Seismic design force for single-span slab-girder skewed bridges

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ABSTRACT

This paper investigates the validity of seismic design force recommended by AASHTO for single-span bridges. The prescribed force is equal to the products of soil factor , acceleration and tributary weight of the structure. A three dimensional finite element analysis of straight and skewed bridges with skew angles varying from 0 to 60 degrees is used for this study. In the longitudinal direction, the bridges are assumed to be supported either by elastomeric bearings or a pinned support. In the transverse direction, the stiffness of end cross-frames is considered in the analysis. AASHTO 's recommended seismic design force for single-span bridges is compared with the El Centro time history and response spectrum analysis. It is concluded that AASHTO's recommended design force for single-span straight and skewed bridges could be unsafe in certain cases. An increase in the design force to a level equal to response spectrum value is recommended for such cases.

KEYWORDS

1. Introduction

The recent edition of American Association of State Highway and Transportation Officials, AASHTO-LRFD [1], proposes three methods for linear dynamic analysis of bridges in seismic zone 4: Single-mode, Uniform Load and Multi-mode methods. The single-mode (SM) and uniform load (UL) methods are used for regular bridges and the multi-mode (MM) method, which is a response spectrum analysis, is used for irregular bridges. Irregularity in a bridge may be defined as the possibility of coupling among the modes of vibration. This can happen in multi-span bridges with varying support stiffness, curved or skewed bridges.

In single-mode method (SM), a uniform load is applied to the bridge deck and its displacement calculated. By equating the kinetic and potential energies, the fundamental period of vibration in each direction is obtained. The formulation requires integration of displacement over the length of the bridge. In uniform load method (UL), the stiffness of the bridge is estimated based on the maximum displacement of the deck due to applied uniform loading. The period is obtained from a single degree oscillator model with known mass and stiffness. The multi-mode method (MM) is a three dimensional computer analysis, which results the exact periods of vibration. Using the AASHTO's design response spectrum in conjunction with Multi-mode analysis is a common practice for computer analysis of bridges.

For single-span bridges, AASHTO does not require any seismic analysis, regardless of seismic zone. However, it prescribes a seismic force equal to the products of site coefficient (S), acceleration coefficient (A) and tributary permanent load, for the design of superstructure supporting elements. Herein, this design method is called SxA method and is described in Articles 3.10.9.1 and 4.7.4.2 of AASHTO. For acceleration of 0.4g and site coefficient of 1.2, this force equals to 0.48 times the tributary weight of the structure. It is also mandatory to have cross-frames or diaphragms at the ends of a bridge to transfer lateral loads to the substructure. It

is implicitly understood that the code intends to use the above force for the design of cross-frames and bearings of single-span bridges, as well. In addition, AASHTO article 4.6.2.8.2, requires such members to be designed and detailed to remain elastic. However, as will be shown later, AASHTO's design response spectrum (RS) can yield much higher forces for cross-frames and bearings.

It is the objective of this paper to assess the accuracy of SxA method for single-span straight and skewed bridges with possible elastomeric bearing support in the longitudinal direction and end cross-frames in the direction of skew. Three dimensional finite element models of slab-girder bridges with elastic supports and skew angles of 0,15,30,45 and 60 degrees are used in this study. Bridge spans of 10m, 15m and 30m with widths of 10m and 14m are analyzed with SAP2000[2] finite element program. In each case the SxA method is compared with AASHTO's multi-mode (MM) response spectrum analysis and a typical time history (TH) analysis using El Centro ground motion.

