

NCHRP Project 12-71
*Design Specifications and Commentary for Horizontally Curved Concrete Box-Girder
Highway Bridges*

Appendix C
Global Analysis Guidelines

a. Three Dimensional Spine Beam Analysis

General – This analysis approach requires the structure to be modeled as a three-dimensional space frame in which the superstructure is comprised of a series of straight beam elements located along the centerline of the superstructure at its center of gravity in the vertical direction. Substructure elements are also modeled as beams that are oriented so that their member properties coincide with the three-dimensional orientation of the piers or columns. Three-dimensional computer software is required to perform this analysis. Many common commercially available software packages have this capability. The computational effort will be greatly simplified if this software can automatically model prestress tendons and has vehicle live load generation capabilities.

Computer Model – An example of a typical computer model for a curved concrete box girder bridge is shown in Figure C-1.

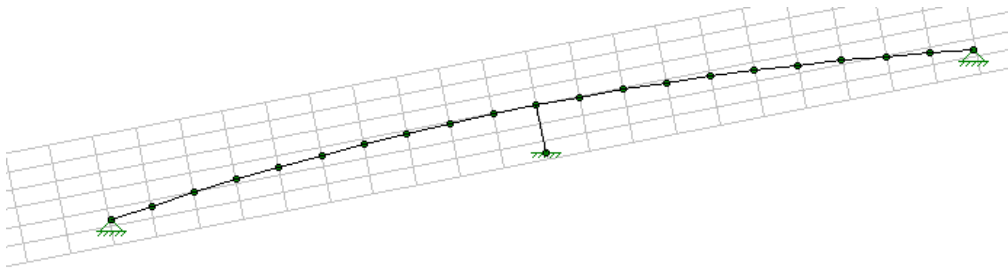


Figure C-1 – Typical Spine Beam Model of a Curved Concrete Box Girder Bridge

This model is recommended when the central angle for any one span is between 12 and 46 degrees. Individual beam segments in the superstructure should have central angles of no more than 3.5 degrees. Often it is convenient to divide each span into 10 segments or more. This allows the results along the length of the span to be easily interpreted for design purposes.

Boundary conditions at the supports should be oriented in three-dimensional space as they are in the actual structure. Therefore a longitudinal release for an expansion joint at the abutments should be oriented along the longitudinal axis of the bridge and a transverse restraint from shear keys should be oriented transverse to the superstructure. Moment releases should also be properly oriented. The same is true for modeling pinned conditions at the base of columns or piers. When bearings are oriented transverse to the superstructure, the torsional restraint about the superstructure should be provided. The flexibility of the bearing system can be modeled as a boundary spring or as a system of

weightless rigid links with the individual vertical stiffnesses of the bearings placed at the ends of these rigid links. Flexible foundations should also be modeled. Uncoupled boundary springs are often sufficient for this purpose.

Substructure element such as columns and piers should be oriented in three-dimensional space as they are in the actual structure. When columns and piers are cast monolithic with the superstructure, a stiff element should be provided between the soffit of the bridge and the center of gravity of the superstructure to model this condition.

Members – It is usually sufficient to define four section properties of each of the beam elements in the model. These are defined in what most programs refer to as the local coordinate system. This system is usually oriented along the longitudinal axis of the member under consideration with orthogonal axes referenced to the positive vertical direction. The section properties to be defined are cross-sectional area, torsional moment of inertia, and two bending moments of inertia about the two transverse local axes.

Loads – The model is capable of analyzing response to a wide variety of loads. For specific load types the following should be kept in mind.

Dead Load (DC & DW) – The dead load of structural components is calculated in most programs as a product of the dimensions and the material properties of the beam member. These loads are located along the main axis of the member and generally oriented in the negative vertical direction. In the case of curved bridges this load is actually slightly eccentric to the superstructure centerline because the segment is wedge shaped in plan as shown in Figure C-2. Accounting for this eccentricity is a refinement that can be simulated by applying a uniform torsional moment to each of the superstructure elements, although it is often not significant for design purposes. Similarly, the dead load of overlays and utilities can be applied as uniform loads and moments along the axis of the superstructure members.

