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SEISMIC DESIGN OF SINGLE SPAN STEEL GIRDER BRIDGES AND BRIDGES IN SEISMIC PERFORMANCE CATEGORY A

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ABSTRUCT

This paper studies the validity and accuracy of the seismic design force recommended by AASHTO for single span bridges. A parametric study for single steel girder bridges is presented, included the effect of span length and elastomeric bearing and lateral bracing (cross-frame) stiffness. The results of simplified AASHTO method are compared with response spectrum and time history analysis. Also studying the seismic design reqiurements for continuous steel girder bridges in seismic performance category (A), included the effect of span length, seismic zone, effect of elastomeric bearing and cross-frame stiffness and bridge skew on their seismic responses. It is concluded that the AASHTO simplified analysis method for single span bridges underestimates the seismically induced forces at supports and the proposed seismic design force of (2.5 multiplied by acceleration coefficient multiplied by tributary weight w(x)) has been recommended for single span bridges for seismic zone 3 and 4 and for soil type II. Also it is observed that the seismic design force for two span continuous bridges in performance category A is safe and conservative method to predict the shear forces transferred by connection elements to the substructures.

الخلاصة

يدرس هذا البحث صلاحية ودقة قوى التصميم الزلزالية الموصاة من قبل (AASHTO) للجسور ذات الفضاء الواحد. تم عمل دراسة مقارنة للجسور ذات العوارض الفولاذية بفضاء واحد متضمنة تأثير طول الفضاء و صلابة الوسائد المطاطية وانظمة التثبيت الجانبي. تم مقارنة نتائج طريقة ال AASHTOالمبسطة مع طريقة طيف الاستجابة والتحليل الزمني. أيضاً تم دراسة متطلبات التصميم الزلزالي لجسور العارضة الفولاذية المستمرة في صنف الأداءِ الزلزالي (A)، متضمنة تأثير طول الفضاء، المنطقة الزلزالية، تأثير صلابة الوسائد المطاطية وانظمة التثبيت الجانبي وإنحراف الجسر على استجاباتهم الزلزالية. تم التوصل الى ان طريقة ال (AASHTO) المبسطة لتصميم الجسور ذات فضاء واحد تقلل من مقدار القوى عند المساند وان القوى التصميمية المقترحة من (2.5) مضروبة في معامل التعجيل (A) مضروبة في و زن منتظم W(X) ينصح بها لتصميم الجسور ذات الفضاء الواحد للمناطق الزلزالية 3 ,4 و لنوع التربة II. وايضاًاظهرت الدراسة ان قوة التصميم الزلزالية (20%من وزن المنشأ) الموصى بها من قبل ال (AASHTO) للجسور الواقعة في صنف الاداء الزلزالي (A) أمينة ومحافظة للتنبأ بمقدار قوى القص المنتقلة عبر عناصر الربط الى الهيكل السفلي.

KEYWORDS: Seismic; Design; Steel girder; Bridge; Elastomeric bearing; Cross frame

SEISMIC DESIGN OF SINGLE SPAN STEEL GIRDER BRIDGES

INTRODUCTION

The recent edition of AASHTO specification ***(AASHTO, 2002)*** does not required any seismic analysis, regardless of seismic zone for single span bridges. However, AASHTO required that the connection between the superstructure to substructure shall be designed to resist a force equal to design acceleration coefficient (A) multiplied by the site coefficient (S) multiplied by the tributary weight at the abutment.

To study the validity and accuracy of the seismic design force recommended by AASHTO for single span bridges, a parametric study for single span steel-girder bridges is presented in this paper included the effect of span length and support stiffness (bearing and cross-frame stiffness) on seismic response of these bridges.

DESCRIPTION OF BRIDGES

A steel-girder bridge consisting of (0.24m) reinforced concrete slab built integrally with rolled steel beams spaced at (2 m) is studied. The carriage way is (10 m) and the slab has a (1 m) overhang on both sides of the deck. The span lengths of these bridges range between 20 and 60 m with increment of (10 m). The end of steel beam is placed on elastomeric bearing in the longitudinal direction and the steel girders are connected together by cross-frames as shown in Fig. (1). The bridges are designed according to the AASHTO requirements and the bearings are designed according to Iraqi loading. The properties of bridges are summarized in tables (1) and (2).

The slab is modeled with (2×2 m) shell elements and the girders are modeled by frame elements connected to the shell elements at each joint. The end of each girder is attached to a spring representing the elastomer's lateral stiffness in longitudinal direction and in transverse direction it is attached to a spring representing the lateral stiffness of end cross-frame. The value of stiffness for both elastomeric bearing and lateral bracing system is determined as explained in the following sections. The finite element model of the bridges is shown in Fig. (2). Modeling of the superstructure is consistent with recommendations of ***(Tarhini and Frederick, 1989)*** and ***(Mabsout, et. al., 1997)***. SAP 2000 finite element program is used for analysis (***Computer and Structures, SAP 2000, 1998***).

