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Seismic Analysis of Skew Bridges

Vaibhav Kothari[1], **Pranesh Murnal**[2]

[1]*ME Postgraduate Student*
Government College of Engineering, Aurangabad
vaibhav18041991@gmail.com
[2]*Associate Professor*
Government College of Engineering, Aurangabad
pmurnal@yahoo.com

Abstract: **The criticality to ensure the function of highway bridges remains an important issue after earthquakes. Many major earthquakes in the past have led to a better understanding of the seismic performance of bridges. Nonetheless, detailed guidelines addressing the performance of skewed highway bridges still requires more research to study the effect of skew angle and other related factors. Several parameters affect the response of skewed highway bridges under both service and seismic loads which makes their behavior complex. Building on the work of other researchers, the present paper considers a 3-D model bridge using the finite element method (SAP2000) subjected to linear time history analysis with skew angles varying from 0 to 50 degrees. An earthquake ground motion record for Northridge earthquake and Imperial Valley earthquake is applied in the longitudinal as well as transverse direction of the bridge. The results of finite element (FE) and modal analysis are presented to study the influence of skew angle on the natural frequency for the entire skewed bridge. On the other hand the structural response for the superstructure covering absolute deck acceleration at the centre, displacement and the internal forces in the deck as well as girders at corners for the entire bridge section subjected to above earthquake forces is also studied. Finally it can be seen that the effect of skew angle and interacting parameters were found to have significant effect on the behavior of skewed highway bridges. The analytical results have indicated that the skewed bridge responses are quite different from the non-skewed bridge and varying with the skew angle.**

Keywords: **skew bridges, seismic response, RC bridges.**

1. INTRODUCTION

Today we can see many design codes and guidelines available for designing the static and dynamic analysis for straight normal bridges. However, structural responses with respect to skewed highway bridges still remain a point of uncertainty significantly. This may be to most extent because of lack of detailed procedures in current guidelines. A skewed bridge is one whose longitudinal axis is not at right angle to the abutment. Many factors such as natural or manmade obstacles, mountainous terrain, complex intersections or space limitations can result into skewness in bridge. Newly designed bridges are often skew as it allows a large variety of solutions in road construction projects. It consumes less space as compared to normal bridges and if properly designed can be constructed even in the most congested places. In fact, as evidenced by past seismic events, skewed highway bridges are particularly vulnerable to severe damage due to seismic loads [1].

The force flow in skew bridges is much more complex as compared to right-angle bridges. It exhibits a unique seismic response that is triggered by oblique impact. Skew bridges often rotate in the horizontal plane, thus tending to drop off from the supports at the acute corners. In right angle bridges the load path goes straight towards the support in the direction of the span. In skew bridges this is not the case. For a solid slab skew bridge the load tends to take a short cut to the obtuse corners of the bridge. This behavior results in a coupling of longitudinal and transverse responses at one of the obtuse corners. This finally results in subsequent rotation along the direction of increasing the skew angle (Fig. 1) [2].

