of the coupling between major-axis bending and torsional rotations due to curvature effects.
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Poor prediction accuracy in the flange lateral bending stresses due global nonlinear effects since flange-level lateral bracing is not provided.

(E5) ICCR (I-girder, Continuous-span, Curved, Radial supports)

E5.1 EICCR4 (L_1 = 219 ft, L_2 = 260 ft, L_3 = 211 ft, L_4 = 162 ft, L_5 = 256 ft, L_6 = 190 ft / R_1 = 968 ft, $R_{2,3,4}$ =1108 ft, R_5 =968 ft, ∞ , R_6 = ∞ / w = 44 ft, 5 girders)

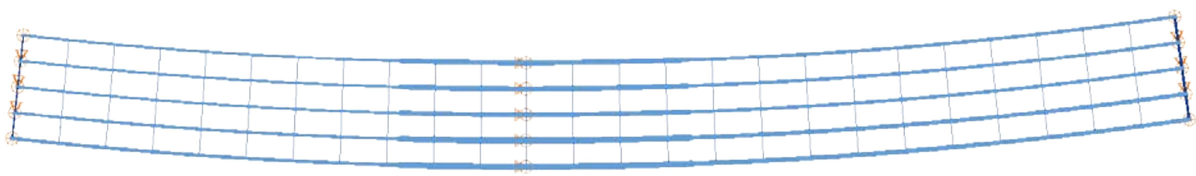


- Ramp GG John F. Kennedy Memorial Highway, I-95 Express Toll Lanes and I-695 Interchange, Baltimore Co., MD
- Relatively long spans and narrow deck. Successful implementation of SDLF detailing.
- I_{S1} = 0, I_{S2} = 0, I_{S3} = 0, I_{S4} = 0, I_{S5} = 0, I_{S6} = 0 / I_{L1} = 1.09, I_{L2} = 1.07, I_{L3} = 1.07, I_{L4} = 1.07, I_{L5} = 1.09, I_{L6} = 1.0 / I_{T1} = 0.61, I_{T2} = 0.64, I_{T3} = 0.59, I_{T4} = 0.56, I_{T5} = 0.64, I_{T6} = 0.50 / I_{C1} = 0.60, I_{C2} = 0.45, I_{C3} = 0.56, I_{C4} = 0.68, I_{C5} = 0.52, I_{C6} = 0
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Overestimation of the flange lateral bending stresses during erection.

E5.2 EICCR11 *(L_1 = 322 ft, L_2 = 417 ft, L_3 = 329 ft / $R_{1,2} = \infty$, R_3 = 511 ft / w = 48.3 ft, 4 girders)*

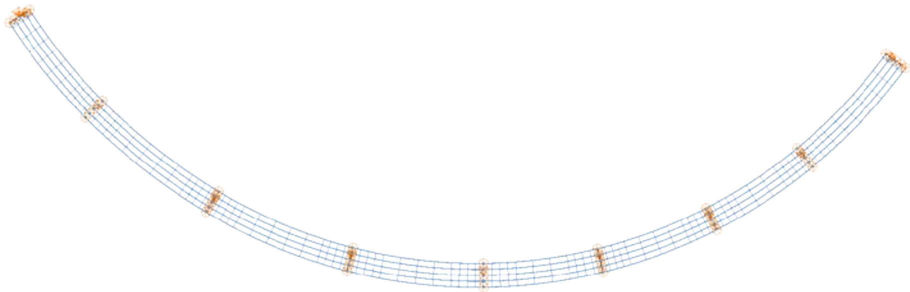
- Ford City Bridge, Ford City, PA
- Extreme geometry exacerbating fit-up during the steel erection. Studied extensively by Chavel and Earls (2006a & b; 2001).
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.0$, $I_{L2} = 1.0$, $I_{L3} = 1.17$ / $I_{T1} = 0.50$, $I_{T2} = 0.50$, $I_{T3} = 0.87$ / $I_{C3} = 0.67$
- Influence of flange lateral bracing system on girder responses
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames.
- Illustration of the overall deflected geometries associated with different types of cross-frame detailing.
- Influence of method of cross-frame detailing on girder responses.
- Influence of method of cross-frame detailing on cross-frame forces.
- Demonstration of the significant locked-in force effects due to DLF detailing.

E5.3 EICCR15 *(L_1 = 210 ft, L_2 = 271 ft / R = 1921 ft / w = 48.9 ft, 5 girders)*



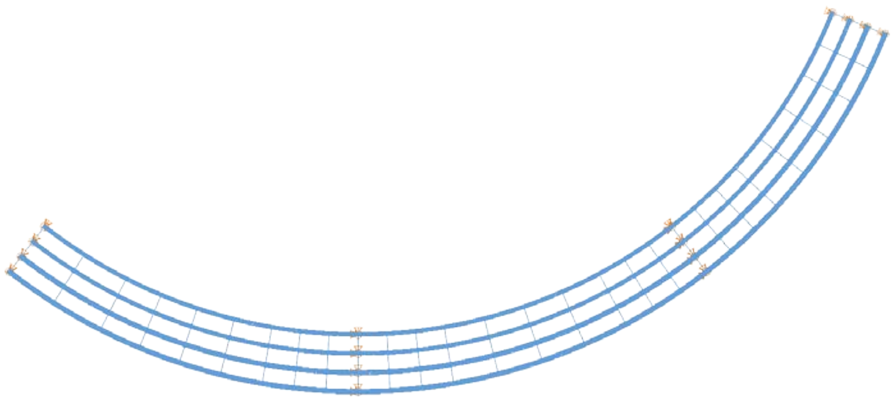
- SR 6220 A11 over SR 6220 NB & SB, Centre Co., PA
- Unbalanced spans. Documentation and field data provided in (Shura, 2004; Domalik, et al., 2005)
- $I_{S1} = 0$, $I_{S2} = 0$, / $I_{L1} = 1.05$, $I_{L2} = 1.05$ / $I_{T1} = 0.55$, $I_{T2} = 0.58$ / $I_{C1} = 0.35$, $I_{C2} = 0.28$
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Illustration of displacement interactions due to continuity effects in adjacent spans..

E5.4 EICCR22a (L_1 =172 ft, L_2 = 217 ft, L_3 = 217 ft, L_4 =195 ft, L_5 = 171 ft, L_6 = 172 ft, L_7 = 162 ft, L_8 = 192 ft / R_1 =791 ft, R_2 = 889 ft, $R_{3,4,5,6,7}$ = 746 ft, R_8 =766 ft (best fit to spiral curve) / w = 43 ft, 5 girders)



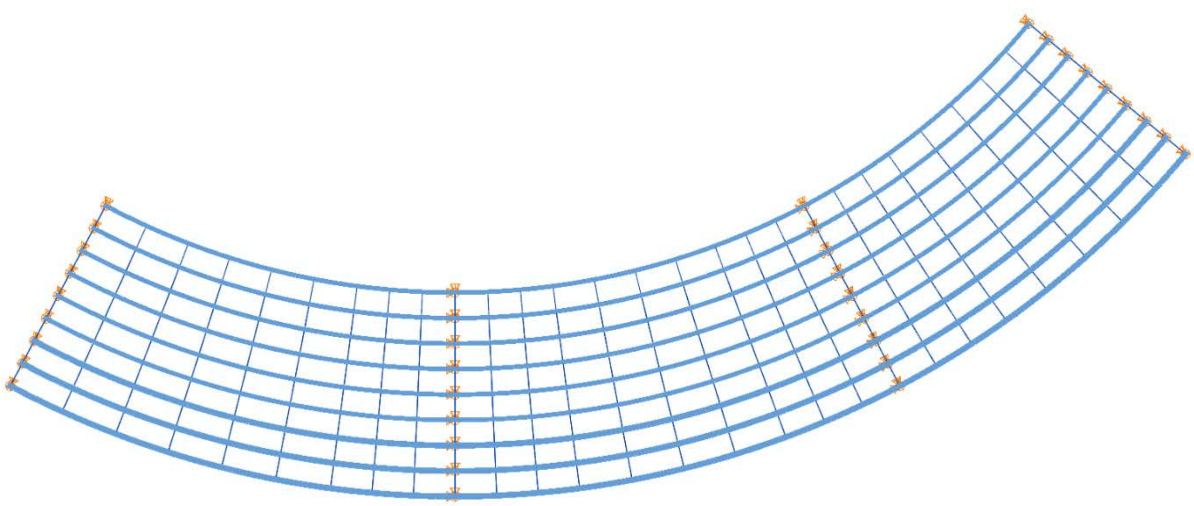
- Bridge No. 12, Ramp B over I-40, Robertson Avenue Project, Davidson Co., TN
- Successful implementation of NLF detailing. Extensive instrumentation placed on the girders prior to their erection. The bridge response was monitored throughout the steel erection, and he concrete deck placement. In addition, live load tests were conducted upon the completion of the bridge prior to opening to traffic. The field studies are documented in (Dykas, 2012).
- I_{S1} = 0, I_{S2} = 0, I_{S3} = 0, I_{S4} = 0, I_{S5} = 0, I_{S6} = 0, I_{S7} = 0, I_{S8} = 0 / I_{L1} = 1.11, I_{L2} = 1.09, I_{L3} = 1.11, I_{L4} = 1.11, I_{L5} = 1.11, I_{L6} = 1.11, I_{L7} = 1.11, I_{L8} = 1.11 / I_{T1} = 0.60, I_{T2} = 0.63, I_{T3} = 0.66, I_{T4} = 0.63, I_{T5} = 0.60, I_{T6} = 0.60, I_{T7} = 0.59, I_{T8} = 0.62 / I_{C1} = 0.95, I_{C2} = 0.65, I_{C3} = 0.77, I_{C4} = 0.84, I_{C5} = 0.91, I_{C6} = 0.84, I_{C7} =0.92, I_{C8} = 0.98
- Poor prediction of the vertical displacements and layovers by 2D-Grid analysis, when multiple elements are used between the cross-frame locations, due to poor torsional modeling of girders.