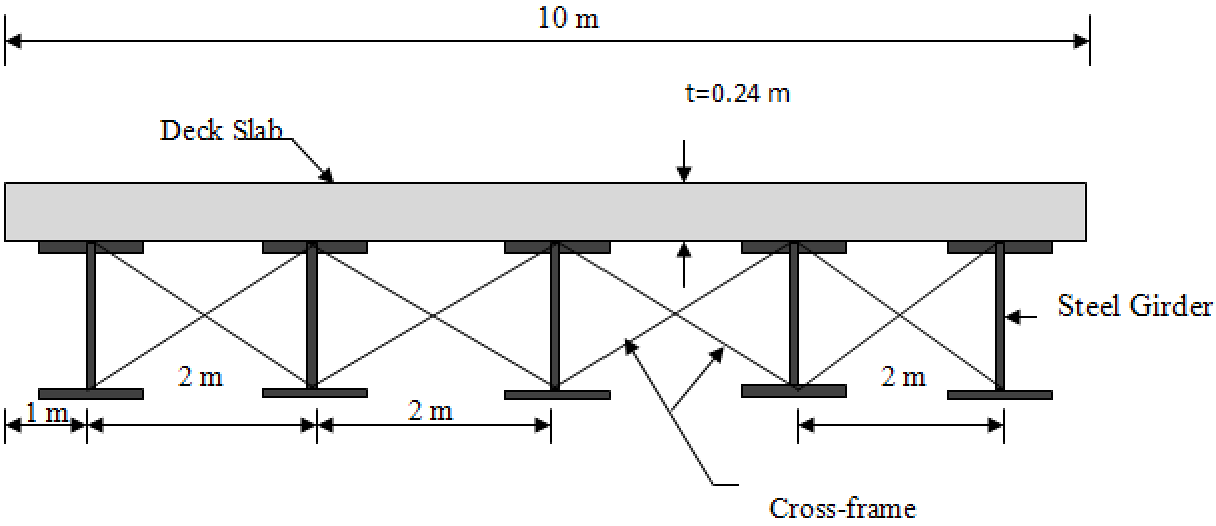


Fig. (1) Cross section of the bridge

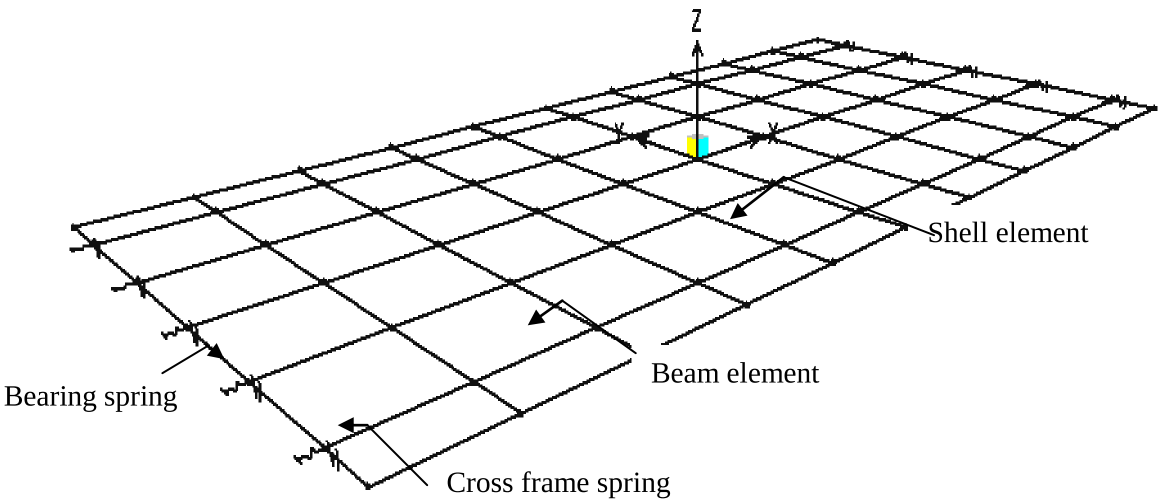


Fig. (2) Finite element model of the bridge

Table (1) Properties of the bridges used in the analysis

L (m)	t_s (m)	Girder properties								
		h (m)	b_{fb} (m)	b_{ft} (m)	t_{fb} (m)	t_{ft} (m)	t_w (m)	A (m^2)	I_y (m^4)	I_Z (m^4)
20	0.24	1.0	0.58	0.5	0.055	0.025	0.008	0.05176	0.00910	0.00116
30	0.24	1.4	0.58	0.5	0.055	0.025	0.011	0.05892	0.01977	0.00116
40	0.24	1.7	0.58	0.5	0.055	0.025	0.014	0.06708	0.03177	0.00116
50	0.24	2.0	0.65	0.6	0.060	0.030	0.015	0.08565	0.05840	0.00191
60	0.24	2.4	1.00	0.8	0.080	0.040	0.018	0.15304	0.15080	0.00800

Table (2) Properties of elastomeric bearing and lateral bracing systems

Span (m)	Elastomeric bearing size(mm) [DIN 4141]	Cross-frame size (mm)	Bearing stiffener size (mm)	K_e (kN/m)	K_b (kN/m)	
					In. beam	Ex. beam
20	200 × 300 ×52	L120 × 10	2PL.130 × 10 × 920	1622	417237	233892
30	200 × 400 × 52	L160 × 10	2PL.150 × 14 × 1320	2162	309669	173148
40	300 × 400 × 74	L180 × 12	2PL.150 × 14 × 1620	2264	262602	141496
50	300 × 400 × 74	L180 × 14	2PL.180 × 16 × 1910	2264	273469	148843
60	350 × 450 × 69	L200 × 15	2PL.200 × 18 × 2280	3214	197475	104898

STIFFNESS OF LATERAL BRACING SYSTEM

Diaphragms provide an important load path for the seismically induced load acting on slab steel-girder bridges. ***Zahrai and Bruneau*** *(1998)* have shown that the intermediate cross-frames do not affect the seismic response of straight slab on girder bridges, in either the elastic or inelastic range also proposed a simplified model for bridge with only end cross-frames as shown in Fig. (3).

The stiffness of lateral bracing system (k_b) at one end depends on the geometry of the bridge and the properties of the bearing stiffeners and diaphragm braces. K_b can be calculated by the following equation (***Zahrai and Bruneau, 1998***):

$$k_b = \sum_1^{ng} \frac{12EI_s}{h_w^3} + \sum_1^{ng-1} \frac{2EA_b \cos^2\theta}{L_b} \qquad (1)$$

The k_b for each interior steel beam can be determined from the following formula:

$$k_b = \frac{12EI_s}{h_w^3} + \frac{2EA_b \cos^2\theta}{L_b} \qquad (2)$$

The k_b for exterior steel beam can be determined from the following formula:

$$k_b = \frac{12EI_s}{h_w^3} + \frac{EA_b \cos^2\theta}{L_b} \qquad (3)$$

where:
I_S : moment of inertia of the bearing web stiffener about the longitudinal axis of girder.
ng : the number of girders.
h_w : the web height between top and bottom flanges.
A_b : cross sectional area of the brace.
L_b : length of brace.
θ : slope angle of brace.

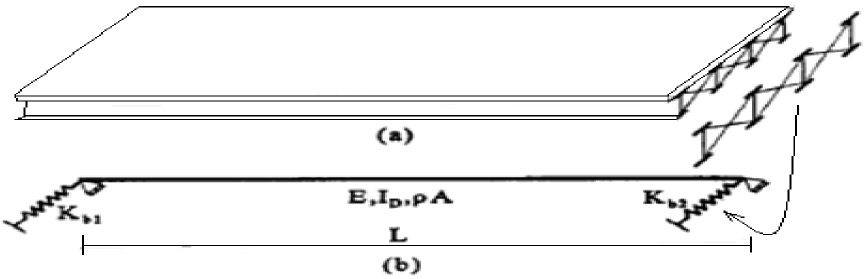


Fig. (3) Schematical simplified model for bridges with end diaphragms
(*Zahrai and Bruneau, 1998*)

Elastomeric Bearings Stiffness

The elastomeric bearings transmit the force from the superstructure to substructure. Spring is used to model the stiffness of elastomeric bearing (k_e) in the longitudinal direction. The value of bearing stiffness can be determined from the following equation (***Mast et. al., 1996***):

$$k_e = \frac{G\,A}{T} \tag{4}$$

where:
G : shear modulus of elastomer.
A : area of bearing.
T : total thickness of rubber layers.