A survey of literature shows that the validity of SxA method for single-span bridges with elastic supports has not been investigated. However, seismic response of skewed slab-on-girder bridges supported elastically has been studied by the author [3,4,5] previously. Zahrai and Bruneau [6] have considered the effect of cross-frame stiffness on the seismic response of straight bridges.
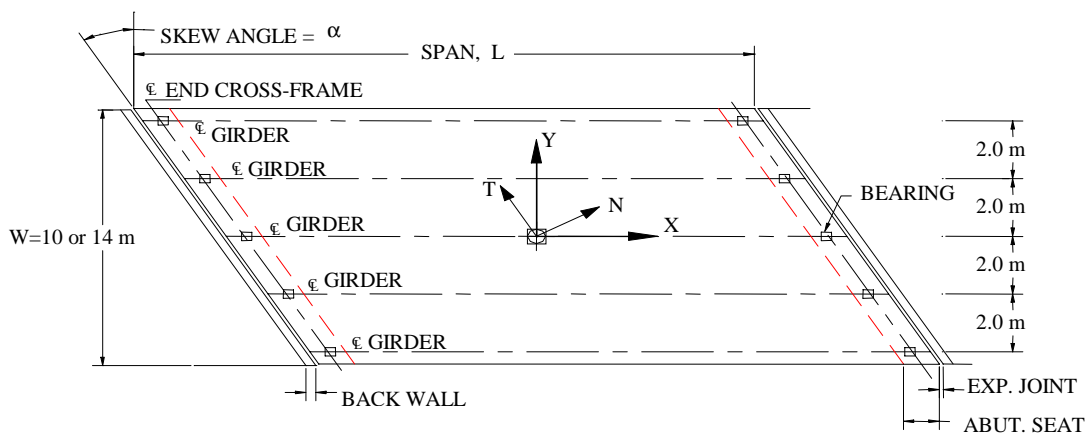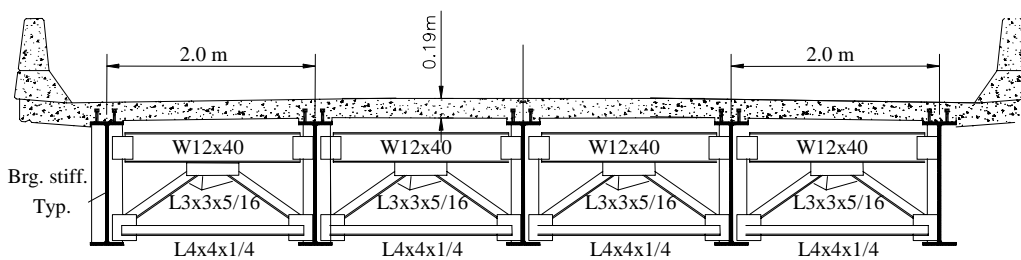

Fig. 1- Typical Skewed Bridge Plan View

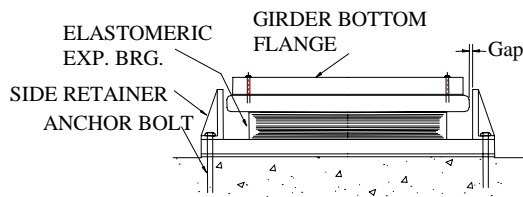**Fig. 2-** Cross-frame Detail

Fig. 3- Elastomeric Bearing Detail

2. Finite element models

A typical plan view of a skewed slab-girder bridge is shown in Fig. 1. These bridges are normally limited to a span of 20 meters with composite action between slab and steel girder. The concrete slab has a minimum thickness of 190 mm and sits on top of a steel rolled shape girder. The cross-sectional view of the bridge over the abutment depicting an end cross-frame is shown in Fig. 2. The elastomeric bearing detail is shown in Fig. 3. The cross-frame and bearing details are standard in the state of Illinois [7].

Note that the bridge and its support stiffness are symmetric and the centers of mass and rigidity coincide. Hence, the bridge will not be subjected to torsional vibration, unless the base motion is torsional. Furthermore, for single-span bridges the abutment stiffness is ignored. The justification for this assumption is described herein. Single-span bridges usually have an expansion joint, at least on one side. A gap separates the deck from abutment backwall. This gap has no effect on the transverse and longitudinal vibration of a bridge. Only in an extreme event activity in the longitudinal direction, the gap could close and the deck could impact the backwall. This study is only concerned with linear elastic behavior under Design Earthquake. The impact effect and non-linear behavior under Maximum Credible Earthquake are ignored.