E5.5 NICCR1 (L_1=150 ft, L_2=150 ft, L_3=120 ft/ R=227 ft / w=30 ft / $\theta_1 = 0^o$, $\theta_2 = 0^o$, $\theta_3 = 0^o$, $\theta_4 = 0^o$/ 4 girders)



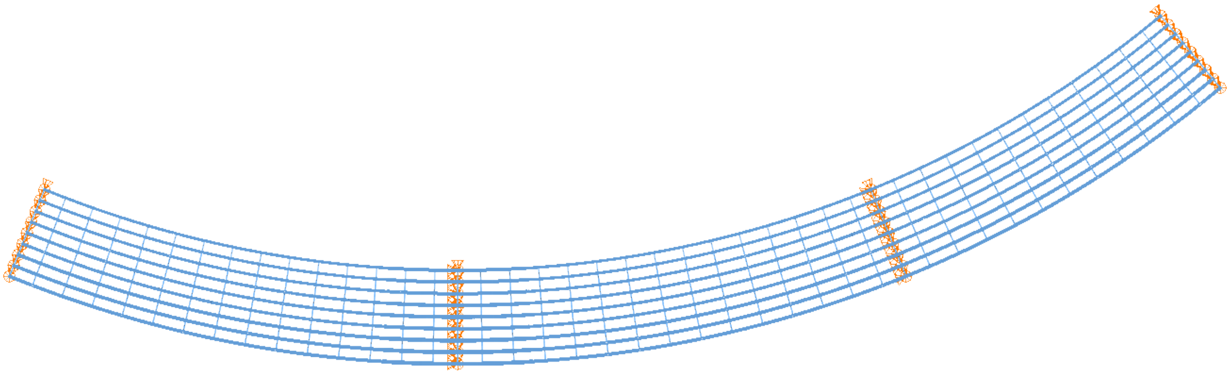
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.11$, $I_{L2} = 1.11$, $I_{L3} = 1.11$ / $I_{T1} = 0.87$, $I_{T2} = 0.87$, $I_{T3} = 0.74$ / $I_{C1} = 3.67$, $I_{C2} = 3.30$, $I_{C3} = 4.13$
- Except for the major-axis bending stresses, the girder responses are mis-predicted by the 2D-grid model. The poor representation of the torsion model has a large influence on the response prediction when more than one element is used to model the girders between the cross-frames..
- The 1D girder line model based on the V-load method yields accurate predictions of the system response.

E5.6 NICCR8 (L_1 = 150 ft, L_2 = 150 ft, L_3 = 120 ft / $R_{1,2,3}$ = 308 ft/ w = 80 ft, 9 girders)



- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.63$, $I_{L2} = 1.63$, $I_{L3} = 1.63$ / $I_{T1} = 0.61$, $I_{T2} = 0.61$, $I_{T3} = 0.58$ / $I_{C1} = 2.71$, $I_{C2} = 2.43$, $I_{C3} = 3.04$
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Tendency for uplift problems during erection due to severe horizontal curvature

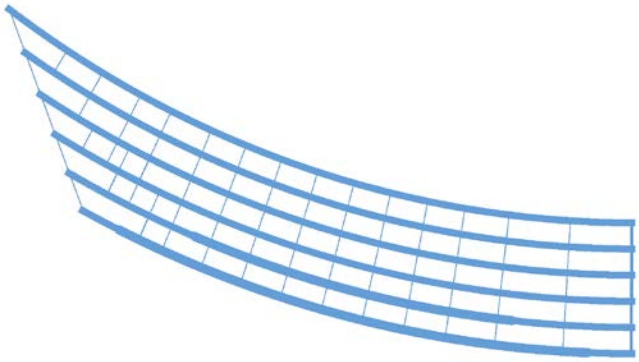
E5.7 NICCR12 (L_1=350 ft, L_2=350 ft, L_3=280 ft/ R=909 ft / w=80 ft / θ_1=0 ^{o}, θ_2=0 ^{o}, θ_3=0 ^{o}, θ_4=0 ^{o}/ 9 girders)



- I_{S1} = 0, I_{S2} = 0, I_{S3} = 0 / I_{L1} = 1.18, I_{L2} = 1.18, I_{L3} = 1.18 / I_{T1} = 0.66, I_{T2} = 0.66, I_{T3} = 0.61 / I_{C1} = 0.55, I_{C2} = 0.55, I_{C3} = 0.69
- The 1D and 2D approximate analysis methods yield results that are an accurate representation of the benchmark responses for the final configuration at the TDL level.
- The flange lateral bending stress responses predicted with the V-load formula are close to those predicted with the 3D FEA.

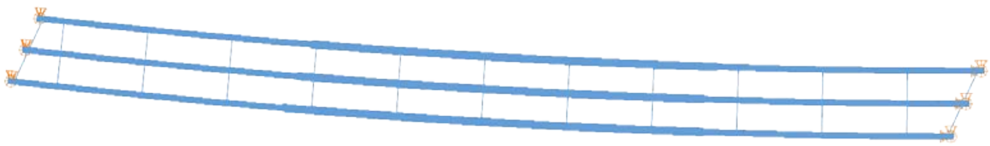
(E6) ISCS (I-girder, Simple-span, Curved, Skewed supports)

E6.1 EISCS3 (L_1 = 153 ft / R = 279 ft / w = 35.6 ft / $\theta = 52.4^o$ and 0, 6 girders)



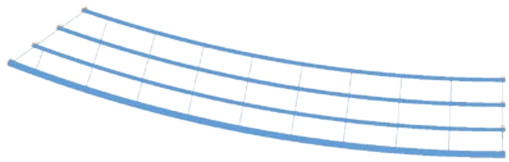
- SR 8002 Ramp A-1, King of Prussia, PA
- Holding crane had to be left on the bridge until four girders were erected. Studied extensively by Chavel and Earls (2003) and Chavel (2008).
- $I_{S1} = 0.25$, $I_{L1} = 0.86$, $I_{T1} = 0.68$, $I_{C1} = 2.99$
- Illustration of the overall deflections due to curvature and skewed bearings.
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Influence of locked-in stresses due to steel dead load fit detailing on girder responses.
- Tendency for uplift during the construction if the bridge is constructed with NLF detailing.