SEISMIC DESIGN FORCE FOR BRIDGE

The bridges are assumed to be located in Iraq (Baghdad city). The contour map in AASHTO is for United State. Depending on UBC code (Uniform Building Code), Baghdad is located in zone 3 and the AASHTO divided the region into contour lines with (A) range (A>0.29), therefore (A) for Baghdad is assumed to equal (0.3).
To study the validity and accuracy of seismic design force recommended by AASHTO for single span bridge, the bridge models are analyzed for three loading cases:

- Multi mode response spectrum analysis ***(MMRS method)***: using the AASHTO'S design response spectrum curve for seismic zone of acceleration coefficient (A) equal to (0.3) and soil profile type II (Site coefficient (S)=1.2).
- Simplified AASHTO method ***(AASHTO method)*** in this method the bridge models are subjected to load of (S×A=1.2×0.3w(x) = 0.36w(x)) in two orthogonal directions.
- Time history analysis ***(TH method)*** in this method the bridges are assumed to excite by a real earthquake time history accelerogram. El Centro earthquake accelerogram of May 18, 1940 is used for time history analysis. The El Centro horizontal component (north-south component) is applied in the two horizontal directions (X, Y) and the ground acceleration data includes 1559 data points of equal time intervals of (0.02 sec) (***Chopra, 1996***). The numerical values of the data are in units of the gravitational acceleration (g).

The response spectrum for El Centro ground motion with scale ratio of (3/4) and 5% damping ratio agrees well with the AASHTO design response spectrum for acceleration coefficient (A=0.3) and soil type II (S=1.2) as shown in Fig. (4), therefore, the (3/4) scaled El Centro accelerogram with 5% damping ratio is used for linear time history analysis. The response spectrum of El Centro ground motion is obtained and drawing by using SAP Nonlinear program.

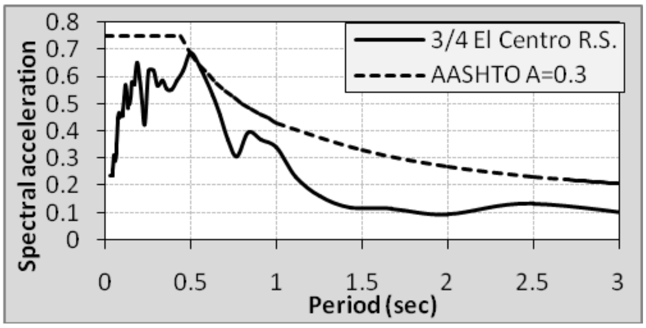


Fig. (4) Comparison of El Centro spectrum with AASHTO design spectrum for A=0.3

To investigate the effect of support stiffness, the bridge models are analyzed with four cases of support conditions which are:

- Case (1) **spring support**: springs (k_e) and (k_b) attached at end of each girder in longitudinal and transverse directions, respectively.
- Case (2) **pin-y:** spring (k_e) in longitudinal direction and (k_b) is replaced with pin support in transverse direction.
- Case (3) **pin-x:** one end is pin support and another is free in the longitudinal direction, while spring (k_b) in transverse direction.
- Case (4) **pin x-y:** one end is pinned and another is free in the longitudinal direction and pin support in the transverse direction.

Fig. (5) shows that the AASHTO design response spectrum have a constant acceleration of (2.5A) for soil type I and II for periods below than (0.43715 sec). The single span bridges which are studied have periods less than (0.43715 sec) of transverse vibration for all support stiffness and of longitudinal vibration with pin-x and pin x-y cases. The bridges are analyzed for seismic force of 2.5 A multiplied by tributary weight.

I

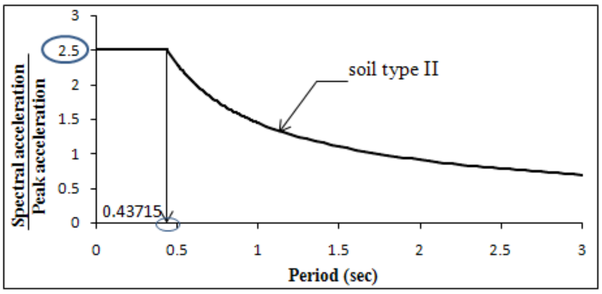


Fig. (5) Normalized response spectra

The variation of longitudinal periods against the span length for bridge models with different support conditions is shown in Fig. (6). Whereas, The longitudinal period decreases severely when the elastomeric bearing stiffness reached infinity (pin-x support). However, the periods of spring and pin-y condition coincide. This means that longitudinal vibration is unaffected by the lateral bracing stiffness (cross-frame stiffness). The longitudinal period for all cases increase as the span length increases. Fig. (7) shows the variation of transverse periods against span length for different support conditions. Comparing the transverse period for spring support and pin-y support condition, it can be concluded that the period decrease as the stiffness of cross-frame increases toward infinity (pin-y). The transverse period for pin-x support is closed to period for elastic support for span length upon (30 m) that means the increasing of elastomeric bearing to infinity for span length upon (30 m) does not affect the transverse period significantly.

Maximum longitudinal and transverse deck displacements due to MMRS method versus span length are plotted in Figs. (8) and (9), respectively. It is shown that the displacement increases as span length increases. The longitudinal displacement for bridges which are supported on elastomers is much higher that for bridges with pin-x support, because that the bridges with elastomers support are more flexible and have vibration periods higher than for pin-x support bridges by several times.

Fig. (10) shows the variation of longitudinal shear forces against span length for the three loading cases. In the longitudinal, the simplified AASHTO and time history forces are very close for all support conditions, but the MMRS method is yielding a higher force than (AASHTO) and (TH) methods.

Fig. (11) shows the variation of transverse shear forces versus span length with different support conditions for the three loading cases. In transverse direction, the simplified AASHTO method yields a higher force than time history force at 20m span length, but for span length beyond 20 m, the simplified AASHTO method yields a lower force demand for all support conditions and it become unsafe. While the MMRS method is yielding higher forces than (AASHTO) and (TH) methods.

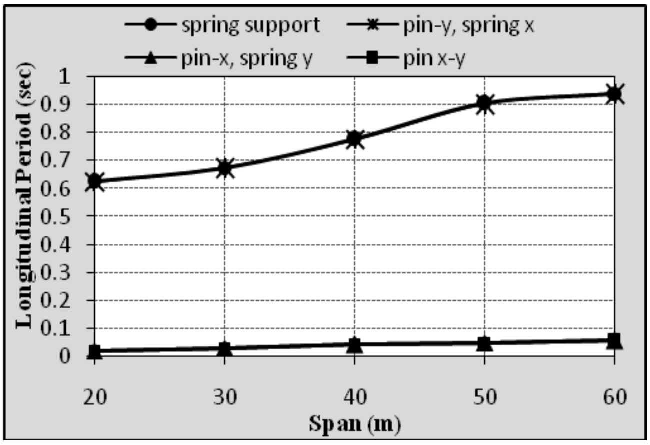


Fig. (6) Longitudinal period variation versus span length for a single span bridge with different support conditions.