The finite element model of the same bridge is shown in Fig. 4. SAP2000 finite element program [2] is used for analysis. The model has two displacement degrees of freedom, u_x, u_y, and one rotational, u_θ. Since cross-frames and lateral load resisting elements of the superstructure are supposed to remain elastic under earthquake forces, only linear dynamic analysis is performed on the models. This is consistent with AASHTO article 4.6.2.8.2.
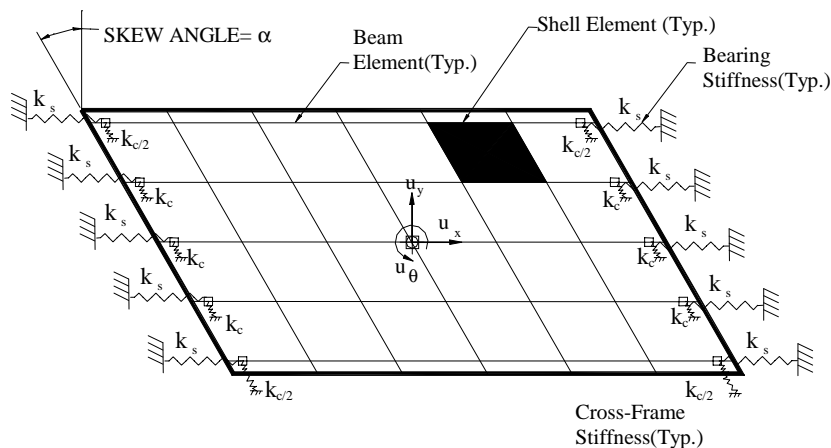
Fig. 4- Typical Finite Element Bridge Analysis model

The springs k_e represent the stiffness of elastomeric bearing in the X direction, and springs k_c represent the stiffness of the end cross-frames in the T direction. For the end girders only half of k_c is used. End cross-frames provide an important load-path for the seismically induced loads. Seismic forces at the deck would have to pass through the cross-frames to arrive at the top of bearings. Zahrai and Bruneau [6], have shown that intermediate cross-frames do not affect the seismic performance of slab-girder bridges significantly. Hence, they are not considered in the model.

Note that abutment stiffness is not modeled. Abutments are, in general, much stiffer than cross-frames and elastomers. Since abutments and these elements are, in effect, springs connected in series, the equivalent spring has a stiffness equal to cross-frame or elastomeric bearing. However, an extreme case of having a pinned support at one end of the bridge, in the longitudinal direction, is considered.

The deck slab is modeled with rectangular shell elements. The girders are modeled with frame elements connected to shell elements at each joint. They are free to rotate but restrained vertically at each end. This will capture the contribution of girders' weak-axis moment of inertia to the superstructure stiffness for transverse loading. In the longitudinal direction, the end of the girder is attached to a spring representing the elastomer's lateral stiffness. The modeling of superstructure is consistent with recommendations of Mabsout et al. [8].

The mass of the bridge is assumed to be uniformly distributed over the bridge deck and it is assigned as mass density to the shell elements. To consider the effect of bridge geometry, span lengths of 10m, 20m and 30m and widths of 10m and 14m are considered in the analyses. This covers short, medium and long span slab-girder bridges. The change in width considers the effect of mass on the response. The author has found that the effect of width is negligible and showing the results for 10m and 14m widths proves this point. This is due to the fact that with higher widths more girders and bearings are added and the cross brace is also extended. This will increase stiffness in all directions and compensates for the increase in mass. Hence, the support reactions are not affected substantially. Note that if the number of girders is not increased for wider bridges, then the spacing between girders must be increased. This is usually not done in practice, because it leads to thick concrete slabs and an uneconomical design. The usual spacing in slab-girder bridges is kept in the range of 1.5-2.5 meters. In all examples to follow a spacing of 2 meters is assumed.

The mesh sizes used for shell elements, girder sizes, spring constants k_c and k_e, and other dimensions and properties of bridges used in the analyses are given in Table 1. Note that spring constants represent typical practical values used for these bridges and correspond to details shown in Figs. 2 and 3.

