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Seismic response analysis of simple span concrete deck girder skewed bridge: effect of skew angles

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Abstract

In this paper seismic response analysis of a simple span concrete deck girder skewed bridge is carried out for a wide range of skew angles. In this regard, a 3-D model bridge using the finite element method is considered in linear time history analysis. A standard direct time integration approach is employed in the time history analysis. An earthquake ground motion record complying with the design acceleration response spectrum obtained from low to moderate magnitude earthquakes is applied in the longitudinal direction of the bridge. The analytical results have indicated that the skewed bridge responses are quite different from the non-skewed bridge and varying with the skew angles and also on ground motion characteristics.

Keywords: Seismic response, skew angle, concrete deck girder, acceleration response spectra

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1. Introduction

Bridges are a crucial part of the overall transportation system as they play very important roles in evacuation and emergency routes for rescues, first-aid, firefighting, medical services and transporting disaster commodities to expatriates. The actual damages (Basoz and Kiremidjian, 1999, Yamazaki *et al.* 2000) to highway bridge systems from past and recent earthquakes, such as the 1971 San Fernando earthquake, the 1994 Northridge earthquake, the 1995 Great Hanshin earthquake in Japan, and the 1999 Chi-Chi earthquake in Taiwan, the 2010 Chile earthquake and 2010 Haiti earthquake have demonstrated that bridges are highly susceptible to damages during earthquakes. Bridges play important role in reducing traffic jam in city areas. Skew bridges are inevitable for planning and design of road networks to maintain the geometry and straight alignment for safe and efficient traffic flow. Nowadays, the number of skew bridges is increasing all over the world to implement the road alignment straight as much as possible. As their structural behaviour and properties are different from the non-skewed bridges, proper attention and measure should be taken to understand the design a safe bridge system for uninterrupted traffic flow. The seismic behaviour of the Foothill Boulevard Undercrossing in the 1971 San Fernando earthquake and the Mission-Gothic and Gavin Canyon Undercrossings in the 1994 Northridge earthquake has indicated that the skew bridges are more susceptible to seismic damage than straight highway bridges with regular geometry (Kalantari and Amjadian, 2010).

It is generally accepted that the skewed bridge exhibits complex response characteristics due to seismic excitations, especially when the skew angles are greater than 30 degrees. Several studies have explored the effects of skew angle on the seismic responses of highway bridges (Maleki, 2002; Saiidi and Orie, 1991). Maleki (2002) conducted seismic performance analysis of slab-girder bridge and showed that the bridges with skew angles more than 30 degrees have significantly different response characteristics to straight bridges. Saiidi and Orie (1991) illustrated the effects of skew angles on the seismic responses of bridges and recommended that simplified models and methods of analysis can be satisfactorily used to accurately predict seismic response of bridges with skew angles of less than 15 degrees.

However, it is well known that the acceptance of numerical results depends on how accurately the skewed highway bridge is idealized in the analytical treatment. The underlying assumptions in this regard may include material modelling, inelastic response characteristics of components, restraining conditions at the boundaries, soil-structure interaction, component geometry, superstructure, seismic mass, etc. For instance, Meng and Lui (2000) concluded that the effects of skew angle on the seismic responses of a bridge may be compensated by properly modeling boundary conditions. Wakefield et al. (1991) accomplished a study showing that the failure can be controlled by rigid-body motion of the skewed bridge. However, a study carried out by Ghobarah and Tso (1970) revealed that the failure of the skewed bridge can be enhanced by flexural and torsional motion. The boundary conditions of the bridge in these two studies were different: the deck was assumed to be fixed at the abutments in the study of Ghobarah and Tso (1970) whereas in the work Wakefield *et al.* (1991), the deck at the abutments was considered to be free in translation modes. Manassa *et al.* (2007) conducted analytical study of simply supported reinforced concrete slab bridge using finite element method. They have considered three parameters of the bridge in the analytical study such as span length, slab width and skew angle, and compared the results with that evaluated using the procedures guide by the American Association for the state Highway and Transportation Officials (AASHTO) Standard Specifications and Load Resistance Factor Design (LRFD). They have shown that AASHTO and LRFD design procedures overestimate the longitudinal bending moment and the trend of this overestimate of the longitudinal bending moment increases with increase in the skew angles, especially when the skew angles are more than 20 degrees. Norton *et al.* (2001) conducted theoretical and experimental studies on single span simply supported composite steel concrete skewed bridge and investigated the behavior of skew bridges during construction. Ashebo (2006) evaluated the vehicle–induced dynamic response of a skewed box girder bridge. Gupta and Misra (2007) investigated the effect of support reactions on T-beam skew bridge by Grillage Analogy method with varying span lengths and skew angle.

