7th Canadian Conference on Earthquake Engineering / Montreal / 1995
7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995

Seismic Analysis of Horizontally Curved Girder Bridges

L-Y. Lai[1]

ABSTRACT

The current AASHTO Guide Specifications for Horizontally Curved Girder Bridges requires that movement at each expansion bearing be permitted in a direction approximately along a line drawn from the fixed bearing to the expansion bearing. In addition, at least one bearing should be restrained in a direction perpendicular to this line. An alternate design practice is to restrict the movements in the radial directions at each end of a continuous superstructure unit while restraining the tangential movements at an intermediate support. Except for friction forces, both design methods essentially develop no reactions at the bearings due to temperature change, except friction forces. However, the optimum bearing design for seismic loads has not been determined.

This paper presents the results of a study on seismic response of curved girder bridges. Three-dimensional models are used to study the effect of expansion bearing layout, skewed support, bridge curvature, and deck superelevation on the seismic response of curved girder bridges.

INTRODUCTION

The system of supporting bearings is used to provide horizontal stability for the superstructure. Yet, movements must also be permitted in some horizontal directions to allow for expansion/contraction due to temperature change (Nakai and Yoo, 1988). The AASHTO Guide Specifications for Horizontally Curved Girder Bridges (AASHTO 1990) requires that movement at each expansion bearing be permitted in a direction approximately along a line drawn from the fixed bearing to the expansion bearing. In addition, at least one bearing should be restrained in a direction perpendicular to this line. An alternate design practice is to restrict the movements in the radial directions at each end of a continuous superstructure unit while restraining the tangential movements at one intermediate support. Any other interior bearings are designed as "floating", or free to move in all directions (Gaylord and Gaylord, 1990). Figure 1 shows the two expansion bearing arrangements for a typical three-span continuous curved girder bridge. Both bearing alignments are essentially statically determinate and develop no forces at the substructures due to superstructure temperature change, except friction forces. Different expansion bearing restraint alignments may affect the structure response to seismic excitation and consequently alter the forces in the substructures. However, the optimum bearing alignment between the two methods has never been investigated.

---

[1] Raytheon Infrastructure Services Incorporated, One Oxford Valley Mall, Suite 215, Langhorne, PA 19047

Ground motion at a site during an earthquake is highly irregular. Two horizontal components and one vertical component are usually present (Buckle et al, 1987). For seismic design, bridges are assumed to respond to earthquake excitations in one of the two horizontal directions, typically along the transverse and longitudinal axes of the bridge. Actual seismic excitation will most likely be oriented somewhere between these two principal directions. To account for this possibility, the current AASHTO Standard Specifications (AASHTO, 1993) "Division IA: Seismic Design" require that a combination of orthogonal seismic forces be applied to bridges. The elastic forces in the structure members are calculated by combining 100% of the earthquake-induced forces in one direction with 30% of the forces induced in the perpendicular direction. The bridge members are then designed for the larger of the two combined responses with the appropriate elastic reduction factor.

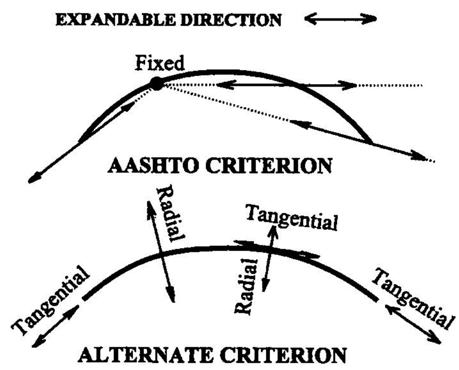


Figure 1. Bridge Expansion Arrangements

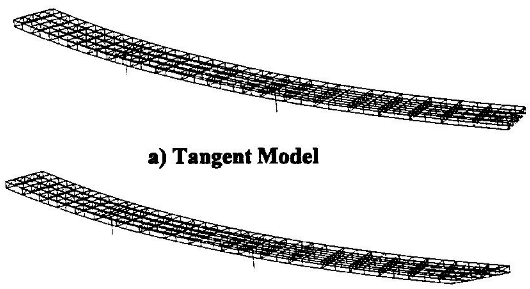
For a curved bridge, the chord connecting the abutments is usually considered the longitudinal direction. However, this arbitrarily chosen axis and the corresponding perpendicular axis may not be the most critical combination of seismic directions. Critical directions for applying seismic loads need to be identified to ensure proper design of the structure.

Significant error may occur from a line girder analysis if the bridge has skewed supports, because the transverse stiffness varies with respect to the longitudinal location along the bridge. Current seismic analyses are usually conducted by modelling the superstructure as a single line girder, except for unusual structures. All the superstructure mass and stiffness are lumped into this line element in the analysis. The effect of skewed support is not considered in this simplified model, and therefore, the accuracy of seismic analysis using a simulated line girder model is questionable.