Table 1- Bridge Properties Used in Analyses

Span (m)	Width (m)	Deck Thk. (m)	Girder Size (US Std.)	Number of Girders	Shell Size (m)	Elastomer Ke (kN/m)	Cross-frame Kc (kN/m)	Mass (kg)
10	10	0.19	W30x99	6	2x2	1000	162338	54450
20	10	0.19	W40x221	6	2x2	1000	162338	130500
30	10	0.19	W40x268	6	2x3	1000	162338	208500
10	14	0.19	W30x99	8	2x2	1000	162338	75600
20	14	0.19	W40x221	8	2x2	1000	162338	180000
30	14	0.19	W40x268	8	2x3	1000	162338	287000

The models described above are analyzed using SAP2000 program under three loading conditions. These are SxA force, AASHTO's response spectrum force and forces from El Centro ground motion. The loads are discussed and compared in the next section.

3. Seismic design force for bridges

As explained earlier, according to AASHTO Article 4.7.4.2, single-span bridges require no seismic analysis and only the connection of the superstructure to substructure is designed for an acceleration of SxA; where, A is the peak ground acceleration for the seismic zone and S is the site coefficient. For soil type II, the coefficient S is equal to 1.2. Therefore, supporting elements have to be designed for a force equal to 1.2A times the tributary weight. It is interesting to note that choosing the more elaborate response spectrum (RS) analysis method yields a design force equal to 2.5A times the tributary weight for pin supported bridges. This is because single-span slab-girder bridges with pinned supports have a very low period and in that range (below 0.44 sec.) AASHTO's response spectrum shows a constant acceleration of 2.5A for soil types I and II. This is more than twice the recommended 1.2A force for soil type II, per SxA method. However, the fundamental period of vibration can be higher than 0.44 seconds when the bridge is supported on elastomeric bearings on both sides.

To investigate the accuracy of SxA force for single-span bridges, the bridge models are subjected to a response spectrum with constant acceleration of (SxA=1.2x0.4g=)0.48g in two orthogonal directions. The results are compared with AASHTO's design response spectrum for soil type II, with peak ground acceleration A=0.4, and a response modification factor R=1. In addition, a linear dynamic time history analysis using El Centro accelerogram with 2% damping is performed on the models, for illustrative purposes. The force demand on supporting elements, such as, elastomeric bearings, pinned supports and cross-frames, are compared for all three loading cases.

Figs. 5a-5c show the variation of elastomeric shear force versus span length for a bridge supported on elastomeric bearings on each side for the three loading conditions discussed above. Figs. 5d-5f are the plots of the same variables for a bridge pinned at one end and free at the other end. The plots in Fig. 5 are for a 10 m wide bridge. The same variables are plotted in Fig. 6 for a 14m wide bridge. In each case, the shear force is the reaction of an individual k_e spring of the analysis model.

Comparing Fig. 5 and Fig.6, it is observed that the bridge width (or mass) is not a factor in the conclusions to be drawn. This was discussed in the previous section and expected. In all cases, and for all loading conditions, it is concluded that the reaction shear force in the longitudinal direction increases with increasing span lengths. However, bridges with 45 degrees skew or higher, and with span lengths of 30m behave erratically under time history loading. The behavior is highly dependent on the frequency content of the input motion. Higher modes of vibration and torsional modes contribute to the behavior of these long-span highly skewed bridges. In addition, for bridges with skew angles over 45 degrees, the maximum response reverses its direction. This means that the maximum reaction in the X-direction is obtained by applying the earthquake motion in the Y-direction and vice-versa. Comparing parts (a) and (c) or parts (d) and (f) of Figs. 5 or 6, it is concluded that using the SxA method can be highly unsafe for these kinds of bridges.

For ordinary bridges, supported on elastomeric bearings, the SxA force yields lower reaction than response spectrum and time history analyses. For pin supported bridges, SxA yields lower forces than response spectrum and higher forces than El Centro time history.

Note that the periods in the longitudinal direction are several times lower for pin supported bridges than bridges supported on elastomers. This varies the force demand in response spectrum and time history analyses for pinned bearings, but the SxA method remains unaffected, because it is not period dependent.