From the above facts it is revealed that the responses of skewed highway bridges are significantly affected by several parameters especially when subjected to seismic excitations, making their behaviour complex. The studies conducted by previous researchers were limited to use of an arbitrary set of earthquake ground motion records. However, the use of design earthquake ground motion records or a set of earthquake ground motion records conforming to the design acceleration response spectrum in seismic analysis of highway bridge is a standard practice for comparing the results with other standard methods. The objective of the current study is to investigate the effect of skew angles on the seismic responses of a simple deck girder highway bridge subjected to an earthquake ground motion records compatible to the design acceleration response spectrum (JRA, 2002). To this end, linear time history analysis using finite element method is conducted to evaluate the seismic responses of the bridge. A comparative assessment of the seismic responses is carried out for varying skew angles from 0 to 60 degrees. Three seismic responses of the bridge are considered: abutment base shear, deck acceleration and bearing reactions.

2. Description of the bridge

A typical single span simply supported highway bridge of 100 ft length is used in this study as shown in Fig. 1. Fig. 1(a) shows the plan of the bridge with the location of the girder and Figs. 1(b) and 1(c) present the longitudinal elevation and transverse section of the bridge. The superstructure consists of 8 inch continuous concrete slab with 4 inch of asphalt layer supported on four continuous concrete girders. The depth of the continuous concrete girder is considered to be 5 ft. The substructure of bridge consists of rigid abutments at the two ends. Table 1 presents the details of geometric properties of the bridge. Stiff steel bearings are used below the concrete girders with the objectives of transferring the superstructure loads to the abutments and accommodating the horizontal deformations due to environmental loads.

3. Analytical model of the bridge

The entire bridge is approximated by a 3-D model bridge using SAP2000 (SAP, 2000) as shown in Fig. 2. In general, the bridge deck is modelled as rigid body model in seismic response analysis of bridge. It is well understood and discussed in literature (Ghobara and Ali, 1988., Ghobora, 1988) and from the authors experience that the assumption of rigid bridge deck does significantly affect on the seismic response of the bridge, especially when the bridge is subjected to seismic excitations in longitudinal direction. The bridge deck and abutment are modelled as linear elastic shell elements. The girder is modelled using linear elastic frame elements. Two joint link elements are used to model the bearings installed between the abutment top and the bottom of girders. The vertical translation and rotation of the deck about the longitudinal direction were restrained at the abutment levels.

Table1

Geometric properties of the bridge

Properties	Specifications
Cross-section of the Girder (in^2),	12x48
Cross-section of the Abutment (in^2)	144x48
Number of Girders	4
Young's modulus of elasticity of concrete(N/mm^2)	25000
Young's modulus of elasticity of steel (N/mm^2)	200000