E6.2 EISCS4 (L_1 = 252 ft / R = 2269 ft / w = 26.6 ft / $\theta_1 = -24.71^o$, $\theta_2 = -18.36^o$/ 3 girders)



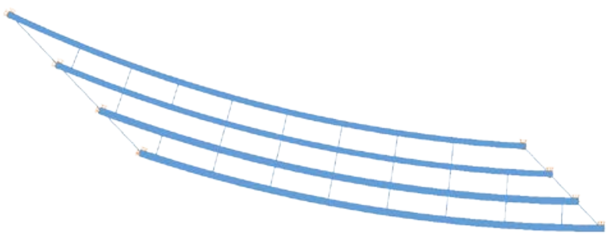
- Long Shoals Road Overpass, Buncombe Co., NC
- Third phase in a three-phase construction project. This three-girder unit over-rotated during the placement of its deck. The deck was removed, then shoring and bracing was provided to the span, and the deck was successfully placed.
- $I_{S1} = 0.04$, $I_{L1} = 1.0$, $I_{T1} = 0.64$, $I_{C1} = 0.55$
- The structure experiences large amplifications in the girder responses due to second order effects.
- This bridge highlights the importance of conducting a nonlinear analysis via a 3D FEA to properly predict the behavior of a long-and-narrow system.
- The 1D and 2D models are based on linear analysis; hence, they do not capture the expected response of the bridge.

E6.3 NISCS3 (L_1 = 150 ft / R = 436 ft / w = 30 ft / θ_1 = -35°, θ_2 = 0° / 4 girders)



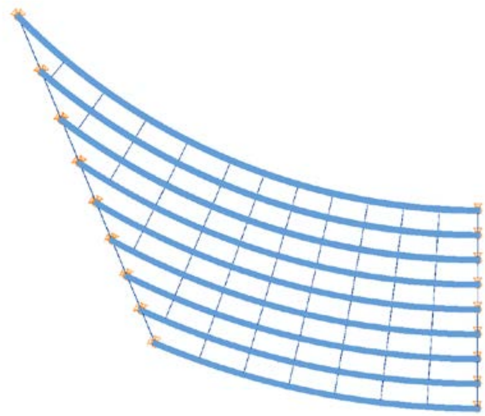
- I_{S1} = 0.11, I_{L1} = 1.18, I_{T1} = 0.71, I_{C1} = 3.44
- In this structure the orientation of the skew makes the girders twist in the same direction as the rotations in the girders due to the curvature. Hence, the effects of the skew and the curvature are additive.
- The combination of the curvature and the skew induces flange lateral bending stresses that are in the order of 25 ksi. None of the approximate analysis methods are able to capture this response.
- Similarly, the deflection predictions obtained from the 1D and 2D analyses do not captured the expected response, as predicted by the 3D FEA.

E6.4 NISCS9 (L_1 = 150 ft / R = 438 ft / w = 30 ft / θ_1 = 65.2°, θ_2 = 45.6° / 4 girders)



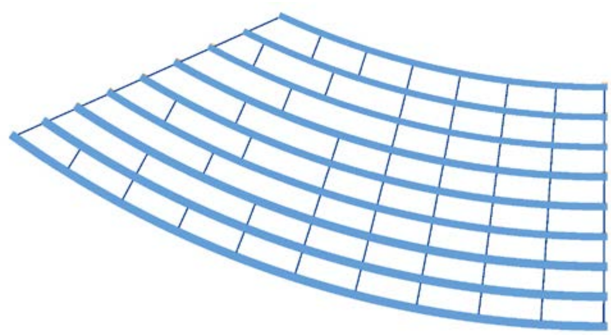
- I_{S1} = 0.35, I_{L1} = 0.88, I_{T1} = 0.63, I_{C1} = 3.11
- In this structure the effects of the skew in the left support counteracts the effects of the horizontal curvature. In the right support, these effects are additive since they both make the girders rotate in the same direction.
- Due to its complex geometry, the approximate 1D and 2D methods do not capture the behavior of the bridge properly. The vertical displacements and girder rotations are severely misrepresented by the approximate models.

E6.5 NISCS14 (L_1 = 150 ft / R_1 = 280 ft/ w = 80 ft /θ_1 = 53.7°, θ_2 = 0°, 9 girders)



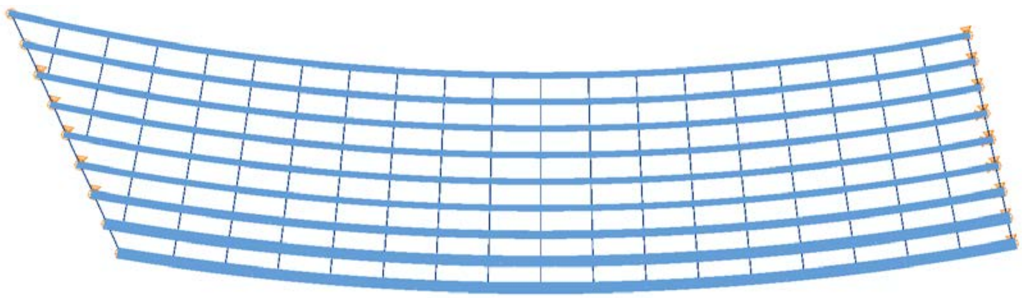
- I_{S1} = 0.67, I_{L1} = 0.65, I_{T1} = 0.55, I_{C1} = 4.46
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..

E6.6 NISCS15 (L_1 = 150 ft / R_1 = 280 ft/ w = 80 ft /θ_1 = -35°, θ_2 = 0°, 9 girders)



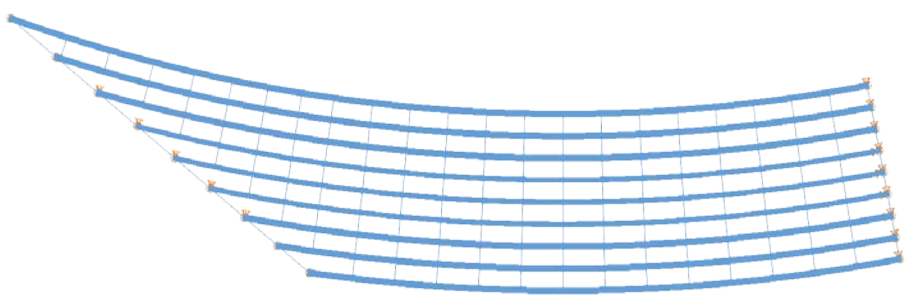
- I_{S1} = 0.36, I_{L1} = 1.88, I_{T1} = 0.67, I_{C1} = 4.46
- Demonstration of the overall bridge deflections due to curvature and skewed bearing lines
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Poor prediction of the results due to uplift

E6.7 NISCS37 *(L_1 = 300 ft / R_1 = 730 ft/ w = 80 ft /θ_1 = 35°, θ_2 = 0°, 9 girders)*



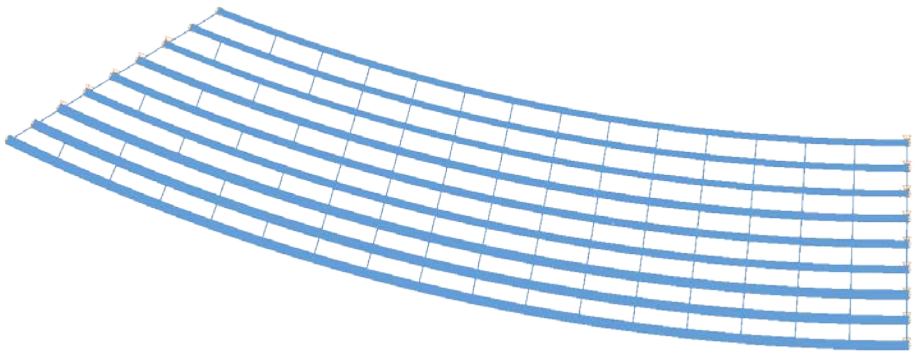
- I_{S1} = 0.35, I_{L1} = 0.93, I_{T1} = 0.62, I_{C1} = 1.03
- Demonstration of the importance of erection sequence on fit-up of the components.
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of the girders.

E6.8 NISCS38 (L_1 = 300 ft / R = 730 ft / w = 80 ft / θ_1 = 62.6°, θ_2 = 0° / 9 girders)



- I_{S1} = 0.48, I_{L1} = 0.68, I_{T1} = 0.59, I_{C1} = 0.94
- The interaction between the skew and the curvature is not captured by the approximate models. Except for the major-axis bending stresses, the rest of responses are inaccurately predicted by the 1D and 2D analyses.
- The inaccuracy of the results obtained from the 2D model is mostly due to the inability of this analysis method to represent the torsion properties of the I-girders.
- Due to the skew, significant levels of flange lateral bending stress are observed near the skewed end.