In this paper, three-dimensional finite element models are used to study the effects of bearing expansion alignments, skewed support, and superelevation on seismic responses of curved girder bridges.

ANALYTICAL BRIDGE MODELS

An existing three-span continuous, five-girder bridge is used as the base line structure for generating the analytical finite element models. This bridge has a 33 degree skewed support at one abutment, measured from the tangential direction of the bridge. The span lengths are 52.43m-35.05m-25.60m on a single curvature with a radius of 298.7 m, measured along the center line of the bridge width. The central angle subtended by the abutments is 21.7 degrees and the ratio of the radius of curvature to the total bridge length is 2.64. The plate girders are 2.13 m apart, and the deck width is 8.69 m curb to curb with two traffic lanes. The 203 mm thick deck is fully composite with the plate girders. All piers are hammer-head type with the cap oriented in the radial direction, and are assumed to have the same height, same section properties and a fixed base. The fixed bearing is located at Pier 1 when the AASHTO bearing alignment is assumed. The abutments are assumed to be infinitely rigid and fixed at the bottom. The finite element models include the deck slab and diaphragms. The heights of the girders are also taken into account in the model. The concrete slab deck and the webs of the plate girders are modelled as plate elements. The flanges of the girders and the piers are modelled as beam elements. For the alternate bearing alignment, only three interior bearings at Pier 1 are restrained in the tangential direction in accordance with the common practice. The remaining two bearings are free to move in all directions.



a) Tangent Model

b) Skewed Model

Figure 2. Finite Element Models (228.6m Radius)

In order to study the effects of a skewed support, another model is generated from the base line model by changing a skewed support to a tangent support, but keeping the span lengths along the center line of the bridge width the same. Two other sets of finite element models are generated from the above models by changing the radius of the curvature from 298.7 m to 228.6 m and 182.9 m. The arc lengths and the cross section properties of the bridges are kept the same. By changing the radius length, the ratios of the arc span length to the radius are 2.02 and 1.62 for the radii of 228.6 m and 182.9 m, respectively. The tangent and skewed support models with a radius of 228.6 m are shown in Figure 2. Pier 1 is the pier near the skewed support.

All analyses are conducted by using the STAAD-III program (STAAD-III, 1994) on a personal computer. Multimode response spectral method with the AASHTO response spectra and SRSS modal combination with twenty modes were used to calculate the member responses. The earthquake acceleration was assumed to be 0.3G with soil type II at the bridge site. A damping ratio of 5% was assumed for all the bridges.

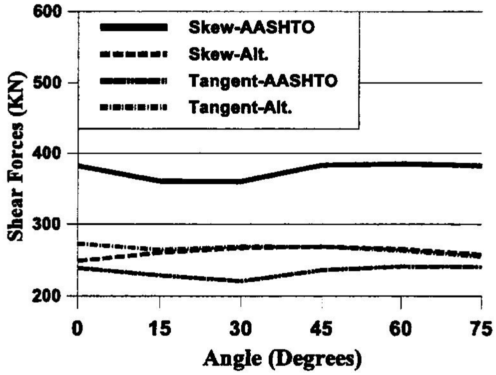
RESULTS

The eigenvalue analyses are conducted for the bridge model with a radius of curvature of 298.7 m. Table 1 summarizes the first mode natural periods for various combinations of bearing alignments and support conditions. The results show that bridge dynamic characteristics are significantly influenced by the bearing alignments. The structures with alternate bearing alignments are generally stiffer (smaller natural periods) than those using the AASHTO bearing alignments. The skewed support also influences the dynamic characteristics of the models with the AASHTO bearing alignment. However, skewed support has negligible effect on the structures using the alternate bearing alignment.

Table 1. Natural Periods (Seconds) 298.7m Radius

Skewed		Tangent	
AASHTO	Alt.	AASHTO	Alt.
0.87	0.66	0.72	0.66

The elastic forces in the substructures are computed as the bridge is excited by ground motion in various directions. Figures 3 and 4 show the unreduced elastic forces at the base of Pier 1 (fixed bearing



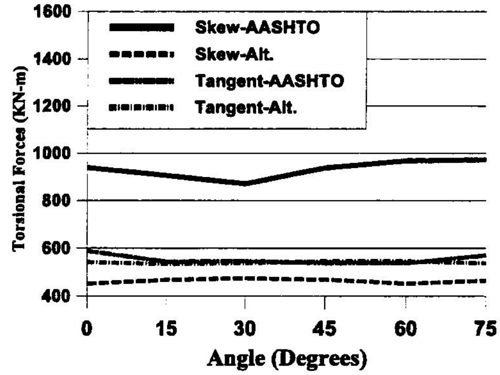


Figure 3
Shear forces in Pier 1

Figure 4
Torsional forces in Pier 1

for AASHTO bearing alignment). This location is usually the most critical in seismic resistance design. The forces are calculated by combining 100% of the earthquake-induced forces in one direction with 30% of the forces induced in the perpendicular direction. The abscissas in these figures are the angles of ground motion directions measured from the chord connecting the abutments, which represents the direction corresponding to zero degrees. For structures with skewed support, both shear and torsional forces in Pier 1 are significantly reduced if the alternate bearing alignment is used compared to the AASHTO alignment. The effect of bearing alignment reduces for structures with tangent supports.