Fig. 7 shows the variation of cross-frame shear force versus span length for different skew angles and support conditions for a 10m wide bridge. Fig. 8 shows the same variables for a 14m wide bridge. Comparing the two figures indicates that the trend in behavior is the same.

It is observed that the cross-brace shear force increases with increasing span lengths. The shear is almost the same for all skew angles ranging from 0 to 30 degrees. However, for skews of 45 degrees or higher the force increases with increasing skew angle. In all cases, the response spectrum method has yielded a higher force than SxA method. Time history analysis has yielded a lower force than SxA method in all cases, except for 30 m span with 60 degrees skew (Fig. 6(f)) in a pin supported bridge. This indicates that long-span and highly skewed bridges require special attention and the actual forces induced in supporting members can be several times higher than SxA method. However, even in an extreme case described above, the forces are lower than the response spectrum method.
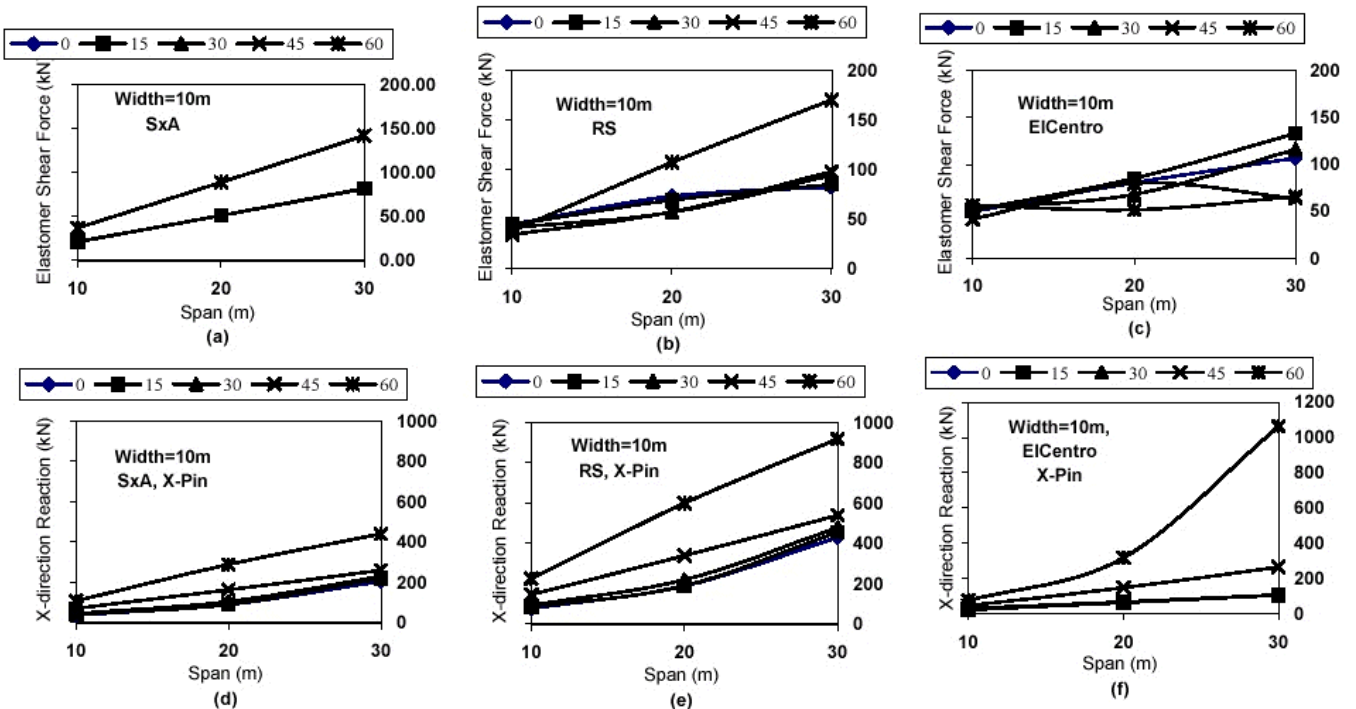
Fig. 5- Longitudinal Shear Force vs. Span, 10m wide bridge; (a)&(d): SxA Method, (b)&(e): AASHTO Response Spectra, (c)&(f): El Centro Time History; (a),(b),(c): Elastomeric Bearing;(d),(e),(f): Pinned Bearing
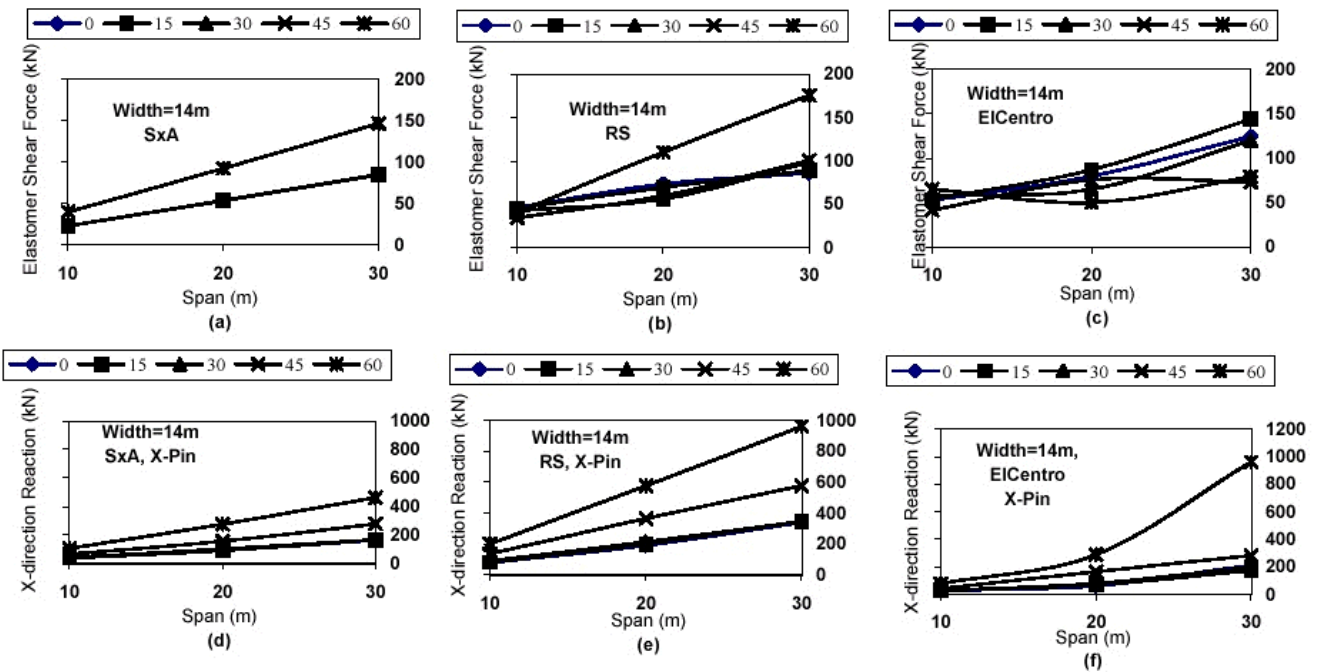