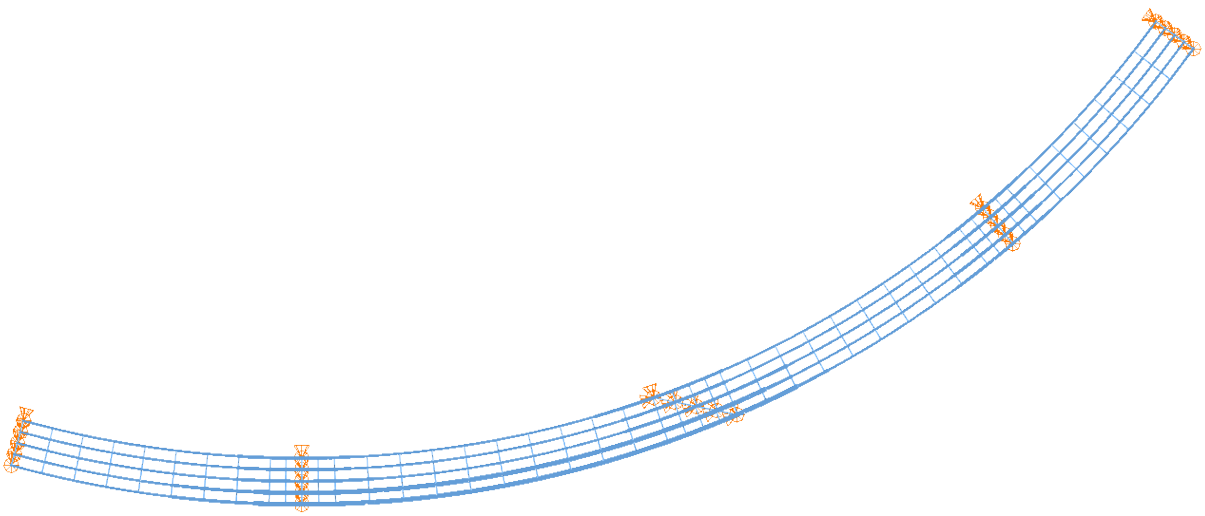
E6.9 NISCS39 (L_1 = 300 ft / R = 730 ft / w = 80 ft / θ_1 = -35°, θ_2 = 0° / 9 girders)



- I_{S1} = 0.17, I_{L1} = 1.32, I_{T1} = 0.68, I_{C1} = 1.21
- In this bridge, the effects of the skew are added to the effects of the horizontal curvature. The girders twist in the same direction, inducing larger levels of flange lateral bending stresses and layovers.
- The approximate analyses yield results that are different to those predicted by the 3D FEA. The main reason is the inability of the girder line and grid models to properly capture the effects of the skew.

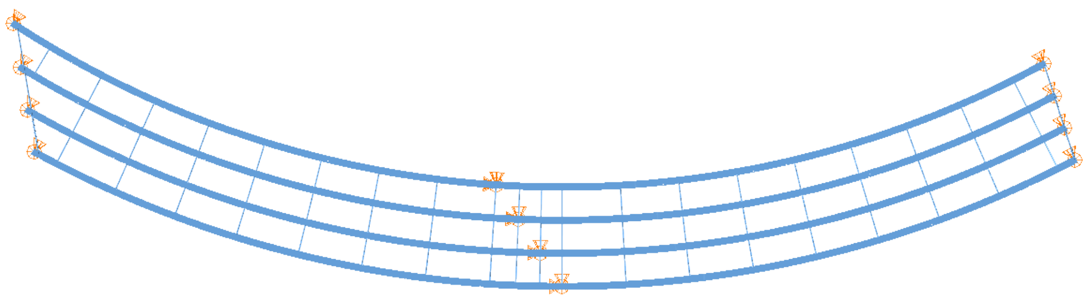
(E7) ICCS (I-girder, Continuous-span, Curved, Skewed supports)

E7.1 EICCS1 (L_1 = 204 ft, L_2 = 278 ft, L_3 = 252 ft, L_4 = 185 ft / R = 757 ft / w = 40.2 ft / $\theta_1 = 0^o$, $\theta_2 = 0^o$, $\theta_3 = 32.7^o$, $\theta_4 = 0^o$, $\theta_5 = 0^o$, 5 girders)



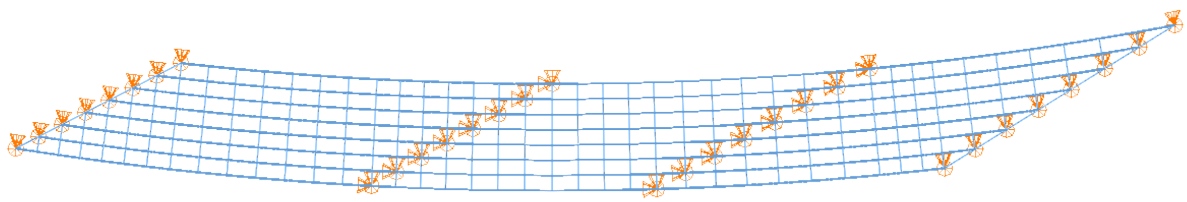
- US 31 Interchange Flyover A, Jefferson Co., AL
- Successful implementation of total dead load fit detailing. Extensive documentation of fabrication and erection provided by Osborne (2002).
- $I_{S1} = 0$, $I_{S2} = 0.08$, $I_{S3} = 0.08$, $I_{S4} = 0$ / $I_{L1} = 1.05$, $I_{L2} = 1.25$, $I_{L3} = 0.85$, $I_{L4} = 1.05$ / $I_{T1} = 0.65$, $I_{T2} = 0.80$, $I_{T3} = 0.70$, $I_{T4} = 0.62$ / $I_{C1} = 0.99$, $I_{C2} = 0.66$, $I_{C3} = 0.66$, $I_{C4} = 0.99$
- None of the approximate methods capture the expected responses of this structure, as predicted by the 3D model.
- In the case of the 1D model, it cannot capture the influence that the intermediate skewed support has on the behavior of the bridge.
- In the case of the 2D analysis, the torsion stiffness model that neglects the contribution of flange warping has a severe effect in the response predictions.

E7.2 EICCS10 (L_1=145 ft, L_2=150 ft / R=286 ft / w=33.4 ft / θ_{left} = 40.1°, θ_{mid} = 34.8°, θ_{right} = -10.4°, 4 girders)



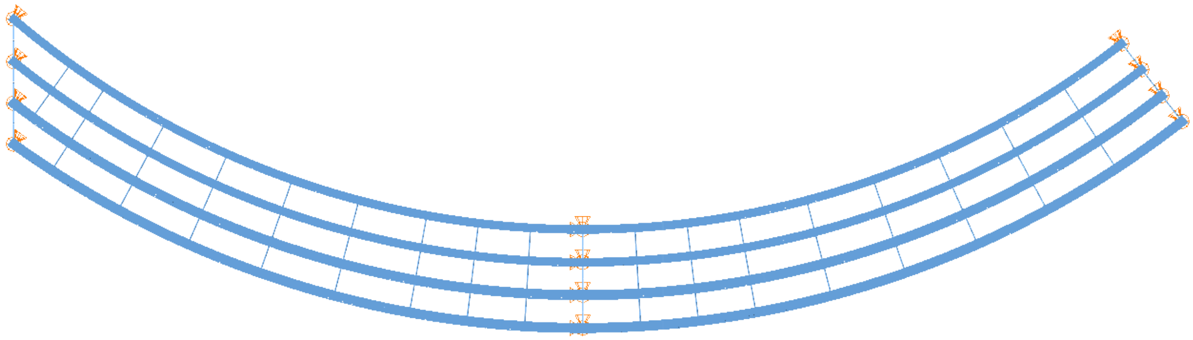
- MN/DOT bridge No. 27998, TH94 between 27th Avenue and Huron Boulevard, Minneapolis, MN
- Instrumented extensively and studied by Galambos et al. (1996). Used by Nowak, et al. (2006) in calibration of LRFD Specifications for curved steel bridges.
- I_{S1} = 0.16, I_{S2} = 0.13, / I_{L1} = 1.07, I_{L2} = 1.07 / I_{T1} = 0.73, I_{T2} = 0.72 / I_{C1} = 2.19, I_{C2} = 2.19
- The 2D model does not capture accurately the displacement responses of the bridge due to the poor torsion model used in the analysis when more than one element is used to model the girders between the cross-frames.
- The 1D girder line analysis yields better results than those obtained from the grid analysis.