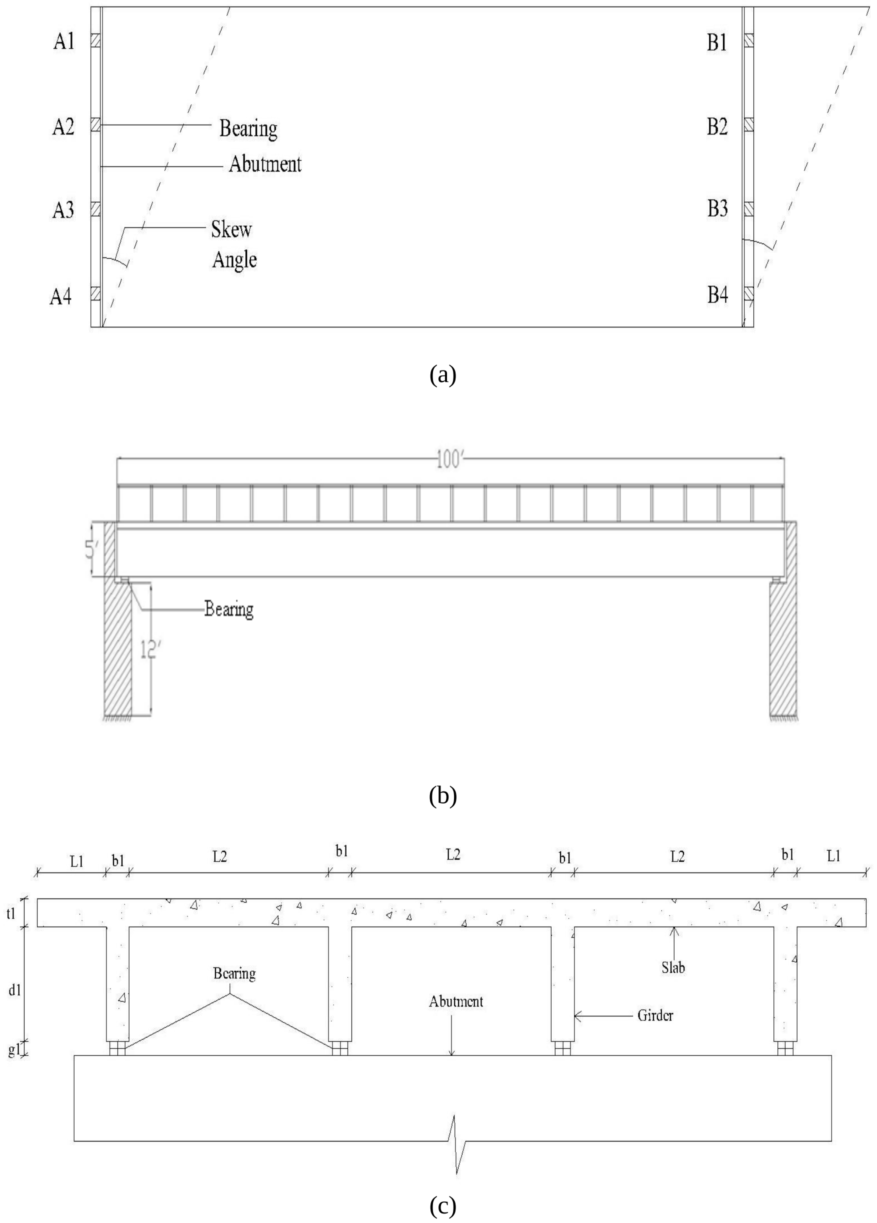


Fig. 1. Geometric details of the model bridge (a) plan of the bridge with location of girders (b) longitudinal elevation section (c) Transverse section; t1 = 1 ft; d1 = 4 ft; g1 = 0.5 ft; L1 = 3 ft; b1 = 1 ft; L2 = 9 ft.