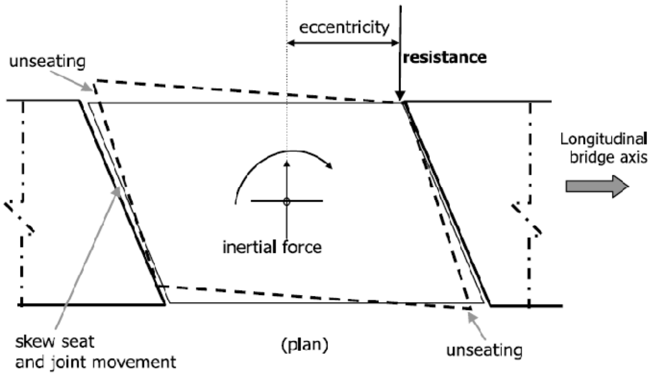


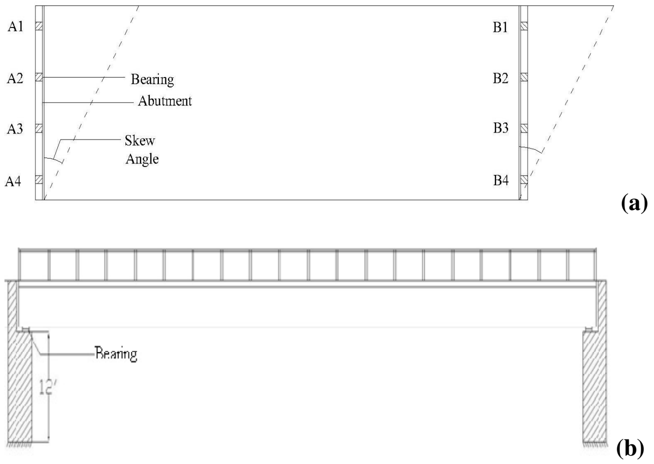
Fig. 1. Rotation mechanism of skew bridges

Inspite of having large number of experiences from past earthquake failures, which gives the importance of this mechanism, as well as the empirical vulnerability methodologies that acknowledge skew as a primary vulnerability factor in bridges, there are only few attempts to comprehend this mechanism. K. J. Tao and Z. J. Jie tried to solve the problem of in plane rotation in skew bridges by doing a philosophical analysis. They brought forward an idea regarding the application of slant-leg frame skew bridges without abutment which can fundamentally solve the tough defect of skew bridges to utmost extent because of its structural characteristics [3]. P. Apirakvorapinit demonstrated that certain damage potentials in skewed bridges during earthquakes can be captured analytically. There are cases in which the angle of skew is approximately 40°; the percentage increase in stress due to the skewness effect at the end girders can be as high as 50–60% [4]. Maleki 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 [5].

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 modeling, restraining conditions at the boundaries, component geometry, seismic mass, soil-structure interaction, etc. For instance the effects of skew angle on the seismic responses of a bridge to a great extent may be compensated by properly modeling boundary conditions. For the present study a simple span concrete deck girder skewed bridge for wide range of skew angles is modeled using FE method (SAP2000). Modal analysis and linear time history analysis for the same is carried out and finally the results are compared for various angles of skew angle.

2. BRIDGE DESCRIPTION

A typical single span simply supported highway bridge of 30m 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.



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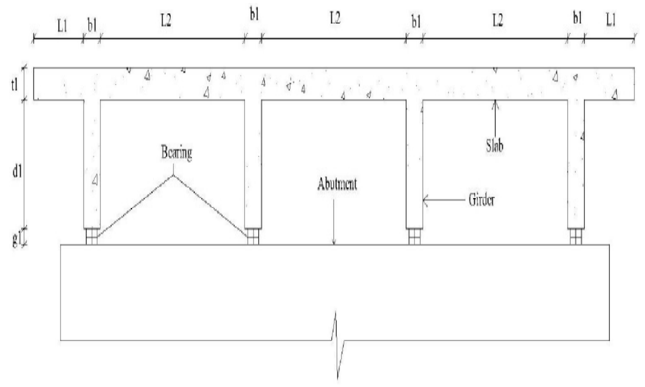


(c)

Fig. 2: Geometric details of the model bridge (a) plan of the bridge with location of girders (b) longitudinal elevation section (c) Transverse section; t1 = 0.3048m; d1 = 1.2192m; g1 = 0.1524m; L1 = 0.9144 m; b1 = 0.3048m; L2 = 2.7432m

The superstructure consists of 0.3048m thick deck supported on 4 girders. The depth of the continuous concrete girder is considered to be 1.2192m. 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.

TABLE 1: Geometric properties of the bridge

Properties	Specifications
Cross-section of the Girder (m^2)	0.3048x 1.2192
Cross-section of the Abutment (m^2)	3.6576x 1.2192
Number of Girders	4
Young's Modulus of elasticity of concrete (N/m^2)	$25x10^9$
Young's Modulus of elasticity of steel (N/m^2)	$2x10^{11}$
Stiffness of bearings along horizontal directions (kN/m)	1.00E+05
Stiffness of bearings along vertical direction (kN/m)	1.00E+07

3. MODELLING OF BRIDGE

The entire bridge is approximated as a 3-D model bridge using finite element software (SAP 2000) as shown in Fig. 3. 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. Stiffness values for the bearings are mentioned in Table 1 with vertical stiffness as 100 times that of horizontal stiffness [10]. The vertical translation and rotation of the deck about the longitudinal direction were restrained at the abutment levels.