E7.3 EICCS27 (L_1 = 279 ft, L_2 = 224 ft, L_3 = 236 ft / R = 2546 ft / w = 88 ft / θ_1 = -53.1°, θ_2 = -59.4°, θ_3 = -64.4°, θ_4 = -69.7°, 8 girders)



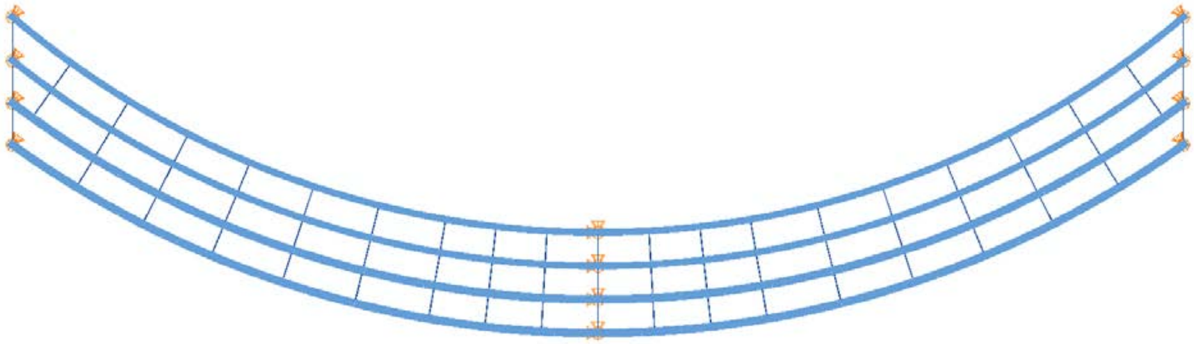
- SR 386 over SR 6 and Ramp F, Sumner Co., TN
- Bolts connecting cross-frames to connection plates sheared after the steel erection and before completion of the bridge.
- I_{S1} = 0.48, I_{S2} = 0.75, I_{S3} = 0.92 / I_{L1} = 0.96, I_{L2} = 0.90, I_{L3} = 0.94 / I_{T1} = 0.51, I_{T2} = 0.49, I_{T3} = 0.47 / I_{C1} = 0.14, I_{C2} = 0.16, I_{C3} = 0.17
- The bridge responses are properly captured by the approximate models.
- The poor representation of the torsion stiffness on the 2D analysis does not have a significant impact in this bridge.

E7.4 NICCS2 (L_1 = 150 ft, L_2 = 150 ft/ R = 227 ft / w =30 ft / θ_1 = 38°, θ_2 = 0°, θ_3 = 0°, 5 girders)



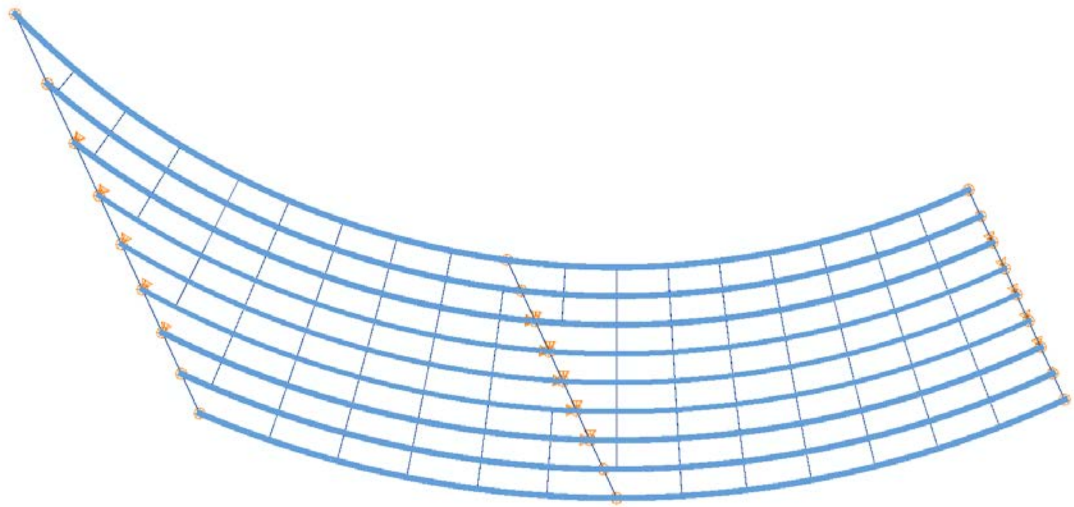
- I_{S1} = 0.13, I_{S2} = 0, / I_{L1} = 0.98, I_{L2} = 1.24 / I_{T1} = 0.81, I_{T2} = 0.87 / I_{C1} = 3.30, I_{C2} = 3.67
- The 2D model does not capture accurately the displacement responses of the bridge due to the poor torsion model used in the analysis when more than one element is used to model the girders between the cross-frames.
- The 1D girder line analysis yields better results than those obtained from the grid analysis.

E7.5 NICCS3 (L_1 = 150 ft, L_2 = 150 ft / $R_{1,2}$ = 227 ft/ w = 30 ft /θ_1 = 38°, θ_2 = 0°, θ_3 = -38°, 4 girders)



- I_{S1} = 0.13, I_{S2} = 0.13, / I_{L1} = 0.98, I_{L2} = 0.98 / I_{T1} = 0.81, I_{T2} = 0.81 / I_{C1} = 3.30, I_{C2} = 3.30
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Tendency for uplift problems during erection
- Overestimation of the flange lateral bending stresses at negative moment regions.

E7.6 NICCS9 (L_1 = 150 ft, L_2 = 150 ft / $R_{1,2}$ = 308 ft/ w = 80 ft /θ_1 = 56°, θ_2 = 28°, θ_3 = 0°, 9 girders)

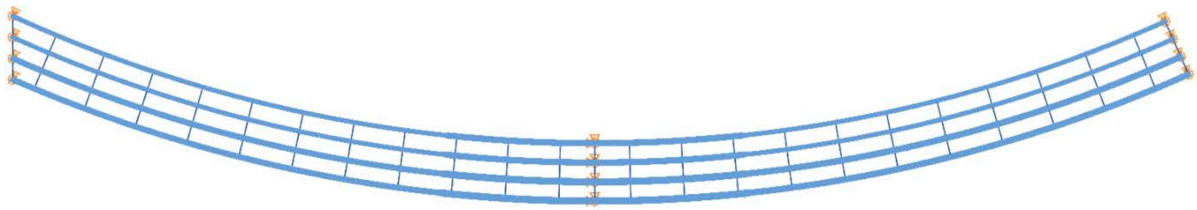


- I_{S1} = 0.73, I_{S2} = 0.26, / I_{L1} = 0.77, I_{L2} = 0.98 / I_{T1} = 0.53, I_{T2} = 0.58 / I_{C1} = 2.21, I_{C2} = 2.71
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames..
- Tendency for uplift problems during erection stages due to severe horizontal curvature.
- Comparison of the improved grid solutions against benchmark solutions.
- Other assumptions with grid solutions that can cause differences in the responses against benchmark solutions.

E7.7 NICCS13 (L_1 = 250 ft, L_2 = 250 ft / $R_{1,2}$ = 597 ft/ w = 30 ft /θ_1 = 47.9°, θ_2 = 24°, θ_3 = 0°, 4 girders)

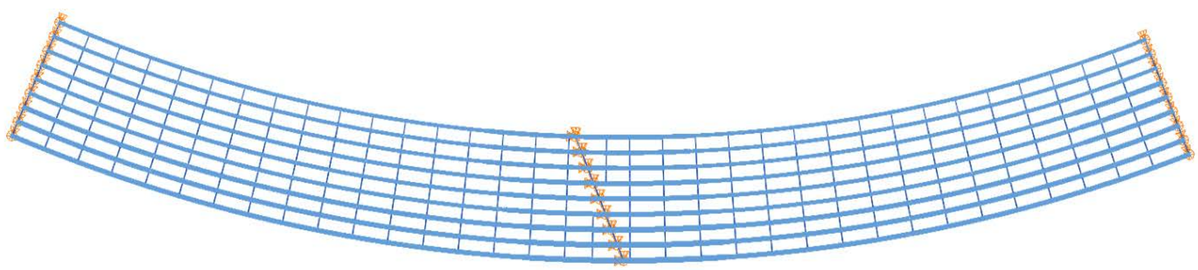
- I_{S1} = 0.11, I_{S2} = 0.04, / I_{L1} = 0.98, I_{L2} = 0.99 / I_{T1} = 0.84, I_{T2} = 0.85 / I_{C1} = 1.05, I_{C2} = 1.05
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames.
- Poor prediction of the flange lateral bending stresses by grid analysis solutions.
- Global second-order effects during construction since there is no temporary supports.