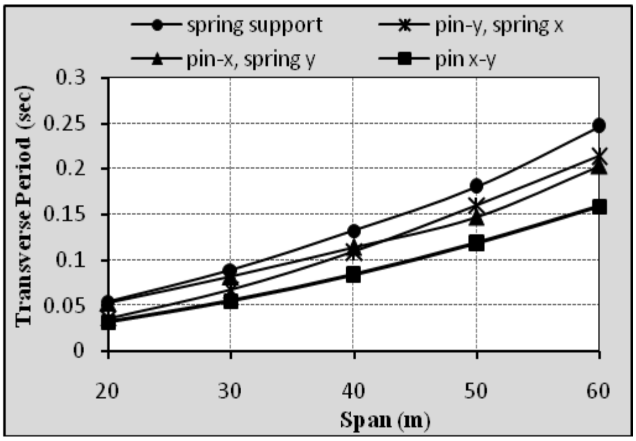


Fig. (7) Transverse period variation versus span length for a single span bridge with different support conditions

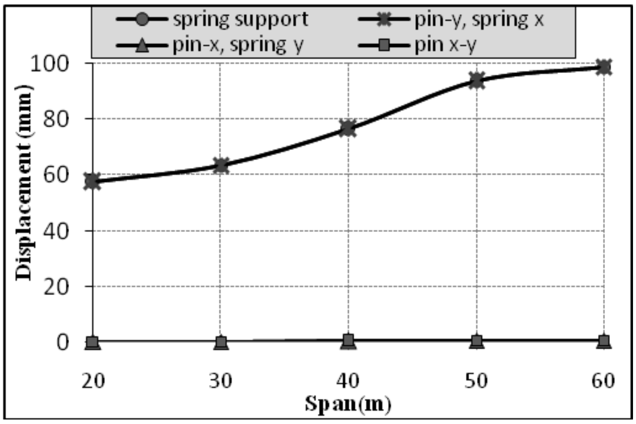


Fig. (8) Longitudinal displacement due to MMRS method versus span length.

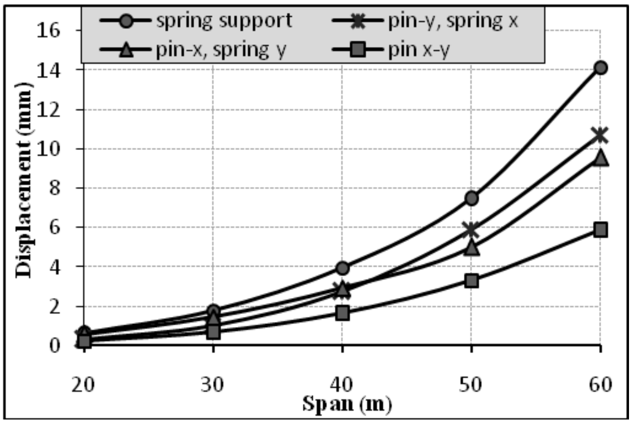


Fig. (9) Maximum transverse displacement due to MMRS method versus span length.