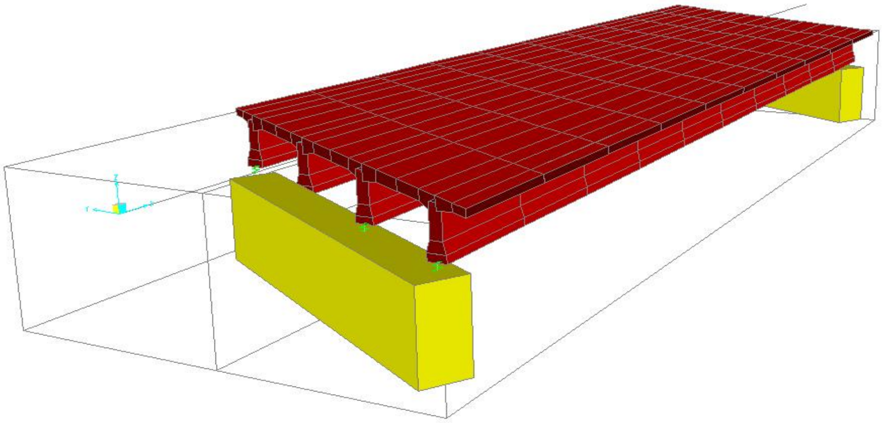


Fig. 2. 3-D model of the bridge in a platform of SAP2000 (SAP 2000)

4. Earthquake ground motion records

Bridges play very important transportation link for providing emergency evacuation routes, first aid, medical services, firefighting, and transporting of urgent goods to the affected people in earthquake disaster area. It is essential to confirm the seismic safety of a highway bridge in the seismic design. In the light of importance of a highway bridge, it refers to a key issue to minimize as much as possible loss of bridge functions due to earthquake disaster. Therefore, in seismic design of highway bridge seismic performance required depending on levels of design earthquake ground motion and importance of the bridge shall be guaranteed (JRA, 2002). Moreover, the structural type of bridge in consideration with topographical, geological and soil conditions, site conditions, etc. shall be properly selected. Furthermore, an increased strength and ductility of the entire bridge system shall be confirmed in the seismic design of highway bridge (JRA, 2002). Two levels of earthquakes are usually considered in the seismic design of highway bridge (JRA, 2002) to meet the three seismic performance levels. Level-1 earthquake refers to an earthquake with high probability of occurrence during the service of the bridge whereas Level-2 earthquake corresponds to an earthquake, which has less probability of occurrence but with strong magnitude to cause detrimental damage to the bridge. For Level-2 earthquake, two types of earthquake ground motion are considered in the seismic design of highway bridge, especially in Japan (JRA, 2002): Type-I and Type-II earthquakes. Type-I earthquake is a ground motion corresponding to a plate boundary type earthquake with large amplitude and long duration such as the Kanto earthquakes (Tokyo, 1923) and Type- II earthquake is one corresponding to an inland direct strike type earthquake with low probability of occurrence, strong acceleration and short duration such as the Kobe earthquake (Kobe, 1995) (JRA, 2002). The uncertainty characteristics of the earthquake ground motions regarding ground type, intensity and frequency contents have a great effect on dynamic analysis of bridge. To account for such characteristics, three records with almost the same acceleration response spectra are considered in this study (Fig.3 (a) and (b)). Fig.3 (a) presents the ground acceleration histories, which are designed for level-2 type-I in JRA (2002) and Fig. 3 (b) shows the acceleration spectra of them superimposed by mean and the design acceleration spectra (). A medium type ground condition was used in the analysis.