E7.8 NICCS14 (L_1 = 250 ft, L_2 = 250 ft / $R_{1,2}$ = 597 ft/ w = 30 ft /θ_1 = 24°, θ_2 = 0°, θ_3 = 0°, 4 girders)



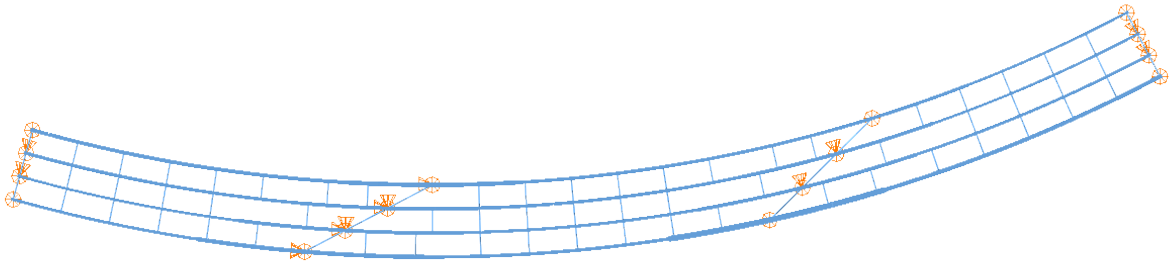
- I_{S1} = 0.04, I_{S2} = 0, / I_{L1} = 0.99, I_{L2} = 1.04 / I_{T1} = 0.85, I_{T2} = 0.88 / I_{C1} = 1.12, I_{C2} = 1.12
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames.

E7.9 NICCS24 (L_1 = 350 ft, L_2 = 350 ft / R =909 ft / w = 80 ft /θ_1 = 0°, θ_2 = 22.1°, θ_3 = 0°, 9 girders)



- I_{S1} = 0.09, I_{S2} = 0.09, / I_{L1} = 1.18, I_{L2} = 1.00 / I_{T1} = 0.68, I_{T2} = 0.65 / I_{C1} = 0.46, I_{C2} = 0.46
- Importance of using temporary supports for large span lengths
- Poor prediction of the vertical displacements and layovers due to poor torsional modeling of girders when more than one element is used to model the girders between the cross-frames.

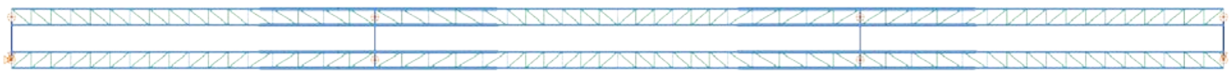
E7.10 XICCS7 (L_1=160 ft, L_2=210 ft, L_3=160 ft/ R=700 ft / w=40.5 ft / θ_1=0 ^{o}, θ_2=-60 ^{o}, θ_3=-60 ^{o}, θ_4=0 ^{o}/ 4 girders)



- Reference: (NHI, 2011)
- I_{S1} = 0.36, I_{S2} = 0.27, I_{S3} = 0.36 / I_{L1} = 0.73, I_{L2} = 1.05, I_{L3} = 1.51 / I_{T1} = 0.55, I_{T2} = 0.64, I_{T3} = 0.65 / I_{C1} = 1.33, I_{C2} = 0.97, I_{C3} = 1.33
- The vertical displacement and layover responses are not properly captured in the 2D-grid model due to the limitations of the girder torsion model used in the analysis.
- The 1D girder line model yields results that are comparatively better than those obtained from the grid analysis. For this bridge, the skew effects are moderate, so the 1D analysis predictions are close to the obtained from the 3D FEA.

(8) TCSN (Tub-girder, Continuous, Straight, No Skewed Supports)

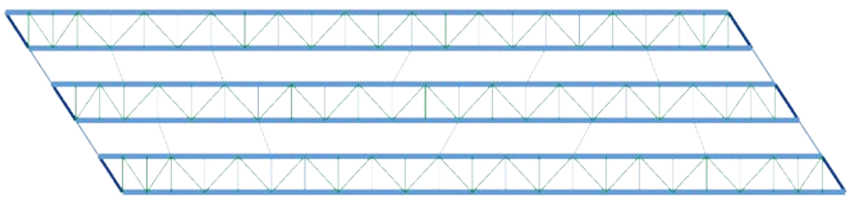
8.1 XTCSN3 (L_1 = 206 ft, L_2 = 275, L_3 = 206 ft / w = 43 ft, 2 tub-girders)



- Reference: (Carnahan, et al., 1997)
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.0$, $I_{L2} = 1.0$, $I_{L3} = 1.0$ / $I_{T1} = 0.5$, $I_{T2} = 0.5$, $I_{T3} = 0.5$
- Internal torsional force caused by the Pratt TFLB system.
- 1D and 2D methods do not capture internal torsional moments and in consequence the forces in the bracing elements are not correctly predicted by Helwig et al. expressions.
- Predicted TFLB force distribution follows the bending moment diagram while they should follow the shape of the torsional moment diagram which is similar to the shear force distribution.

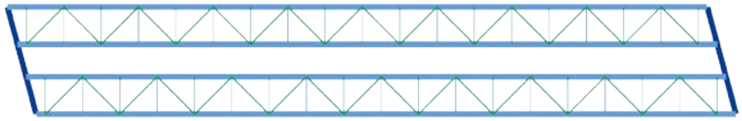
(9) TSSS (Tub-girder, Simple-span, Straight, Skewed supports)

9.1 ETSSS2 (L_1 = 205 ft / w = 113 ft / θ=33.4°, θ=33.4°, 6 tub-girders, phased construction, two units of 3 girders each)



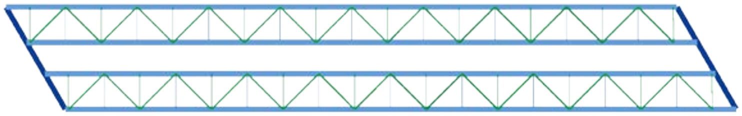
- Sylvan Bridge over Sunset Hwy., Multomah Co., OR
- One unit in a six tub-girder phased construction project.
- I_{S1} = 0.13 / I_{L1} = 1.0 / I_{T1} = 0.5
- Cross-flames are used between girders during stages studied are flexible providing reduced torsional interaction as compared to rigid plate diaphragms.
- Double bearing configuration used at each girder end. Negative reactions found at one of each bearings.
- In 2D analyses the double bearing can be modeled by using an additional rigid member between the bearings.
- Skewed external intermediate cross frames used only during construction. Offset at cross-frames bottom chords due to web slope.
- TFLB and top flange interaction is noticeable as saw-tooth shaped top flange major-axis bending stresses.

9.2 NTSSS1 (L_1 = 150 ft / w = 30 ft / θ=15°, θ=15°, 2 tub-girders)



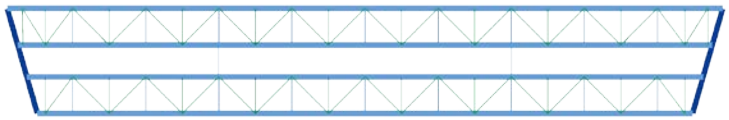
- I_{S1} = 0.03 / I_{L1} = 1.0 / I_{T1} = 0.5
- Torsion due to skew not captured by ordinary 1D analysis. Mechanics approach can provide an approximate torsional moment to apply to 1D model.
- 2D-Grid analysis prediction of the torsional moment depends on the model of the external end diaphragm. The torsional response is mostly insensitive to diaphragm plate thicknesses within a range of commonly used values.
- 3D FEA reports TFLB and girder top flange interaction not captured by 1D or 2D methods. The top flange major axis bending stress distribution has a saw-tooth pattern matching the position of the TFLB locations.
- Plan layout does not permit the use of intermediate cross-frames
- Constant torsional moment on the girders causing a constant force on the TFLB

9.3 NTSSS2 (L_1 = 150 ft / w = 30 ft / θ=30°, θ=30°, 2 tub-girders)



- I_{S1} = 0.06 / I_{L1} = 1.0 / I_{T1} = 0.5
- Increased skew angle with respect to NTSSS1, torsional effects increased.
- Same TFLB interaction as reported on NTSSS1.