Table 2 Forces in Pier 1
298.7 m Radius

	Skewed		Tangent	
	AASHTO	Alt.	AASHTO	Alt.
Shear (KN)	385	269	241	272
Torsion (KN-M)	972	474	588	546

Table 3. Natural Periods (Seconds)
228.6 m Radius

Skewed		Tangent	
AASHTO	Alt.	AASHTO	Alt.
1.72	1.15	1.50	1.15

The forces in Pier 1 are dependent on the direction of seismic excitation. For some cases, the seismic forces applied along the chord connecting the abutments and the corresponding perpendicular axis do not produce the most critical combination of seismic forces. The difference can be as large as 11% between all combinations of earthquake directions and should not be ignored. Table 2 shows the most critical combinations of the earthquake induced elastic forces in Pier 1. These forces are not necessarily excited by the earthquakes along the direction connecting the abutments and the corresponding

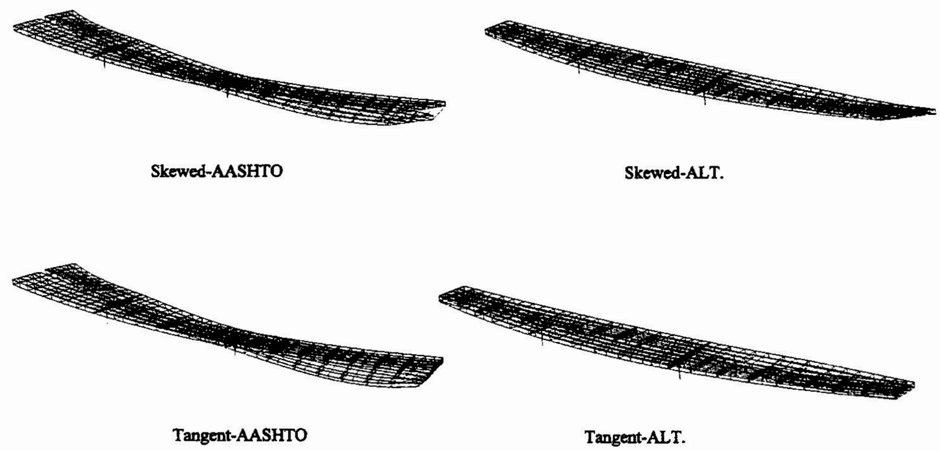


Figure 5. Modal shapes for the first modes (228.6m Radius)

perpendicular direction as recommended by the AASHTO specifications (1992). Generally speaking, the alternate bearing alignment performs better than the AASHTO alignment.

Table 4 Shear forces (KN) in Pier 1, 228.6 m Radius

Skewed		Tangent	
AASHTO	Alt.	AASHTO	Alt.
171	297	293	302

The effect of superelevation on seismic response is conducted by introducing a 0.05 m/m superelevation to the model with a skewed support and the AASHTO bearing alignment. The first mode natural period is computed to be 0.897 seconds, compared to 0.867 seconds for that without superelevation. The calculated elastic forces in Pier 1 are 3% reduced for shear but 37% increase for torsion compared to the model without superelevation. The difference is expected to be larger as the radius of curvature decreases.

To study the effects of curvature on seismic responses, the eigenvalue analyses are conducted for the structural models with the radii of 228.6 m and 182.9 m. Table 3 shows the first mode natural periods calculated for the models with a radius of 228.6 m. The result is similar to that obtained for the models with a radius of 298.7 m. The structures with alternate bearing alignment are stiffer and less sensitive to skewed support than those using the AASHTO alignment. All natural periods for the models with a radius of 228.6 m are larger than those for the models with a radius of 298.7 m. This coincides with the result obtained from a previous study (Kou et al, 1992).

Figure 5 shows the first mode modal shapes for themodels with a radius of 228.6 m. All modal shapes contain torsional mode vibration, which are different from the shapes for normal straight bridges. The modal shapes for the models with a radius of 298.7 m also have the similar patterns. Table 4 shows the shear forces calculated at the base of Pier 1. The AASHTO bearing alignment performs better for both tangent and skewed supports and the shear forces are smaller when a support is made skewed.