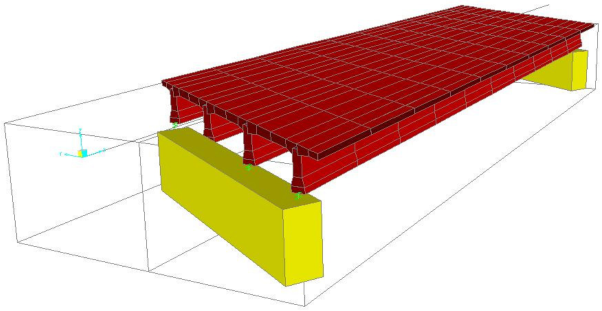
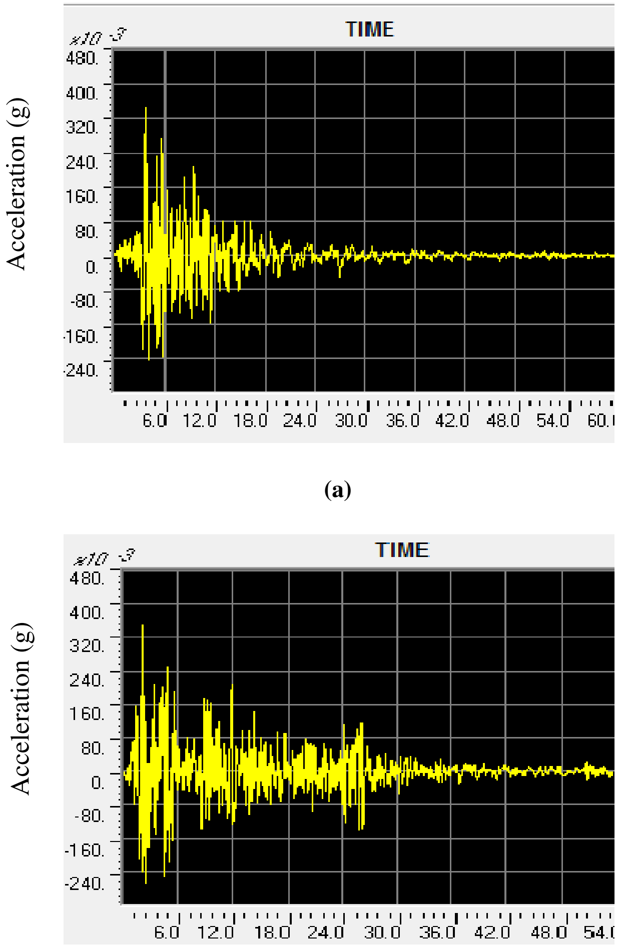


Fig. 3: 3D model in SAP2000

Input data for the analysis consisted of the acceleration ground motion of Northridge earthquake recorded at Arleta and Nordhoff fire station (see Fig. 4a) and Imperial Valley earthquake - EL CENTRO (see Fig. 4b). The ground motion is applied in the longitudinal and transverse direction to each support element of the bridge.



(a)

(b)

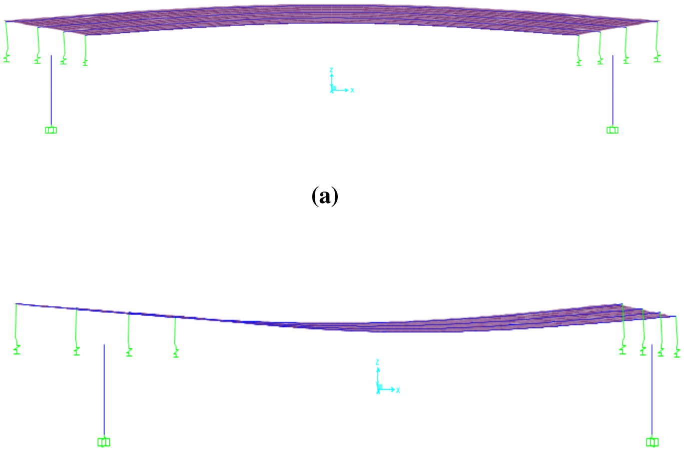
Fig. 4: Ground motions a) Northridge earthquake b) Imperial valley earthquake