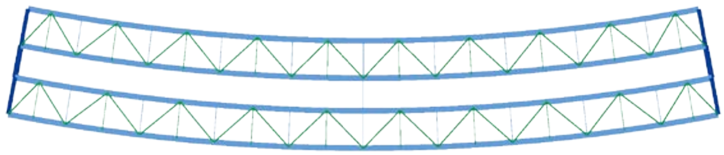
9.4 NTSSS4 (L_1 = 150 ft / w = 30 ft / θ=30°, θ=-30°, 2 tub-girders)



- I_{S1} = 0.03 / I_{L1} = 1.06 / I_{T1} = 0.48
- Due to the equal and opposite skew of the bearing lines, the girder torsional moment is zero, however, the girders exhibit a rigid body twist about their longitudinal axis.
- Girder twist rotation can cause fit-up and slab thickness issues if not accounted for.
- TFLB forces remain low due to rigid body rotation and zero torsional moment.
- No evidence of TFLB and top flange interaction.

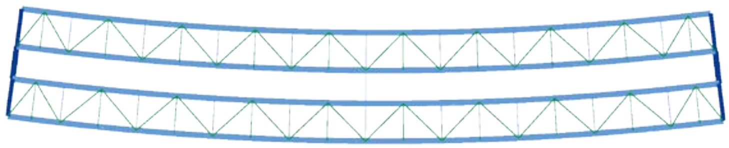
(10) TSCR (Tub-girder, Simple-span, Curved, Radial supports)

10.1 NTSCR1 (L_1 = 150ft / R = 400 ft / w = 30 ft, 2 tub-girders)



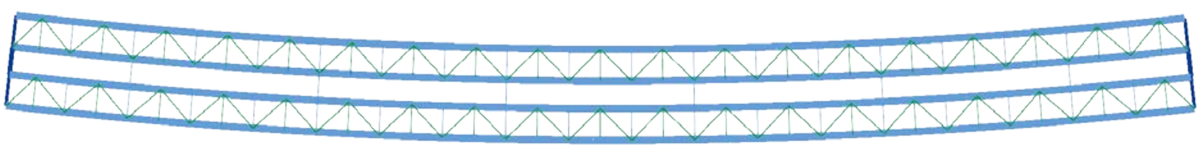
- I_{S1} = 0 / I_{L1} = 1.04 / I_{T1} = 0.83
- Effects of torsional forces are correctly predicted by all the types of analysis.
- Intermediate cross-frame at span center does not affect the vertical displacements or major axis bending stresses predictions for 1D Line-Girder and 2D-Grid analyses.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

10.2 NTSCR2 (L_1 = 150ft / R = 600 ft / w = 30 ft, 2 tub-girders)



- $I_{S1} = 0$ / $I_{L1} = 1.03$ / $I_{T1} = 0.72$
- Reduced curvature with respect to NTSCR1 (higher curvature radius) proves reduced effects due to skew.
  TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses. When compared to NTSCR1 the saw-tooth height is reduced.

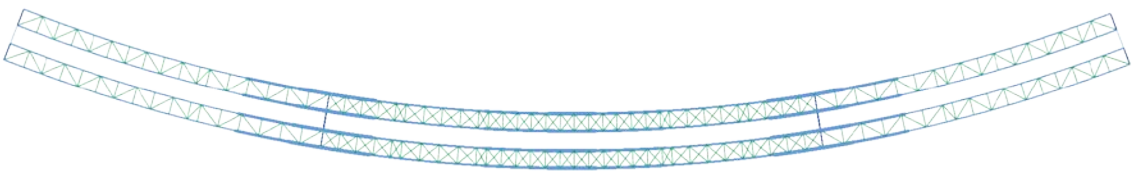
10.3 NTSCR5 (L_1 = 300 ft / R = 1360 ft / w = 30 ft, 2 tub-girders)



- $I_{S1} = 0$ / $I_{L1} = 1.01$ / $I_{T1} = 0.87$
- Longer span layout uses deeper tubs reducing the bottom flange width.
- Linear and Non-Linear 3D FEA analyses results report negligible differences.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

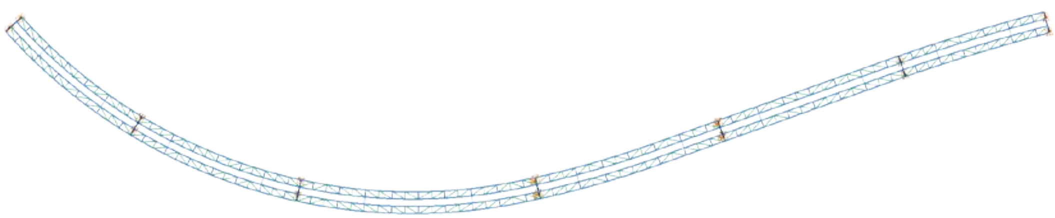
(11) TCCR (Tub-girder, Continuous-span, Curved, Radial supports)

11.1 ETCCR14 (L_1 = 189 ft, L_2 = 291 ft, L_3 = 183 ft / R = 896 ft / w = 40.8 ft, 4 tub-girders)



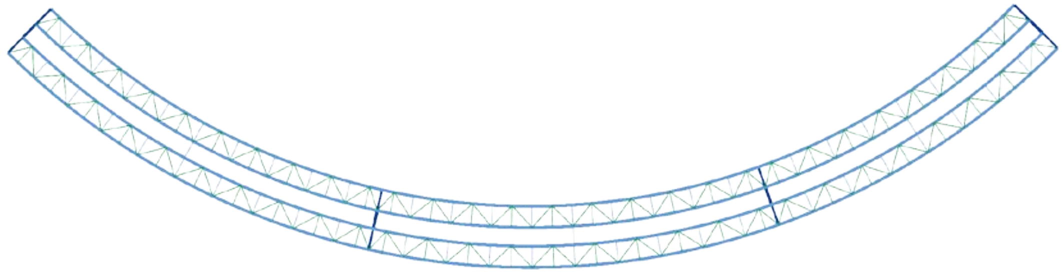
- Connector EB North Beltway 8 to NB I-45, Houston, TX
- Studied extensively by Fan (1999).
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.02$, $I_{L2} = 1.02$, $I_{L3} = 1.02$ / $I_{T1} = 0.66$, $I_{T2} = 0.88$, $I_{T3} = 0.65$
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses at spans 1 and 3 with Warren-type top truss, no noticeable interaction at center span with X-type top truss system.

11.2 ETCCR15 (L_1 = 155ft, L_2 = 169 ft, L_3 = 232ft, L_4 = 185ft, L_5 = 185ft, L_6 = 144ft / R = 515ft, 960ft, ∞, -1904ft / w = 29.5ft, 2 tub-girders)



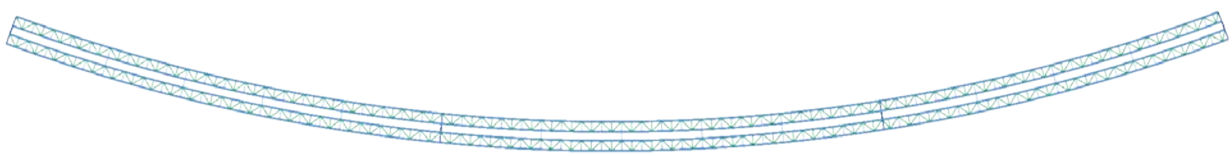
- B-40-1122 Marquette Interchange, Milwaukee, WI
- Change in sign of horizontal curvature along the length.
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$, $I_{S4} = 0$, $I_{S5} = 0$, $I_{S6} = 0$ / $I_{L1} = 1.03$, $I_{L2} = 1.03$, $I_{L3} = 1.03$, $I_{L4} = 1.01$, $I_{L5} = 1.00$, $I_{L6} = 1.01$ / $I_{T1} = 0.79$, $I_{T2} = 0.85$, $I_{T3} = 1$, $I_{T4} = 0.66$, $I_{T5} = 0.50$, $I_{T6} = 0.57$
- Bridge has alternating Pratt layout for TFLB and internal solid plate diaphragms.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses. TFLB layout reduced the number of saw-tooth locations.

11.3 NTCCR1 (L_1 = 150 ft, L_2 = 150 ft, L_3 = 120 ft / R = 268 ft / w = 30 ft, 2 tub-girders)



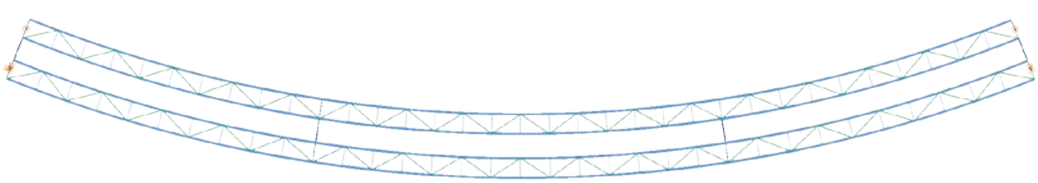
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.06$, $I_{L2} = 1.06$, $I_{L3} = 1.06$ / $I_{T1} = 1$, $I_{T2} = 1$, $I_{T3} = 0.82$
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses. Interaction increased due to curvature.