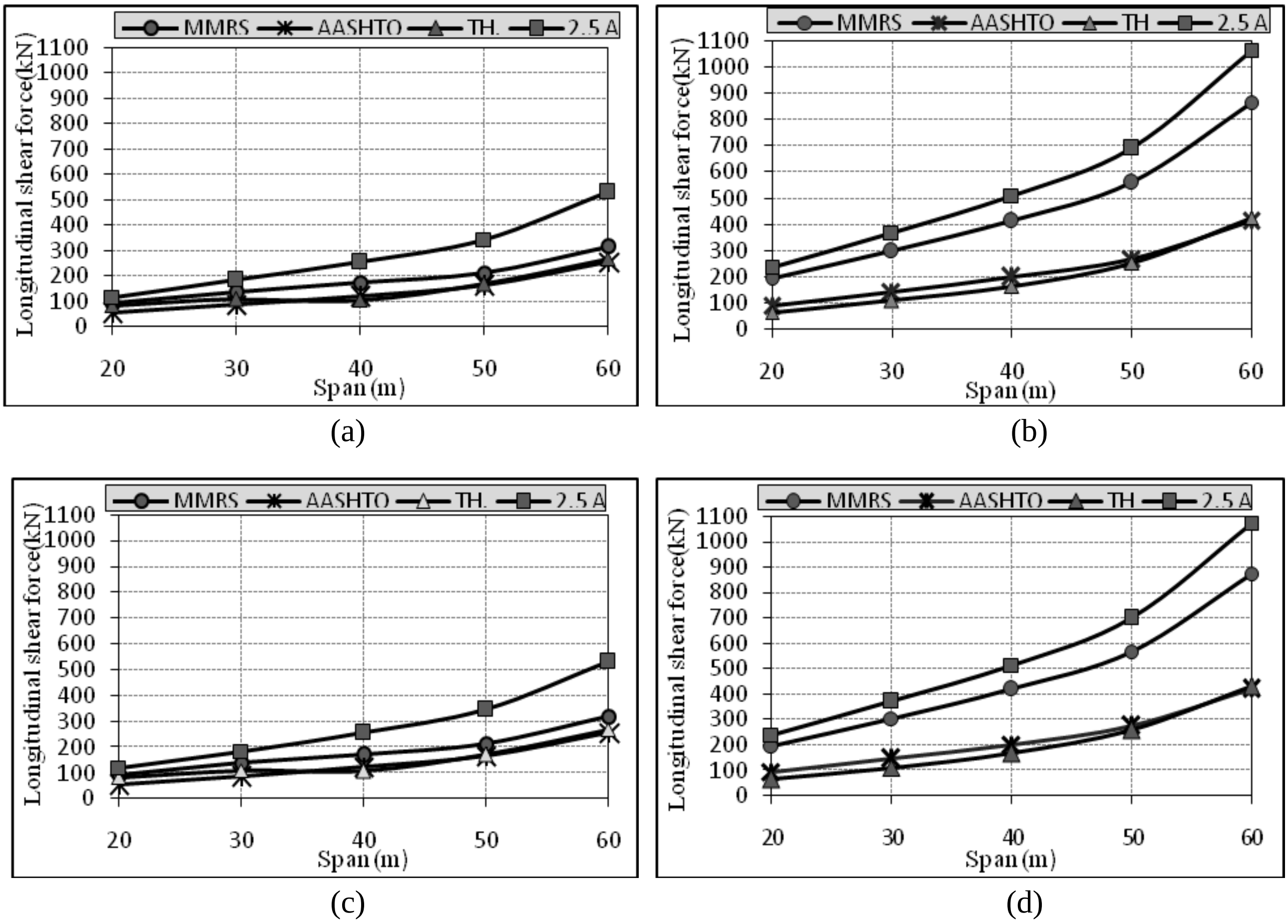
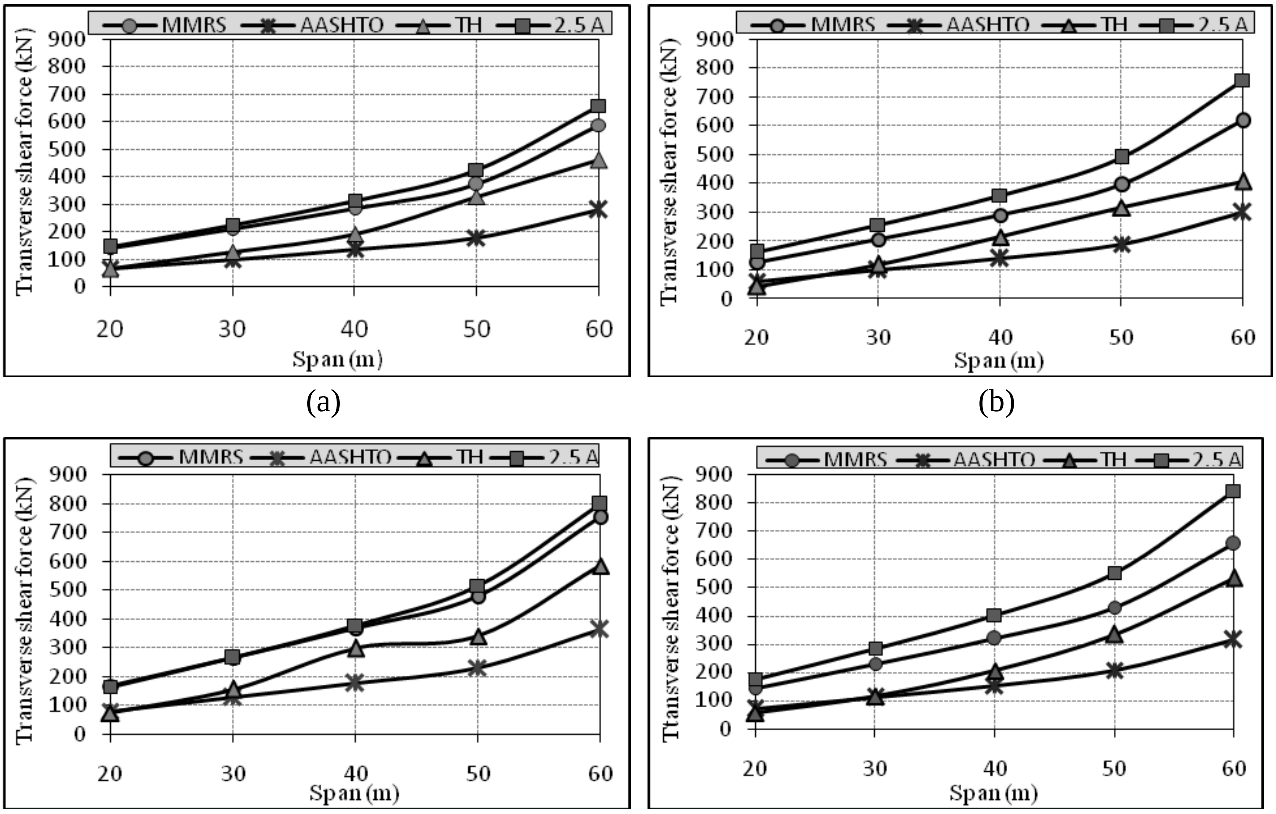


Fig. (10) Longitudinal shear force versus span length (a) spring support (b) pin-x (c) pin-y (d) pin x-y



(a) (b) (c) (d)

Fig. (11) Transverse shear force versus span length (a) spring support (b) pin-y (c) pin-x (d) pin x-y

SEISMIC DESIGN OF BRIDGES IN SPC (A)

INTRODUCTION

AASHTO specification does not consider seismic forces for design of structural components for bridges in low seismic zones such as SPC (A) [A<= 0.09] except for the connection between superstructures to substructures. AASHTO requires that the minimum connection force that must be transferred from superstructure to its supporting through the bearings is 20% of the weight that is effective in the restrained direction.

CASES STUDIED

Two span continuous steel girder bridges are studied. The same cross section properties that were used for single span bridges are adopted here. The span length of these bridges range between 20 and 60 m with increment of 10 m. The straight and skewed bridges with skew angles varying from 0 to 60 degrees are considered. The bridge is supported on elastomeric bearings in the longitudinal direction and cross-frames in the direction parallel to skew of the deck. The values of stiffness for both elastomeric bearings and cross-frames are determined as explained above. The elastomeric bearing and lateral bracing are designed due to Iraqi loading. The properties of elastomeric bearing and lateral bracing system for end support are summarized in table (3) and for central support are the twice of these for end support. Springs are used to model the elastomeric bearing stiffness and cross-frame stiffness. For skewed bridge, the spring in the direction parallel to the skew that simulates the stiffness of cross-frame is modeling using the nonlinear link element of SAP2000. This is only way one can model skewed spring with this program. However, the nonlinear portion of the spring is not activated. The finite element model of the bridge is shown in Fig. (12).