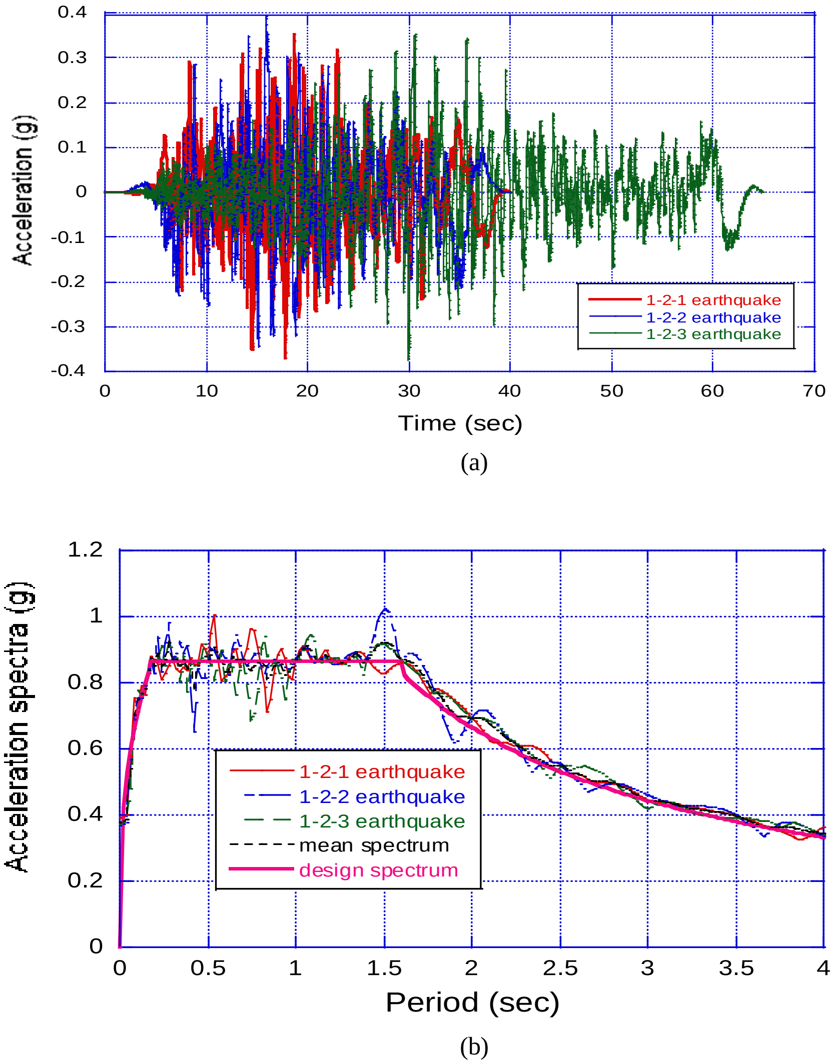


Fig. 3. Earthquake ground motion, (a) acceleration-time history and (b) acceleration response spectrum; the solid line in Fig.4b represents the design acceleration response spectrum (JRA, 2002)

5. Equation of motion of the bridge

Equations that govern the dynamic response of the bridge can be derived by considering the equilibrium of all forces acting on it using the d'Alermbert's principle. In this case, the internal forces are the inertia forces, the damping forces, and the restoring forces, while the external forces are the earthquake induced forces. The equations of motion of the bridge can be written as

$$^{t+\Delta t}\mathbf{M}\ddot{\mathbf{U}}+{}^{t+\Delta t}\mathbf{C}\dot{\mathbf{U}}+{}^{t+\Delta t}\mathbf{K}\mathbf{U}+{}^{t+\Delta t}\mathbf{F}_s={}^{t+\Delta t}\mathbf{P} \qquad (1)$$

where $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping matrices, respectively; $\mathbf{K}$ is the tangent stiffness matrix of the bridge; $\mathbf{U}$ stands for the displacement vector while the single and double dots $(.)$ upon $\mathbf{U}$ represents the velocity and acceleration vector, respectively at $^{t+\Delta t}$; $^{t+\Delta t}\mathbf{F}_S$, the restoring force of bearing at time $^{t+\Delta t}$; and $^{t+\Delta t}\mathbf{P}$, the external force vector at time $^{t+\Delta t}$.