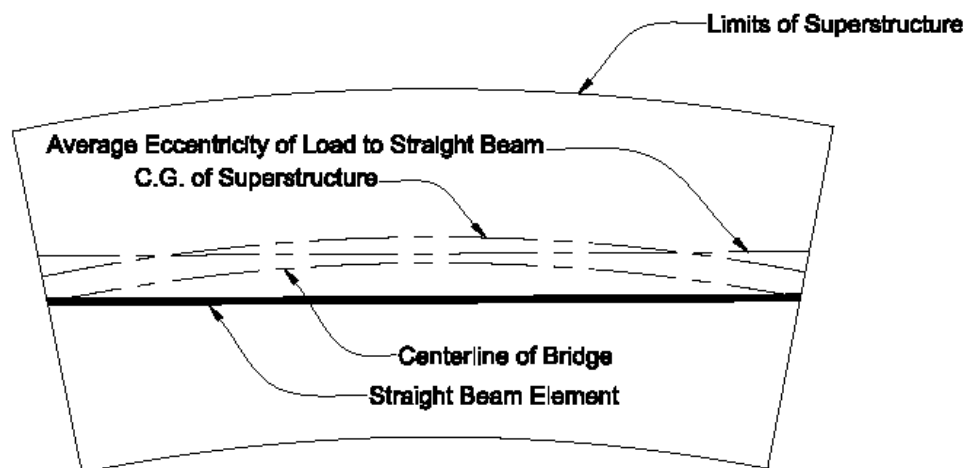


Figure C-2 – Eccentricity of Dead Load

Live Load and Impact (LL & IM) – Live load effect on individual beam units represented by the web and the corresponding portions of the deck and soffit can be determined by using wheel load distribution factors or the whole width design approach. The whole width design approach is much simpler and was found to yield conservative results. The effect of torsion on a curved superstructure must be considered separately and usually requires that live load lanes be applied across the width of the bridge shifted to provide the maximum eccentricity toward the outside of the curve. Applying these loads by hand can be very tedious, and it is helpful if the program has a live load generator that can locate lanes transversely to the centerline of the superstructure as well as move live loads along the longitudinal axis of the bridge.

In the case of the wheel load distribution approach it is recommended that a single live load lane be applied along the centerline of the bridge and that the wheel load distribution factors for various individual girders (i.e. web and slab elements) be used to scale the bending and shear response of the superstructure elements. To determine the torsional response the results from the analysis can be scaled by the number of lanes located across the cross-section. Alternately, a more refined torsion analysis can be performed in which the eccentricity of the live load lanes is considered.

In the case of the whole width design approach, the same results used for the wheel load distribution factor analysis can be scaled by the number of lanes applied to the whole width structure according to the LRFD code. Torsion analysis should be performed in the same manner as for the wheel load distribution approach.

Prestressing – Some programs allow for the definition of individual prestress tendons. These should be located in three-dimensional space. In other words their eccentricity to the centerline of the bridge should be considered. Initial and well as final prestressing forces should be considered. In both cases the transverse bending of the superstructure generated by these tendons will produce axial stresses that should be considered in determining the longitudinal response of the various individual girders.

Other Loads – The three dimensional nature of the model lends itself to the application of other loads. The model is even suitable for a multi-modal response spectrum analysis if the piers are divided into at least three segments to allow for a more uniform distribution of mass.

Results – Results in the form of nodal displacements and member end forces can be used for design. Notice vector sum of the member end forces at a given node must be averaged for design. These results are then factored and combined according to the LRFD Bridge Design Specification to design individual members. A comprehensive Design Example is included in Appendix B.

b. Grillage Analogy Analysis

General – This analysis approach requires the structure to be modeled as a three-dimensional grid of beam elements in which the superstructure is comprised of both longitudinal and transverse beams located at the vertical center of gravity of the superstructure. Longitudinal members are located at the center of gravity of each girder line (web and slabs). Transverse beams are intended to model the bridge deck and soffit and any portion of transverse diaphragms that are present at these locations. Substructure elements are also modeled as beams that are oriented so that their member properties coincide with the three-dimensional orientation of the piers or columns. Three-dimensional computer software is required to perform this analysis. Many common commercially available software packages have this capability. The computational effort will be greatly simplified if this software can automatically model prestress tendons and has vehicle live load generation capabilities.

Computer Model – An example of a typical computer model for a curved concrete box girder bridge is shown in Figure C-3.