Fig. 6- Shear Force vs. Span Length, 14m wide bridge; (a)&(d):SxA Method, (b)&(e):AASHTO Response Spectrum (c)&(f): El Centro time history; (a),(b)(c): Elastomeric Bearing; (d),(e),(f): Pinned Bearing
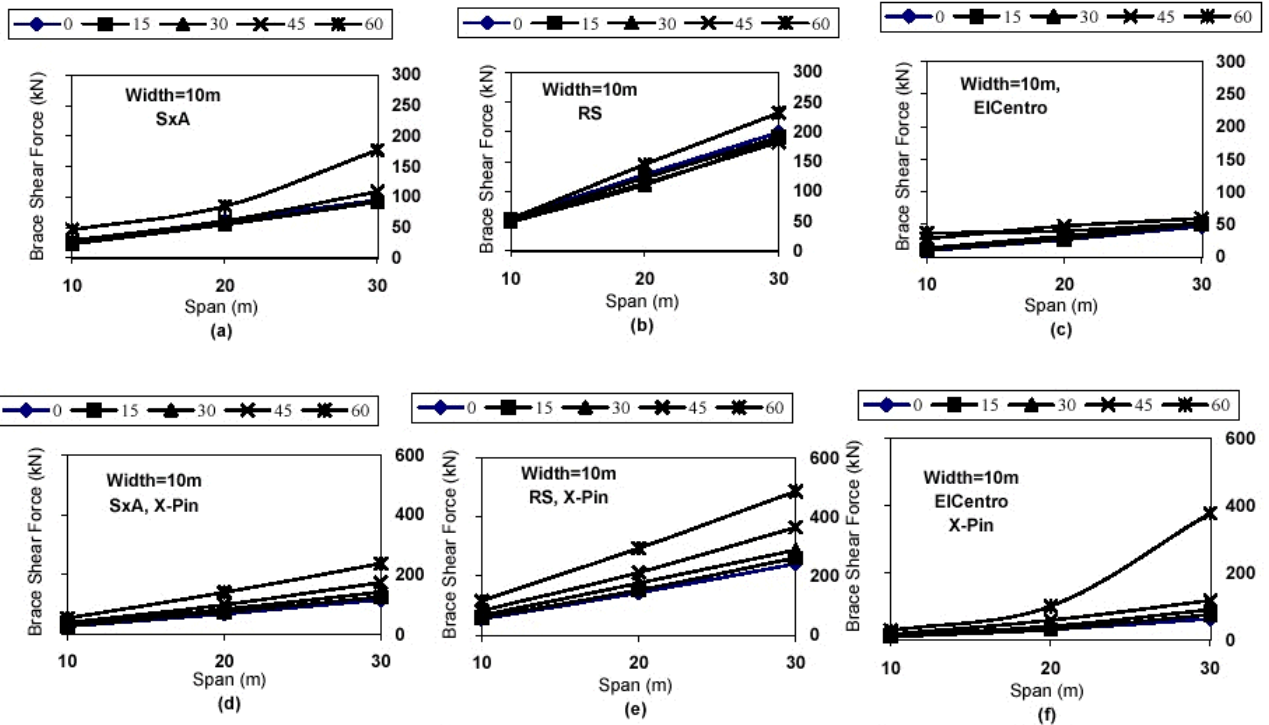
Fig. 7- Brace Shear Force vs. Span, 10m wide bridge; (a)&(d): SxA Method, (b)&(e): AASHTO Response Spectra, (c)&(f): El Centro Time History; (a),(b),(c): Elastomeric Bearing;(d),(e),(f): Pinned Bearing