6. Numerical results and discussion

The prototype bridge with different skew angles was analyzed to investigate the effect of skewness of the bridge on seismic responses. Before conducting time history analysis of the bridge system, an eigenvalue analysis is carried out to compute the fundamental vibration properties of the bridge. The number of modes used for response evaluations is recommended in several seismic codes to include at least 90% of the participating mass for each principal horizontal direction. For purpose of discussion, only the first few dominating modes are considered in the analysis. Table 2 shows the first five modal periods of the bridge for different skew angles. From Table 2 it can be observed that the modal periods are not significantly affected by the skew angles of the bridge. Moreover, the two mode shapes at two skew angles of 0 and 40 degrees are plotted in Fig.4 illustrating that the dominant modes of vibrations of the said bridge are the flexural modes deformations. From the mode shapes shown in Fig. 4 it is observed that the fundamental modes of vibration of the bridge are dominated by the flexural modes of vibrations.

Table 2

Modal periods of the model bridge

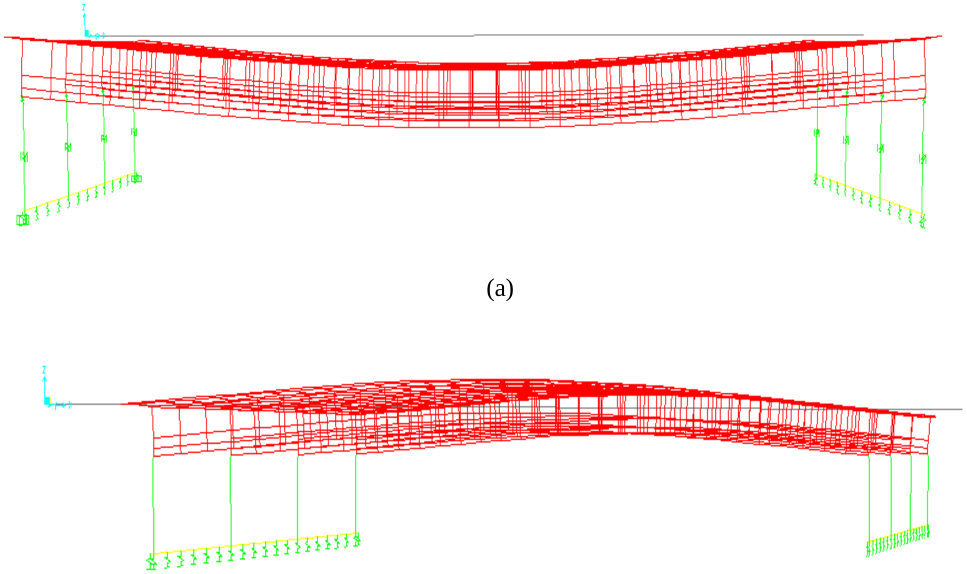
Skew angle	0°	10°	20°	30°	40°	50°	60°
Mode number	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)
Mode-1	0.3226	0.3221	0.3206	0.3177	0.3126	0.3035	0.2872
Mode-2	0.2686	0.2678	0.2653	0.2612	0.2554	0.2490	0.2497
Mode-3	0.1781	0.1789	0.1815	0.1862	0.1926	0.1988	0.1983
Mode-4	0.1231	0.1227	0.1213	0.1141	0.1175	0.1216	0.1325
Mode-5	0.1112	0.1111	0.1128	0.1147	0.1159	0.1167	0.1204

Table 3

Absolute maximum responses of the bridge

Response/ Skew angle	Earth-quake	0°	10°	20°	30°	40°	50°	60°
Base Shear (kip)	1-2-1	472.06	468.92	469.38	474.54	486.23	**505.89**	491.72
	1-2-2	517.65	518.10	**521.25**	517.34	486.44	438.71	449.01
	1-2-3	473.31	472.59	469.48	465.31	497.35	520.97	**523.16**
Deck acceleration (in/sec^2)	1-2-1	**122.10**	122.31	121.91	118.89	112.60	109.63	108.26
	1-2-2	141.26	140.33	139.31	137.33	135.92	142.08	**157.72**
	1-2-3	142.21	142.15	143.12	150.19	165.17	**174.28**	169.02
Bearing reaction at A1 (kip)	1-2-1	117.79	125.27	134.12	144.41	158.37	178.65	**194.14**
	1-2-2	123.38	132.07	141.18	154.33	166.67	181.47	**201.19**
	1-2-3	118.13	126.56	136.62	149.46	167.07	187.87	**205.11**