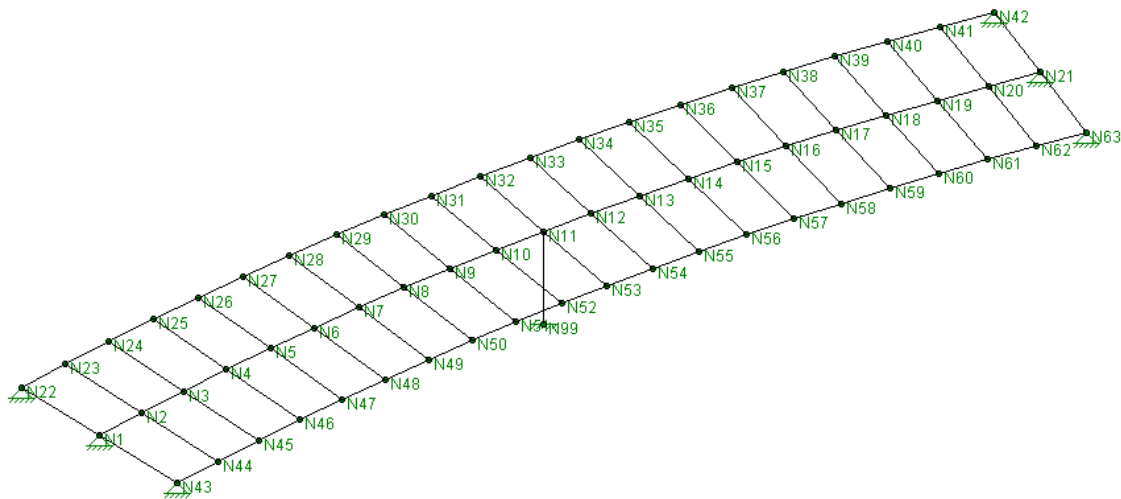


Figure C-3 – Typical Grillage Analogy Model of a Curved Two-cell Concrete Box Girder Bridge

This model is recommended for unusual plan geometry or when the central angle for any one span is greater than 46 degrees. Individual longitudinal beam segments in the superstructure should have central angles of no more than 3.5 degrees. Transverse members should frame into the nodes at each end of a longitudinal member. Often it is convenient to divide each span into 10 segments or more. This allows the results along the length of the span to be easily interpreted for design purposes.

Boundary conditions at the supports should be oriented in three-dimensional space as they are in the actual structure. Often, the designer may wish to orient bearings so that expansion occurs toward the center of bridge movement to prevent binding of the

bearings. However, it is generally acceptable for analysis of gravity loads, to assume a longitudinal release for an expansion joint at the abutments oriented along the longitudinal axis of the bridge and a transverse restraint from shear keys oriented transverse to the superstructure. Moment releases should also be properly oriented. The same is true for modeling pinned conditions at the base of columns or piers. Bearings that are oriented transverse to the superstructure should be placed at their actual positions and a stiff abutment or bent cap diaphragm element placed transversely at the bearings. The flexibility of the bearing system can be modeled as a boundary spring with the individual vertical stiffnesses of the bearings included. Flexible foundations should also be modeled. Uncoupled boundary springs are often sufficient for this purpose.

Substructure element such as columns and piers should be oriented in three-dimensional space as they are in the actual structure. When columns and piers are cast monolithic with the superstructure, a stiff element should be provided between the soffit of the bridge and the center of gravity of the superstructure to model this condition. Bent caps and abutment diaphragms should be explicitly modeled and their member properties lumped into the transverse beam element at their location.

Members – It is necessary to define six section properties of each of the beam elements in the model. This is necessary because these elements are intended to reflect two types of actions (e.g. flexure and shear). These properties are defined in what most programs refer to as the local coordinate system. This system is usually oriented along the longitudinal axis of the member under consideration with orthogonal axes referenced to the positive vertical direction. The section properties to be defined are shown in Figures C-4 and C-5 for longitudinal and transverse beam elements, respectively.

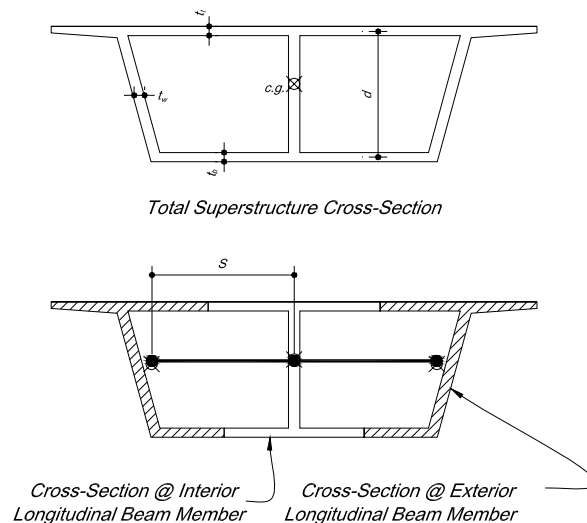


Figure C-4 – Longitudinal Cross-Section of Superstructure and Individual Longitudinal Grillage Members

Section Properties of Longitudinal Grillage Members

A_x = Tributary Cross Section Area of Longitudinal Segment as Shown in Figure C-4

A_y = Vertical Shear Area = Area of web only

A_z = Transverse Shear Area = Area of tributary deck and soffit slabs

I_{zz} = Tributary Moment of Inertia of Longitudinal Segment about Horizontal Axis