Fig. 8- Brace Shear Force vs. Span, 14m wide bridge; (a)&(d): SxA Method, (b)&(e): AASHTO Response Spectra, (c)&(f): El Centro Time History; (a),(b),(c): Elastomeric Bearing;(d),(e),(f): Pinned Bearing
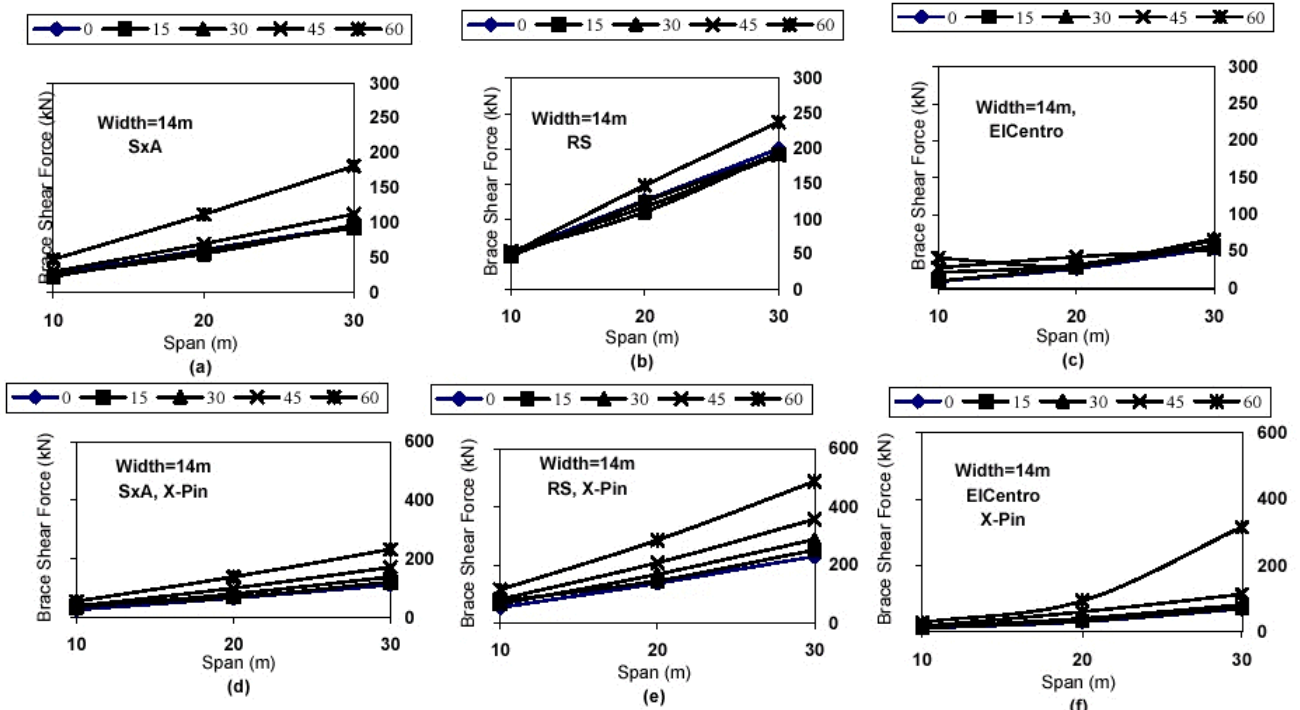
It is concluded that AASHTO's design response spectrum is conservative for both transverse and longitudinal vibrations and for all ranges of support stiffness. For short to medium span ranges of pin supported bridges, the SxA method yields acceptable force demand in the supporting members. However, in other cases, the SxA method yields unsafe results.