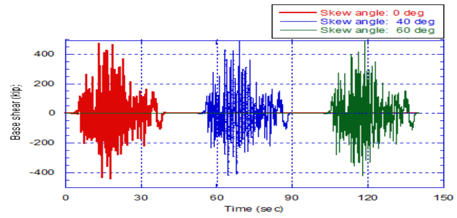
1 kip = 4.48 kN and 1 inch = 25.4 mm



(a)

(b)

Fig. 4. Mode shapes of the model bridge (a) First mode of the non-skewed bridge (b) First mode of the 40° skewed bridge



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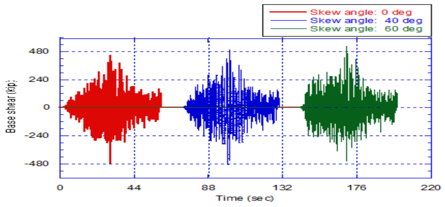

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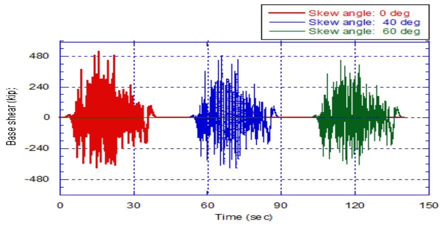

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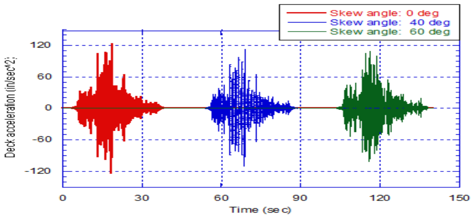
Fig. 5. Time history of base shear of the bridge for (a) 1-2-1 (b) 1-2-2 and (c) 1-2-3 earthquake ground motion records. For a clear understanding, the responses obtained for three skew angles in each earthquake record are separated by 50 sec from each other.



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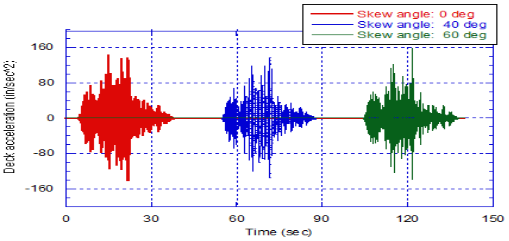

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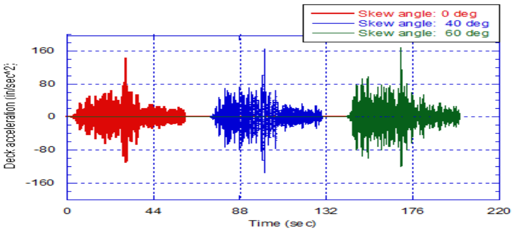

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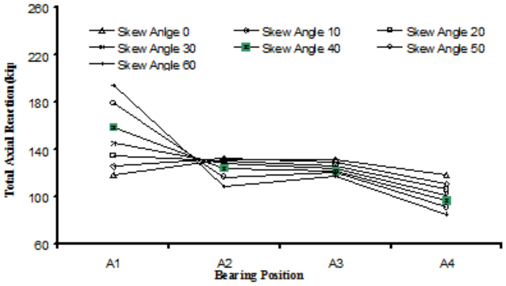
Fig. 6. Time history of deck acceleration of the bridge for (a) 1-2-1 (b) 1-2-2 and (c) 1-2-3 earthquake ground motion records. For a clear understanding, the responses obtained for three skew angles in each earthquake record are separated by 50 sec from each other.