4. NUMERICAL RESULTS AND DISCUSSION

The bridge with different skew angles was analyzed to investigate the effect of skewness on seismic responses of the bridge. Before conducting time history analysis of the bridge system, free vibration value analysis is carried out. The minimum number of modes to be considered in response evaluation should be such that atleast 90% of the total seismic mass and missing mass correction beyond 33 %. If modes with natural frequency beyond33 Hz are to be considered, modal combination shall be carried out only for modes upto 33 Hz. The effect of higher modes shall be included by considering missing mass correction following well established procedures. For purpose of discussion, only the first three dominating modes are considered in the analysis. From Table 2 it can be observed that the modal periods are affected to a very small extent 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.5 illustrating that the dominant modes of vibrations of the said bridge are the flexural modes.

TABLE 2: Modal periods of the model bridge

Skew Angle	0	10	20	30	40	50
Mode number	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)
Mode 1	0.41732	0.44238	0.431	0.41307	0.38761	0.35472
Mode 2	0.30512	0.22983	0.22551	0.2214	0.21936	0.2207
Mode 3	0.21539	0.20317	0.20005	0.19664`	0.18886	0.17518



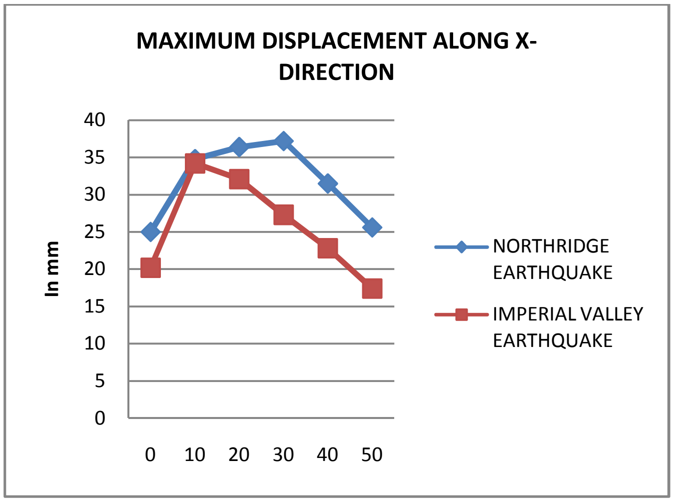
(a)

(b)

Fig. 5: Mode shapes of the model bridge (a) First mode of non-skewed bridge (b) First mode of 40° skewed bridge

The linear time history analysis of the bridge using the analytical model shown in Fig. 2 is applied along the longitudinal direction in order to evaluate the seismic responses of the bridge: the bearing displacements and reactions, deck acceleration at the centre, internal forces in the deck slab and the axial forces in the internal and external girders. Two earthquake ground motion records are applied along the longitudinal directions as shown in Fig. 4. The absolute peak values of the responses obtained from the dynamic analysis of the bridge are shown in Fig.6 to Fig.9 presenting that seismic responses of the bridge are affected by skew angles.

From Fig. 6a it is clear that as the skew angle is increasing, longitudinal displacements in bearings vary with change in skew angle. Simultaneously due to coupling effect displacements along the other direction are also increasing as seen from Fig. 6b. It can be seen that maximum displacement of 37.2 mm for Northridge and 34.2 mm for Imperial Valley are obtained at 40^{0} and 20^{0} along the same direction. On the other hand maximum displacement of 3.1 mm and 2.9 mm is obtained along the other direction for the same earthquakes. Such effect can be observed for acceleration responses as well as shown in Fig.7. Fig.8 gives the internal forces in the deck slab for Northridge earthquake which shows that with every increase of skew angle these forces are increasing. It is important to note the effect of torsion coming into action at higher skew angles which for the maximum time results into failure of the skew bridges. Hence this effect shall also be given a due importance in designing of skew bridges. In case of girders, as the skew angle is increasing axial forces in the external girders are increasing more as compared to that of internal girders. This shows that the external girders are more vulnerable at higher skew angles than that of internal girders. The same effect can be shown for Imperial Valley earthquake as well.



