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# Seismic analysis of skewed multi-span Steel Girder Bridge

S.Muhammad Hasan<sup>1</sup>, N.Sakthieswaran<sup>2</sup>, G.Shiny Brintha<sup>3</sup> & O.Ganesh Babu<sup>4</sup>  
<sup>1,2,3,4</sup>Department of Civil Engineering, Anna University Regional Campus,  
Tirunelveli, Tamilnadu, India.

**Abstract:** A bridge is an important component of the road transportation network. Its performance during and even after an earthquake event is quite crucial to provide relief as well as for security and defense purpose. Most of the past seismic studies on bridges have focused on regular bridges with no skew. However, past earthquakes and studies have shown that skewed bridges are more susceptible to earthquake damage, specifically caused due to coupled response. Therefore, there is a need for more research to study the effect of skew angle and the other relating factors on the performance of highway bridges. This paper examines the seismic performance of a three-span steel girder bridge with skew angles from 0 to 60 degrees, analytically. The bridge was modelled using finite element (FE) method using SAP2000. Different types of analysis were considered on both models such as: modal response spectrum and nonlinear static pushover analyses. 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 deck force, moment and displacement, base reaction, force acting on bent column and bearings 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 bridge; seismic response; steel-girder bridge.

## I. 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 [8].

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

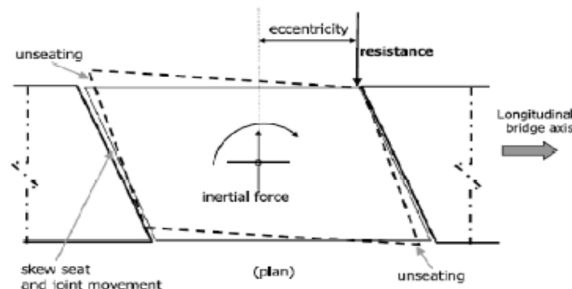


Fig. 1. Rotation mechanism of skew bridges

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Along the direction of increasing the skew angle (Fig. 1) [2] Several studies have investigated the effects of skew angle on the response of highway bridges (i.e. Maleki, 2002; Bjornsson et al., 1997; Saiidi and Orié, 1992; Maragakis, 1984). Saiidi and Orié (1991) noted the skew effects and suggested that simplified models and methods of analysis would result in sufficiently accurate predictions of seismic response for bridges. 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. 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, 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 modelling boundary conditions. For the present study a multi span steel girder skewed bridge for wide range of skew angles is modelled using FE method (SAP2000). Modal analysis and push over analysis for the same is carried out and finally the results are compared for various angles of skew angle.

### II. BENCHMARK BRIDGE

The model used in this study is derived from a non-skewed model developed by Nielson, the characteristics of which are based on data obtained from a survey of numerous bridge plans. As shown in Figure 2, the representative bridge consists of three spans of 12.2 m, 24.4 m, and 12.2 m for a total bridge length of 48.8 m. The bridge consists of a concrete deck supported by eight steel girders sitting on high-type fixed bearings and expansion bearings. Two pile-bent abutments and two multiple-column bents sitting on fixed foundations with 4.6 m high circular concrete columns make up the remainder of the sub-structural elements.

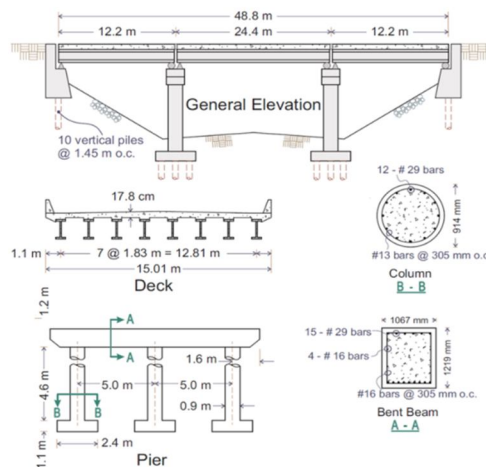


Fig. 2. Typical Non-Skew Bridge Details

The incorporation of skew into the model includes modelling changes to the bridge geometry, abutments, foundations, and impact elements.

Seismic performance of highway bridges is expected to be affected by combination of various parameters such as: skew angle, boundary conditions, superstructure flexibility, stiffness and mass eccentricity, in-span hinges and restrainers, width-to-span ratio, and direction of strong motion components with respect to orientation of bridge bent and abutments. The presented study investigates the effect of some of these parameters summarized as: skew angle, abutment, bearing and direction of earthquake motion.