11.4 NTCCR5 (L_1 = 350ft, L_2 = 350 ft, L_3 = 280 ft / R = 1380 ft / w = 30 ft, 2 tub-girders)



- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.01$, $I_{L2} = 1.01$, $I_{L3} = 1.01$ / $I_{T1} = 1$, $I_{T2} = 1$, $I_{T3} = 0.82$
- Linear and Non-Linear 3D FEA analyses results report negligible differences.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

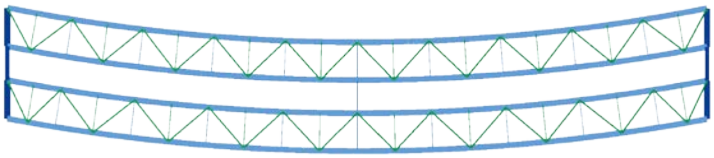
11.5 XTCCR8 (L_1 = 160 ft, L_2 = 210 ft, L_3 = 160 ft / R = 700 ft / w = 40.5 ft, 2 tub-girders)



- Reference: (Kulicki et al., 2005)
- $I_{S1} = 0$, $I_{S2} = 0$, $I_{S3} = 0$ / $I_{L1} = 1.03$, $I_{L2} = 1.03$, $I_{L3} = 1.03$ / $I_{T1} = 0.64$, $I_{T2} = 0.74$, $I_{T3} = 0.64$
- Double bearing per girder modeled as single bearing.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

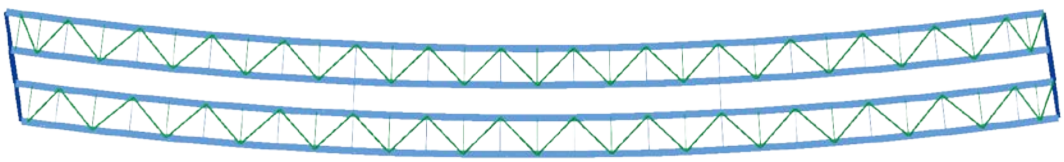
(12) TSCS (Tub-girder, Simple-span, Curved, Skewed supports)

12.1 NTSCS5 (L_1 = 150ft / R = 400 ft / w = 30 ft / θ_1 =10.7°, θ_2 =-10.7°, 2 tub-girders)



- I_{S1} = 0.02 / I_{L1} = 1.00 / I_{T1} = 0.81
- Lateral displacements start at non-zero value at skewed support locations. 2D-Grid matches the results.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

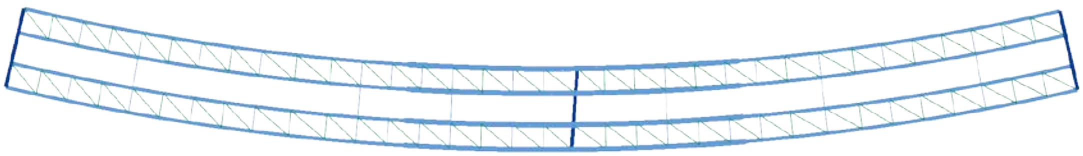
12.2 NTSCS29 (L_1 = 225ft / R = 820 ft / w = 30 ft / θ_1 =15.7°, θ_2 =0°, 2 tub-girders)



- I_{S1} = 0.02 / I_{L1} = 1.00 / I_{T1} = 0.84
- Lateral displacements start at non-zero value at skewed support location. 2D-Grid matches the results.
- Skew adds to torsion due to curvature increasing the torque at left support and reducing at right support.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

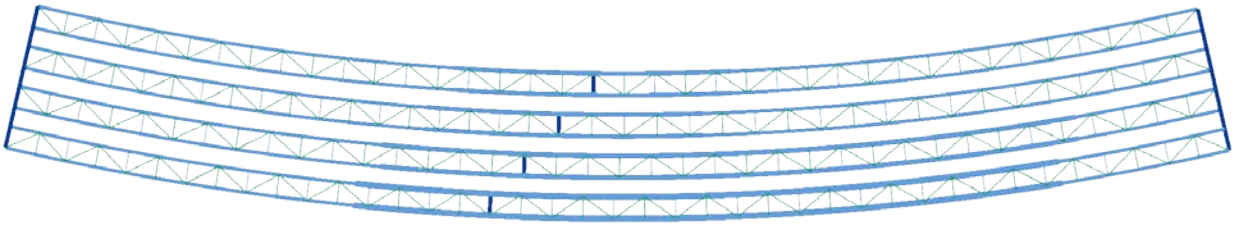
(13) TCCS (Tub-girder, Continuous-span, Curved, Skewed supports)

13.1 ETCCS5a (L_1 = 183 ft, L_2 = 161 ft / R = 765 ft / w = 36.2 ft / θ_1 = 0°, θ_2 = 4.8°, θ_3 = 0°, 2 tub-girders)



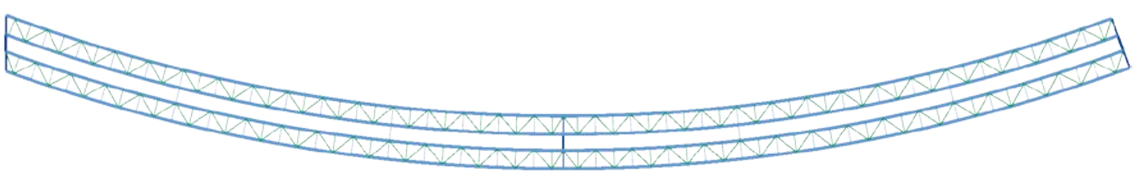
- Ramp A2, SR 9A / SR 202 Interchange, Duval Co., FL
- Small skew at intermediate bearing line.
- I_{S1} = 0.01, I_{S2} = 0.01 / I_{L1} = 1.02, I_{L2} = 1.03 / I_{T1} = 0.70, I_{T2} = 0.67
- Intermediate skew increases the curvature effects on the left span while the skew counteracts the curvature on the left span. This effect is more noticeable when the angle of the skewed support is larger.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

13.2 ETCCS6 (L_1 = 160 ft, L_2 = 207 ft / R = 814 ft / w = 50.5 ft / θ_1 = 0°, θ_2 = 39.2°, θ_3 = 0°, 4 tub-girders)



- McGruder Blvd. to SB I-64, Hampton, VA
- Constructed in two phases of two tub-girders each. Fit-up issues encountered during erection.
- I_{S1} = 0.06, I_{S2} = 0.05 / I_{L1} = 0.95, I_{L2} = 1.07 / I_{T1} = 0.70, I_{T2} = 0.84 (Stage 1 - Interior)
- I_{S1} = 0.06, I_{S2} = 0.04 / I_{L1} = 0.95, I_{L2} = 1.06 / I_{T1} = 0.68, I_{T2} = 0.95 (Stage 2 - Exterior)
- Staged construction of 2 tub-girders each.
- The lack of external diaphragms at the interios pier helps avoiding the torsional effects due to skew but girder rotations are increased.
- Heavily skewed intermediate supports must have collinear diaphragms and cross frames to avoid geometric problems with sloped webs.
- Relative vertical displacements of the most extreme flanges have differences of 8in on the completed 4 tub-girder bridge mainly due to the increased relative length of the internal to external girders. These vertical displacements are usually accommodated in the camber but must be predicted accurately.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.

13.3 NTCCS22 (L_1 = 250 ft, L_2 = 250 ft / R = 713 ft / w = 30 ft / θ_1 =20.1°, θ_2 =0°, θ_3 =0°, 2 tub-girders)



- I_{S1} = 0.02, I_{S2} = 0 / I_{L1} = 1.00, I_{L2} = 1.02 / I_{T1} = 0.98, I_{T2} = 1
- Lateral displacements start at non-zero value at skewed support location. 2D grid matches the results.
- Skew and curvature torsional forces counteract.
- TFLB and top flange interaction is noticeable as saw-tooth shaped major axis bending stresses.
- Linear and Non-Linear 3D FEA analyses results report negligible differences.