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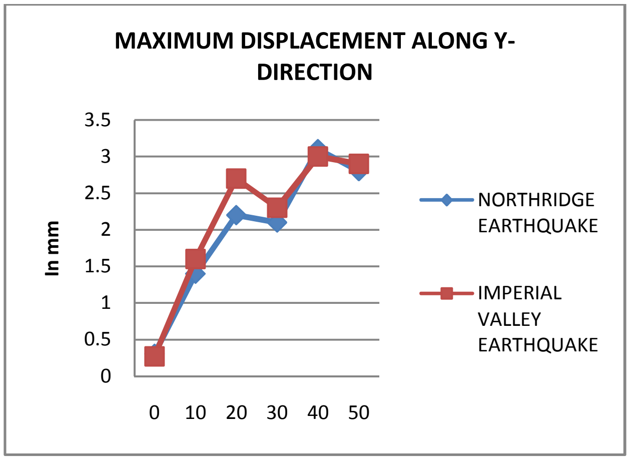

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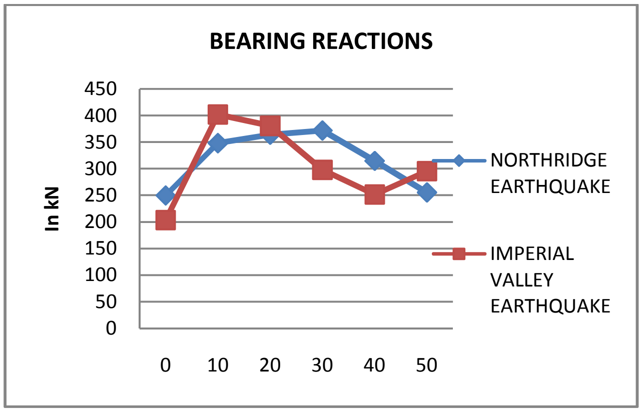

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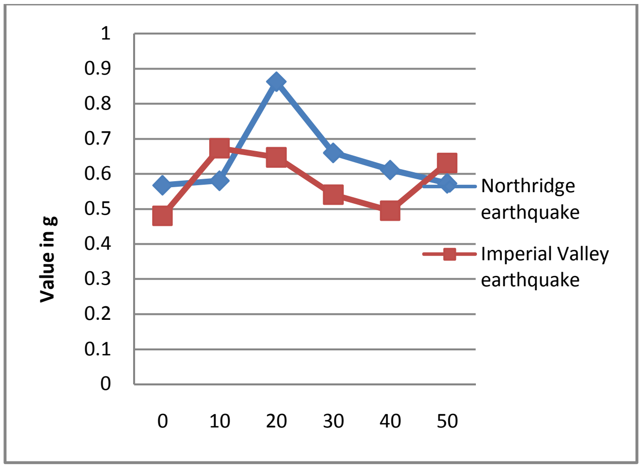
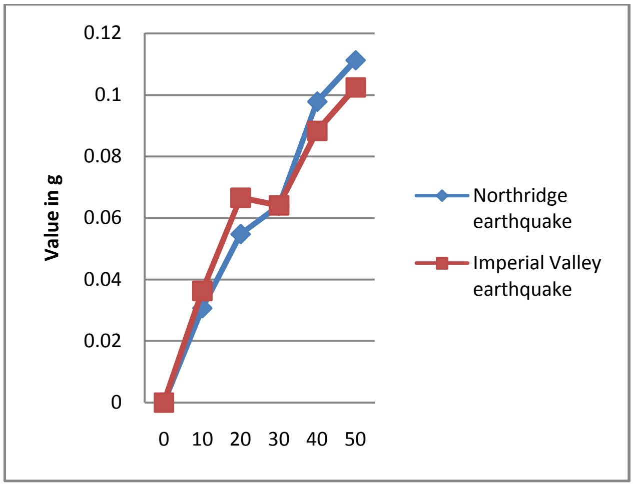
Fig. 6: Response on bearing A1: a) Max deformation along same direction (i.e X-dir) b) Max deformation along other direction (i.e Y-dir) c) Bearing reactions





(b)

Fig. 7: Maximum deck acceleration at centre when time histories applied along longitudinal direction: a) Along X-direction b) Along Y-direction