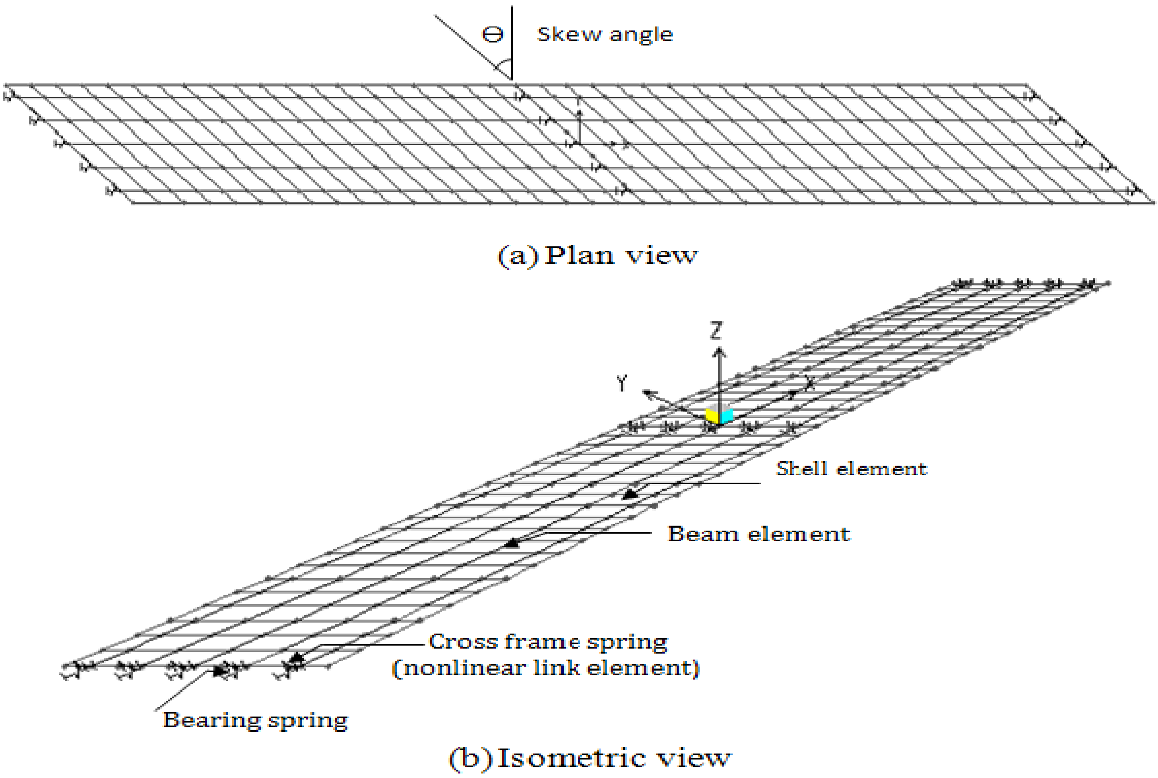


Fig. (12) Finite element model of two span continuous bridge

Table (3) Properties of elastomeric bearing and lateral bracing system

L (m)	Elastomeric bearing size (mm) [DIN 4141]	Cross-frame size (mm)	Bearing stiffener size (mm)	K_e (kN/m)	K_b (kN/m)	
					In. beam	Ex. beam
40	200 × 250 × 52	L120 × 10	2PL.130 × 10 × 920	1352	417237	233892
60	200 × 400 × 52	L130 × 12	2PL.150 × 14 × 1320	2162	298871	167750
80	250 × 400 × 74	L140 × 14	2PL.150 × 14 × 1620	1887	236362	141496
100	250 × 400 × 85	L180 × 14	2PL.180 × 16 × 1910	1640	217565	120891
120	300 × 400 × 96	L200 × 16	2PL.200 × 18 × 2280	1740	181415	101798

Analysis of the Bridge Models

A parametric study is performed to study the validity of seismic design force recommended by AASHTO for bridges in SPC (A). The bridge models are analyzed by two methods:

- Response spectrum analysis (dynamic analysis) using the AASHTO's design response spectrum curve with acceleration coefficient (A) equals to (0.05 & 0.09) and soil profile type II (site coefficient(S)=1.2) which are applied in two horizontal orthogonal directions X and Y.
- Simplified AASHTO method (static analysis): according to his method a static load of [0.2 w(x)] is applied uniformly on the bridge model in two horizontal orthogonal directions X and Y.

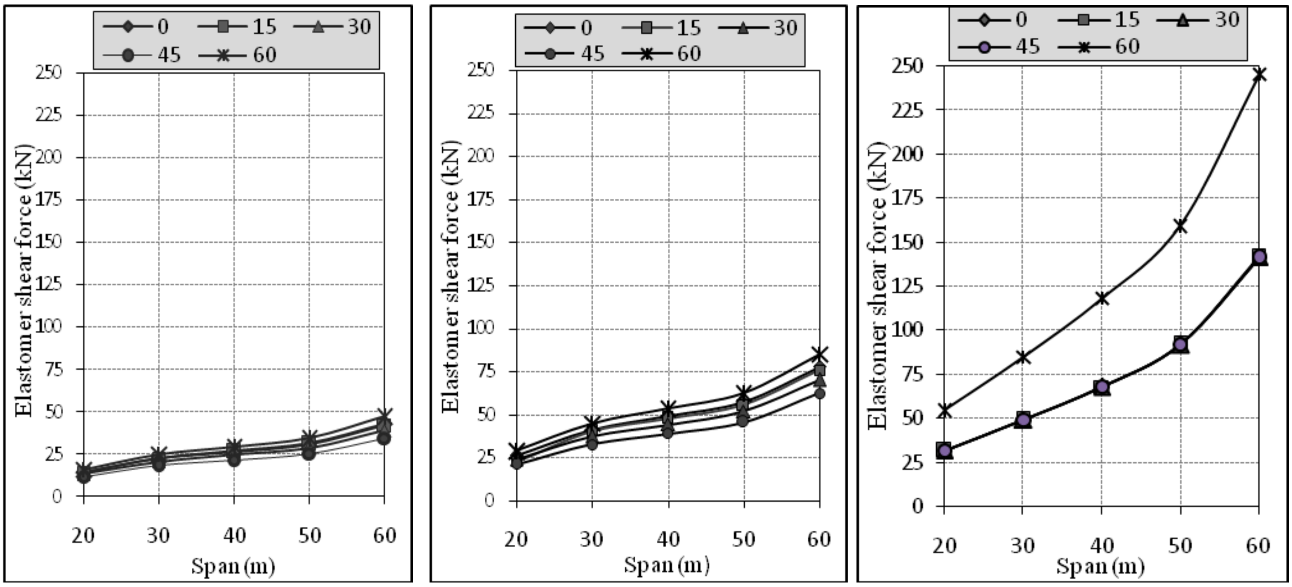
The vibration modes and corresponding mass ratio of the bridge models are summarized in table (4). The variation of the maximum value of individual elastomer shear forces and bracing forces at end and center support against span length when the base excitation in X and Y directions are summarized in Figs. (13), (14), (15) and (16).

It is noticed that the elastomer and bracing shear forces increase as the bridge length increases. In addition the elastomer shear forces at end and center support and bracing forces at end support decrease for all skew angles ranging from 0 to 45 degrees, but remained much closed and for skew angle over 45 degrees the shear forces increase with increasing skew angles, while bracing forces at center support decrease with increasing skew angle from 0 to 60. It is also observed that bridge with 45 degrees skew angle or higher, the max. responses reverses its direction, for example the max. elastomer shear force is obtained by applying the base excitation in opposite direction (Y).

For all cases, the simplified AASHTO method has yield a higher force than response spectrum method with (A=0.05 & 0.09) except for straight and 15 skewed bridges, whereas AASHTO method underestimates the bracing forces at center support by ratio of (3.025 to 12.262%).