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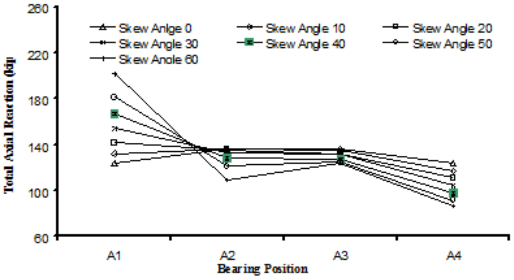

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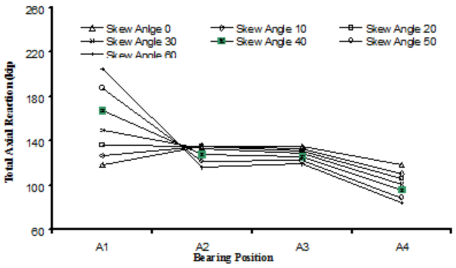

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Fig. 7. Variation of total axial reactions at bearing with their positions for (a) 1-2-1 (b) 1-2-2 and (c) 1-2-3 earthquake ground motion records.

The linear time history analysis of the bridge using the analytical model shown in Fig. 2 is conducted in order to evaluate the seismic responses of the bridge: the base shear, deck acceleration and bearing reactions of the bridge. Three earthquake ground motion records as shown in Fig.3 are used in the analysis. The absolute peak values of the responses obtained from the dynamic analysis of the bridge are given in Table 3 presenting that seismic responses of the bridge are affected by skew angles. For example, the base shear of the bridge attains the maximum value at 50, 20 and 60 degrees, the deck acceleration at 0, 60, and 50 degrees and the bearing reactions (A1) at 60 degree of skew angles, for the earthquakes of 1-2-1, 1-2-2 and 1-2-2, respectively. Figures 5 and 6 present the time histories of base shear and deck acceleration of the bridge for three skew angles of 0, 40 and 60 degrees, whereas Figure 7 shows the bearing reactions at the abutment level for the skew angles of 0 to 60 degrees. From Figures 5 to 7, it has been revealed that the seismic responses are affected with the change of skew angles and the maximum value of the bearing reactions attains at the exterior girder. In this case the bearings of the exterior girders are seen seismically more vulnerable than the interior girders. Apart from the effect of skew angles on seismic responses of the bridges, the effect of characteristics of earthquake ground motion records is also portrayed in the numerical results presented in Figures 5 to 7 and Table 3.

7. Concluding remarks

The effect of skew angle on a simple span concrete deck girder bridge is presented in this paper. A unidirectional ground motion, compatible with design acceleration spectrum is applied in the longitudinal direction of the bridge. The maximum skew angle of 60° as recommended in codes and specification (e.g., AASHTO, 2000) is considered in the analysis. Three seismic responses of the bridge are discussed: base shear, deck acceleration and bearing reactions of the bridge. A standard numerical method is employed in the dynamic analysis of the bridge. From the numerical results of the bridge it is observed that the seismic responses of the bridge are significantly affected by skew angles of the bridge. For example, large skewness is likely to increase base shear, deck acceleration and bearing reactions of the bridge, which may cause an increase in axial forces, shears, moments and torques in the supporting bridge piers. Moreover, the characteristics of the earthquake ground motion play a significant role in evaluating the seismic responses of the bridge. Finally, it can be said that a careful consideration of geometry of the highway bridge as well as the characteristics of earthquake ground motion records is urgently required in evaluating the seismic performance of highway bridge.

In the current study, a simply supported bridge model subjected to a single type of earthquake for a particular ground condition (medium ground type) is considered in the analysis; however, a rigorous model of the bridge considering the deck flexibility, foundation flexibility with different types of earthquakes for different ground conditions is needed for portraying comprehensive conclusions on the results.

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