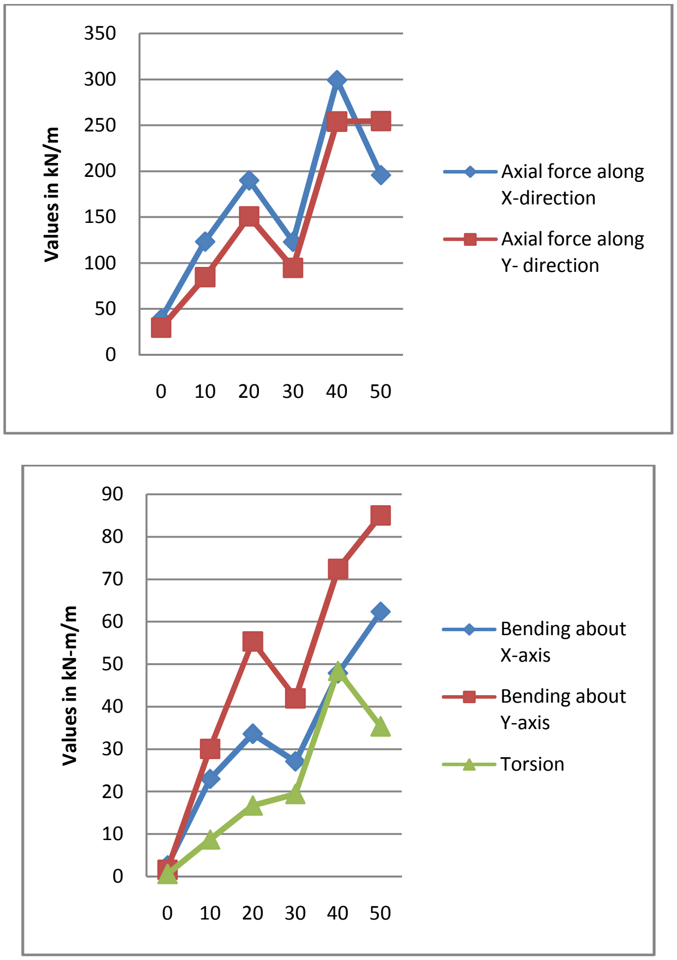


Fig. 8: Internal forces in deck slab for Northridge earthquake

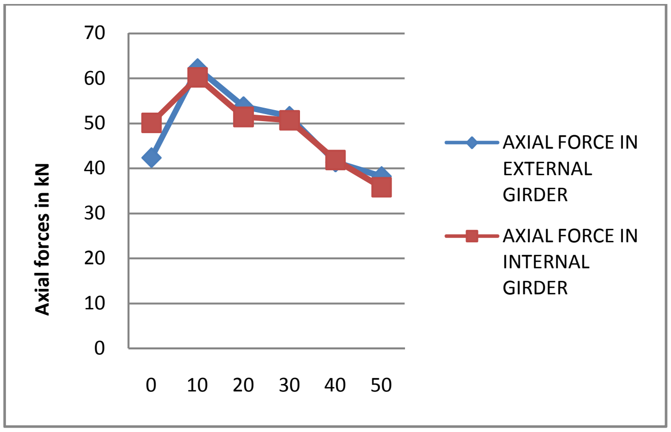


Fig. 9: Axial force in internal and external girders for Northridge earthquake

5. 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 50° is considered in the analysis. Three seismic responses of the bridge are discussed: bearing displacements and reactions, deck acceleration and axial forces in girders of the bridge. A standard numerical method is employed in the dynamic analysis of the bridge. Based on the results of this limited study following conclusions can be made:

1. The seismic responses of the bridge are significantly affected by skew angles of the bridge. For example, large skewness is likely to increase deck acceleration and bearing reactions of the bridge.

2. Due to skewness, the bridge does not only produce response in the direction of applied force but also gives response along the other direction. This behavior is mainly due to coupling effect which leads to rotation and finally resulting into an increase in the skew angle.

3. Further it can be concluded that the effect of torsion cannot be neglected along with other internal forces as the skew angle increases.

4. It was found that with an increase in skew angle, axial forces in the exterior girders increases more than that of the interior girders. Hence exterior girders are more susceptible to earthquake forces than interior girders at higher skew angles.

5. 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.

6. In the current study, a simply supported bridge model subjected two earthquake ground motions for a particular ground condition are 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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