The author recommends that the design force for single-span bridges, in seismic zones 3 and 4, be changed to 2.5xA. This is almost equal to peak value of the design response spectrum for soil types I and II. The above discussion and Figs. 5-8 have shown that this value is conservative for all cases. Alternatively, for bridges with periods higher than 0.44 seconds, a response spectrum analysis can be performed to yield a more economical design.

4. Conclusions

Analytical study of single-span slab-girder bridges with spans ranging from 10 to 30 meters, and widths of 10 and 14 meters, has revealed that the prescribed seismic force by AASHTO Articles 3.10.9.1 and 4.7.4.2 (SxA method) can lead to analysis forces that are lower than response spectrum (RS) method. Both straight and skewed bridges have been considered in this study. In addition the longitudinal girder support was examined under two cases of elastomeric and pinned support. A linear dynamic three dimensional finite element analysis was utilized.

Results from AASHTO's response spectrum analysis were compared to SxA force method. The design RS of AASHTO represents an ensemble of design basis earthquakes and is taken as a prime measure of safety here. A time history analysis based on El Centro ground motion was also added for illustrative purposes. It was shown that AASHTO's RS yields more conservative results for both transverse and longitudinal vibrations and for all ranges of support stiffness. However, time history analysis can yield support shears several times higher than SxA method. Since El Centro is a typical design basis earthquake with a peak ground acceleration of only 0.32g, the SxA method is considered unsafe for design. The author recommends that the design force for single-span bridges, in seismic zones 3 and 4, be changed to 2.5xA. This is equal to peak value of AASHTO's design response spectrum for soil types I and II and it is conservative for all cases.

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