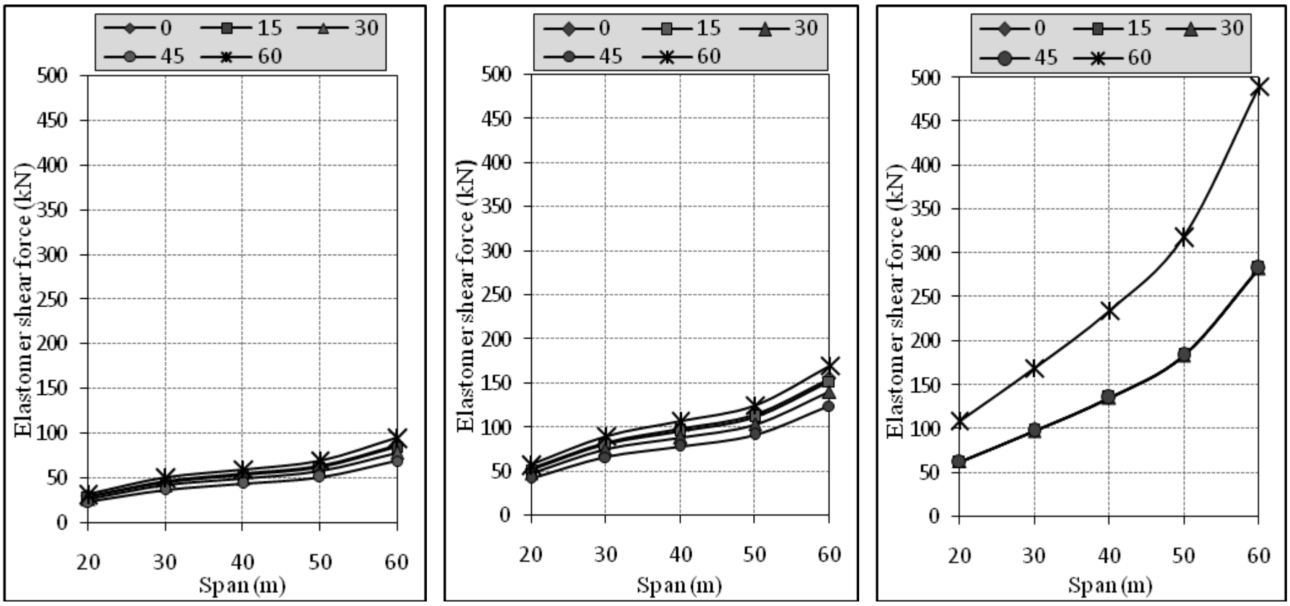
Table (4) Vibration modes and corresponding mass ratio of the bridge models

Skew angle		0			15			30			45			60		
L (m)	mode	T (sec)	(x) mass%	(y) mass%	T (sec)	(x) mass%	(y) mass%	T (sec)	(x) mass%	(y) mass%	T (sec)	(x) mass%	(y) mass%	T (sec)	(x) mass%	(y) mass%
40	1	0.6829	100.00	-	0.7902	93.24	6.76	0.7913	74.82	25.18	0.9697	49.77	50.23	1.3719	24.84	75.16
	2	0.0521	-	96.07	0.0517	6.45	89.38	0.0505	23.89	70.95	0.0494	44.88	44.45	0.0538	25.21	8.31
	3	00268	-	1.23	0.0276	0.10	1.35	0.0302	0.61	1.83	0.0353	3.89	3.87	0.0426	47.09	15.58
60	1	0.6749	100.00	-	0.6990	93.14	6.86	0.7804	74.55	25.50	0.9569	49.45	50.55	1.3546	24.63	75.37
	2	0.0817	-	94.89	0.8084	6.51	88.19	0.0785	23.89	69.88	0.0759	44.95	43.90	0.0802	26.89	8.73
	3	0.0233	-	4.16	0.0237	0.28	3.90	0.0466	0.47	1.39	0.0544	3.35	3.32	0.0652	44.19	14.48
80	1	0.8502	100.00	-	0.8806	93.09	6.90	0.9834	74.44	25.56	1.2061	49.34	50.66	1.7075	24.56	75.44
	2	0.1157	-	93.64	0.1142	6.46	87.00	0.1102	23.74	69.00	0.1051	45.00	43.71	0.1094	25.86	8.35
	3	0.0333	-	5.85	0.0338	0.40	5.53	0.0353	1.53	4.56	0.0751	2.44	2.41	0.0901	44.03	14.38
100	1	1.0618	100.00	-	1.0998	93.08	6.92	1.2283	74.40	25.60	1.5064	49.31	50.69	2.1322	24.56	75.43
	2	0.1521	-	91.78	0.1497	6.36	85.24	0.1431	23.33	67.60	0.1344	44.70	43.36	0.1364	26.01	8.40
	3	0.0436	-	7.81	0.0442	0.54	7.45	0.0463	2.13	6.36	0.0948	1.26	1.24	0.1143	41.43	13.52
120	1	1.2787	100.00	-	1.3248	93.01	6.98	1.4802	74.23	25.77	1.8160	49.12	50.88	2.5710	24.45	75.55
	2	0.2048	-	92.12	0.2016	6.45	85.52	0.1925	23.62	67.79	0.1801	45.37	43.66	0.1801	28.58	9.17
	3	0.0583	-	7.49	0.0591	0.52	7.13	0.0616	2.02	6.04	0.1264	1.11	1.09	0.1525	40.17	13.03



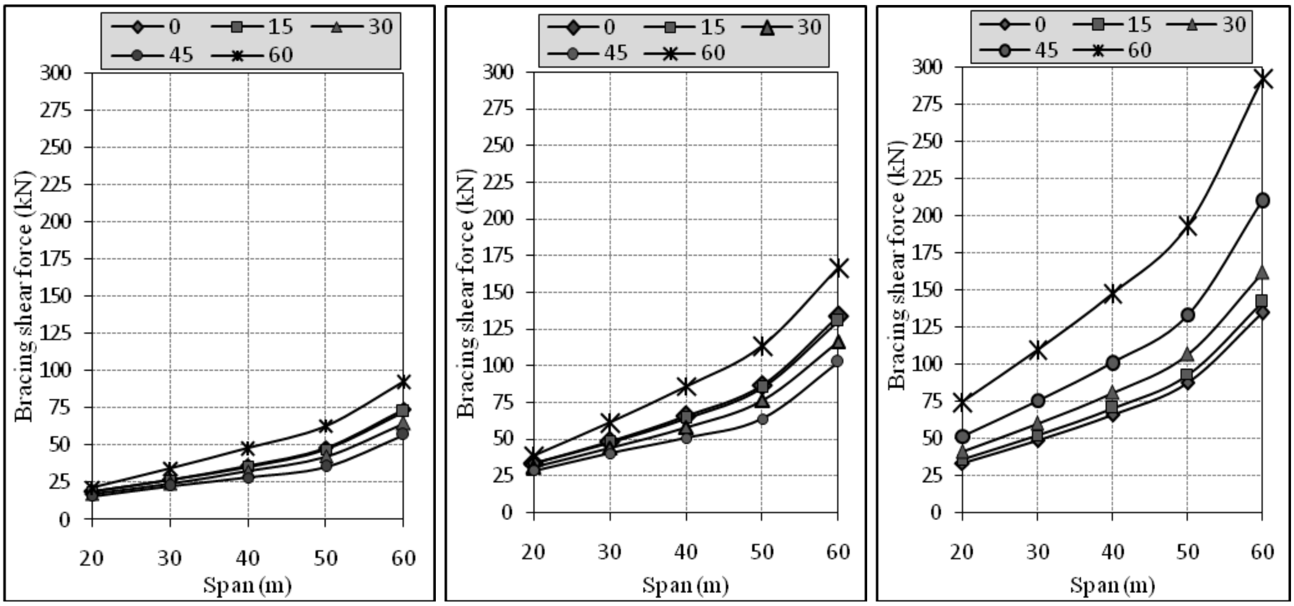
(a) (b) (c)