I_{yy} = Tributary Moment of Inertia of Longitudinal Segment about Vertical Axis

J = Torsional Moment of Inertia of entire cross section/Number of webs

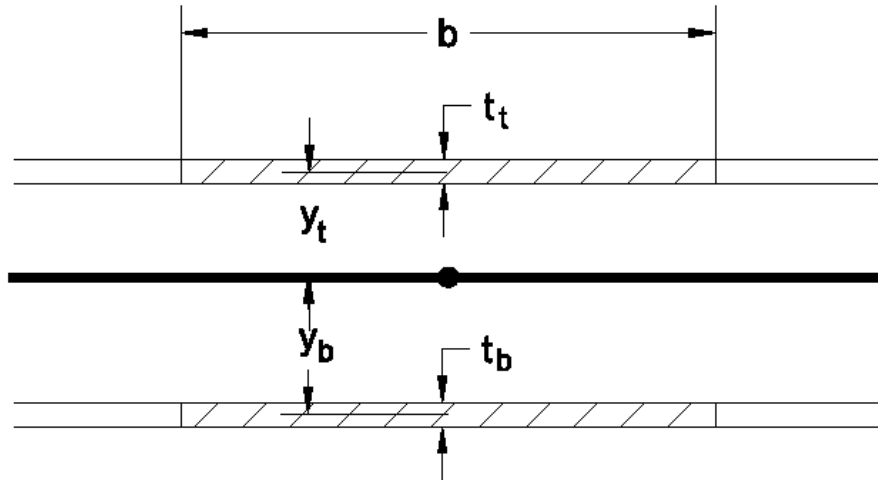


Figure C-5 – Transverse Section at Node Point

Section Properties of Transverse Grillage Members

$$A_x = b \cdot (t_t + t_b)$$

$$A_y = [(t_t^3 + t_b^3)/S] \cdot [t_w^3 / (S t_w^3 + (t_t^3 + t_b^3) \cdot d)] \cdot (E/G) \cdot b$$

$$A_z = b \cdot (t_t + t_b)$$

$$I_{zz} = b^3 \cdot (t_t + t_b) / 12$$

$$I_{yy} = (b) \cdot (t_t^3 + t_b^3) / 12 + b \cdot (t_t y_t^2 + t_b y_b^2)$$

$$J = b \cdot [2d^2 t_t t_b / (t_t + t_b)]$$

Where:

b = Average of longitudinal member lengths on each side of node

Loads – The model is capable of analyzing response to a wide variety of loads. For specific load types the following should be kept in mind.

Dead Load (DC & DW) – The dead load of structural components is calculated in most programs as a product of the dimensions and the material properties of the beam member. These loads are located along the main axis of the members and generally

oriented in the negative vertical direction. Unlike the spine beam model the grillage analogy model distributes this load much more accurately because the longitudinal members to the outside of the curve are longer than those to the inside. This automatically accounts for some of the eccentricity of dead load with respect to the centerline of the bridge. There still may be some eccentricity with respect to each line of longitudinal members, and this should be accounted for as uniformly applied torsional moments. Similarly, the dead load of overlays and utilities can be applied as uniform loads and moments along the axis of the superstructure members. Because the longitudinal members and transverse members representing caps and diaphragms include all self-weight of the superstructure, the remaining transverse members shall be weightless.

Live Load and Impact (LL & IM) – Live load effect on the bridge can be accounted for by placing live load lanes directly on the bridge, thus accounting for the eccentricity of these live loads directly. With this approach there is not need for wheel load distribution because the model accounts for it. Applying these loads by hand can be very tedious, and it is helpful if the program has a live load generator that can locate lanes transversely to the centerline of the superstructure as well as move live loads along the longitudinal axis of the bridge. In general fully loading all possible lanes will yield the maximum results for a given element, but load combinations involving loading of fewer lanes should be used to verify this.

Prestressing – Some programs allow for the definition of individual prestress tendons. These should be located in three-dimensional space. In other words their eccentricity to the centerline of the bridge should be considered. Initial and well as final prestressing forces should be considered. In both cases the transverse bending of the superstructure generated by these tendons will produce axial stresses that should be considered in determining the longitudinal response of the various individual girders.

Other Loads – The three dimensional nature of the model lends itself to the application of other loads. The model is even suitable for a multi-modal response spectrum analysis if the piers are divided into at least three segments to allow for a more uniform distribution of mass.

Results – Results in the form of nodal displacements and member end forces can be used for design. Notice the vector sum of the member end forces at a given node must be averaged for design. In the case of the grillage analogy, a correction must be made for the extra shear generated in some webs by what is termed residual torsion. This torsion is manifested in the longitudinal members, which have been made artificially stiff in torsion. The torsional forces in these members at any single bridge section must be combined and applied in a section analysis of the entire section to determine the shear flow resulting from torsion. This residual shear flow must be combined with flexural shear in the longitudinal members to obtain the correct shear demands for design. These results are then factored and combined according to the LRFD Bridge Design Specification to design individual members. A comprehensive Design Example is included in Appendix B.