Table 5 Natural Periods (Seconds) 182.9 m Radius

Skewed		Tangent	
AASHTO	Alt.	AASHTO	Alt.
1.18	0.92	0.59	0.76

Table 6 Shear forces (KN) in Pier 1 182.9m Radius

Skewed		Tangent	
AASHTO	Alt.	AASHTO	Alt.
136	325	142	293

The first mode natural periods for the models with a radius of 182.9 m are shown in Table 5. For the structural models with a skewed support, the alternate bearing alignment design yields a lower natural period. However, the result is the opposite for the structural models with tangent supports. Also, the alternate bearing alignment design is influenced by the support skewed condition. The phenomena observed for the previous two structural model sets (298.7 m and 228.6 m radii of curvature) do not exist any more. The magnitudes of all natural periods are between the two previous models with larger radii, except the model with tangent supports and the AASHTO bearing alignment which has the lowest natural period among the three radii. The calculated natural period is not increased as the radius of curvature further decreases. This contradicts the conclusion made in the previous study (Kou et al, 1992). The modal shape corresponding to the Tangent-AASHTO model contains triple curvature torsional mode vibration, as can be seen in Figure 6, and is very different from the shapes computed for the models with larger radii of curvature.

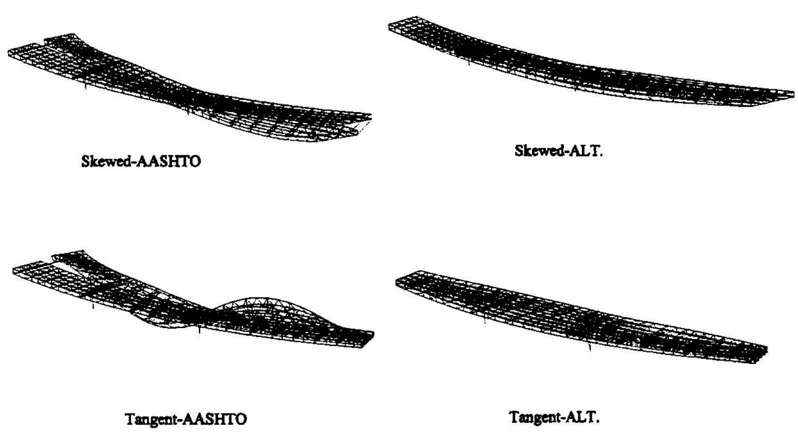


Figure 6. Modal shapes for the first modes (182.9m Radius)

The shear forces in Pier 1 are summarized in Table 6 for the models with a radius of 182.9 m. These forces are the combination of the earthquake induced forces along the direction connecting the abutments and the corresponding perpendicular direction. All shear forces in Pier 1 are larger when the alternate bearing alignment is used. This result is similar to that obtained from the models with a radius of 228.6 m, but is the opposite for the models with 298.7 m radius.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Bearing alignment and support skewed condition have significant influence on dynamic characteristics of curved girder bridge structures, especially when the curvature of the bridge is sharp.
2. For bridges with sharper curvature, the torsional mode vibration is more profound.
3. Seismic induced forces in the bridge components are dependent on the direction of seismic excitation. The seismic loads applied along the chord connecting the abutments and the perpendicular direction do not always yield the most critical combination.
4. The AASHTO bearing alignment appears to be better than the alternate bearing alignment when the curvature of a bridge is sharp. The structures using the alternate bearing alignment are stiffer and less sensitive to support skewed condition than those using the AASHTO alignment, when the radius of curvature is large.
5. If the arc length of a curved girder bridge is kept the same, the first mode natural period increases as the radius of curvature decreases. However, this relationship does not exist when the radius of curvature is decreased to a limit. Further study is needed to determine this dividing condition.
6. The result of a seismic analysis can be affected by including the superelevation in the analytical model of a curved girder bridge. The influence of superelevation may be magnified as the radius of curvature decreases.

REFERENCE

AASHTO, (1990). "Guide Specifications for Horizontally Curved Highway Bridges" Washington D. C..

AASHTO, (1992). "Standard Specifications for Highway Bridges, Division IA-Seismic Design", 15th Ed., Washington D. C.

Buckle, I. G., Mayer R. L., Button M. R., (1987). "Seismic Design and Retrofit Manual for Highway Bridges", FHWA-IP-87-6, Federal Highway Administration.

Gaylord, H. E, Jr., Gaylord, C. N., (1990). "Structural Engineering Handbook", McGraw-Hill, Inc. New York, NY.

Kou, C-H, Benzley, S. E., Huang, J-Y, Firmage, D. A., (1992). "Free Vibration Analysis of Curved Thin-Walled Girder Bridges", ASCE Structural Journal, Vol. 118, No. 10, October.

Nakai, H., Yoo, C. H., (1988). "Analysis & Design of Curved Steel Bridges", McGraw-Hill, Inc., New York, NY.

Research Engineers, Inc., (1994). "STAAD-III/ISDS, Integrated Structural Design System User's Manual, v. 19.0".