Fig. (13) Elastomer shear forces at end support due to (a) response spectrum with A=0.05 (b) response spectrum with A=0.09 (c) AASHTO methods.



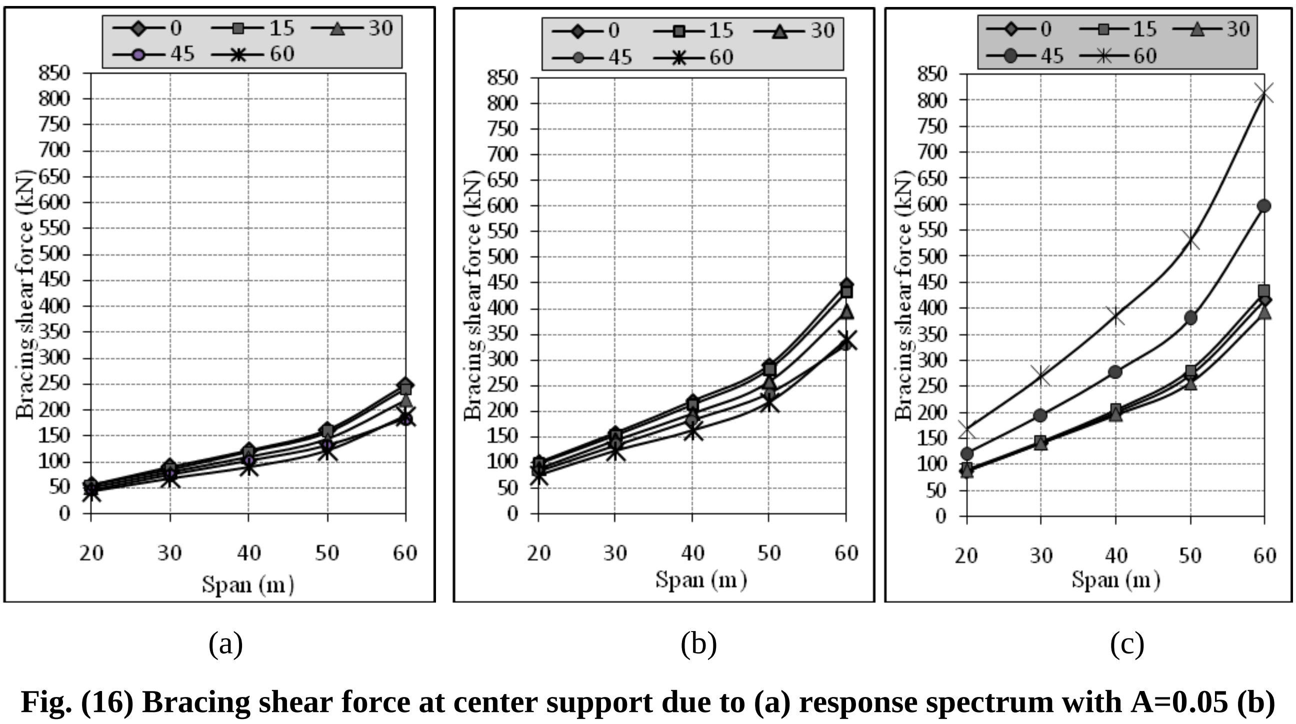
(a) (b) (c)

Fig. (14) Elastomer shear force at center support due to (a) response spectrum with A=0.05 (b) response spectrum with A=0.09 (C) AASHTO method



(a) (b) (c)

Fig. (15) Bracing shear force at end support due to (a) response spectrum with A=0.05 (b) response spectrum with A =0.09 (c) AASHTO method.



(a) (b) (c)

Fig. (16) Bracing shear force at center support due to (a) response spectrum with A=0.05 (b) response spectrum with A=0.09 (c) AASHTO method.

CONCLUSIONS

- For the case studies considered, the results indicate that the simplified AASHTO method for single span bridges when compared with MMRS method can underestimate the seismically induced transverse shear forces (cross- frame forces) with different support conditions by as much as 52%. The same trend for the longitudinal shear forces (elastomeric bearing forces) for bridges with supports that restrained in the longitudinal direction X (pin-x) and with supports that restrained in the longitudinal and transverse directions (X and Y) (pin x-y) supports. The underestimate ratio range between (19.98–39.05%) for the longitudinal shear force (elastomeric bearing forces) of bridges with spring support and with supports that restrained in transverse direction (Y); therefore, the simplified AASHTO method can become unsafe for zone 3 and 4 and soil type II.

- The results shows that the proposed seismic design force of (2.5 multiplied by acceleration coefficient multiplied by tributary weight w(x)) is suitable and safety method for all cases and can be recommended for single span bridges in lieu the simplified AASHTO method for seismic zone 3 and 4 and for soil type II.

- A parametric study on seismic design force for two span continuous bridges in performance category A (SPC A) shows that the seismic design force [0.2 w(x)] which is recommended by AASHTO is safe and conservative method to predict the shear forces transferred by connection elements to substructures for practical bridge systems in SPC (A).

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
Ex.	Exterior
In.	Interior
MMRS	Multi mode response spectrum method
SAP 2000	Structural Analysis Program
UBC	Uniform Building Code

SYMBOLS

A	Cross sectional area of steel beam
b_{fb}	Bottom flange width of steel beam
b_{ft}	Top flange width of steel beam
h	Depth of steel beam
I_y, I_z	Second moment of area about y and z axes respectively
k_b	Lateral bracing stiffness
k_e	Elastomeric bearing stiffness
L	Bridge length
t_{fb}	Bottom flange thickness of steel beam
t_{ft}	Top flange thickness of steel beam
t_s	Deck slab thickness
t_w	Web thickness of steel beam