### III. MODELLING OF BRIDGE

To facilitate a comparative parametric study of the seismic response of skewed highway bridges, a number of detailed three-dimensional (3D) finite element (FE) models were developed (Figure 3) using SAP2000 (2005). In all of the models, the superstructure was assumed to be linear-elastic shell elements, and all of the nonlinearity was assumed to take place in the

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substructure elements including bents, bearings, and abutment. The benchmark bridge was altered to produce models with different skew angles, but with the same overall dimensions. Skew angles of 0, 30, 45, and 60 degree were of interest. Finite element mesh was used to model deck. On the other hand, girders, and bent columns and footing were modelled using 3-D frame elements.

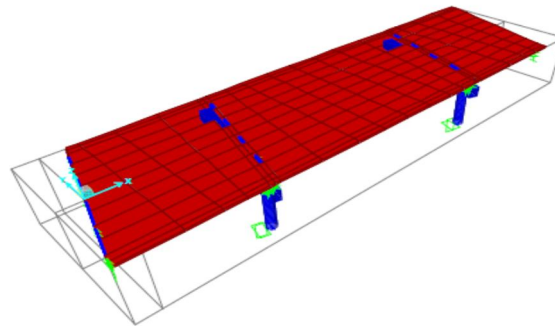


Fig. 3. 3D model in SAP2000

For the nonlinear analyses, nonlinearity is assumed to take place in the form of localized plastic hinges at the top and bottom of columns. The behaviour of nonlinear [uncoupled] axial and moment hinges is characterized by the axial force-displacement and moment-rotation relationship, respectively. Two joint link elements are used to model the bearings installed between the abutment top and the bottom of girders. It should be noted that the abutments are modelled by providing restrains at the end of the girders and deck slab.

Input data for the analysis consisted of the acceleration ground motion of PGA of 0.4g, and soil type B. The ground motion is applied in the longitudinal and transverse direction to each support element of the bridge.

### IV. 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 push over 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 at least 90% of the total seismic mass. For purpose of discussion, only the mode I longitudinal dominant mode and mode V transverse dominant mode are considered in the analysis.

Table 1. Modal stiffness and time period

Skew	Modal Stiffness (KN-m)	Time periods (seconds)
0	50	0.896
15	60	0.8098
30	90	0.661
45	132	0.5460
60	216	0.427

Table 1 shows the modal stiffness and time period of fundamental mode from modal analysis, which shows an increasing trend with the increase in skew which in contrast to the previous study showing skewed bridges more vulnerable to earthquake. But it has been found that the abutment stiffness increases with increase in the skew which significantly contributes to stiffness of the bridge [7]. Hence the increase in the modal stiffness is justified. Thus there is decrease in the modal periods.

Further Fig 4 shows the mass participation ratio from modal analysis of longitudinal dominant mode 1 and transverse dominant mode 5, the mass distribution along x increases slightly with the rapid increase along the orthogonal direction, for mode 5 vice versa .this due the fact that the load along each axis are transferred to the other axis which indicates the coupling effect between the axes.

The push over analysis of the bridge using the analytical model is applied along the longitudinal direction and transverse direction in order to evaluate the seismic responses of the bridge: base shear, bent column forces, bearing reactions, displacement of deck slab.

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The absolute peak values of the responses obtained from the dynamic analysis of the bridge are shown in Fig.5 to Fig.9 presenting that seismic responses of the bridge are affected by skew angles.

From the Fig 5, the base reaction of push over analysis for earthquake force applied along longitudinal direction, the force in y direction increases slowly while in x direction decreases slowly, and for the earthquake force applied along transverse direction the force along x direction increases rapidly while in y direction decreases slowly.

From the Fig 6, the bent column moment increases with the skew. And from the Fig 4, the support bearing graph shows a general increasing trend in the force with skew.

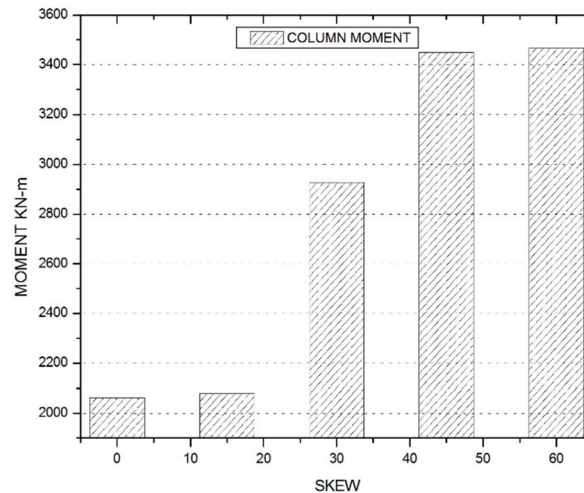


Fig. 6. Bent Column Moment

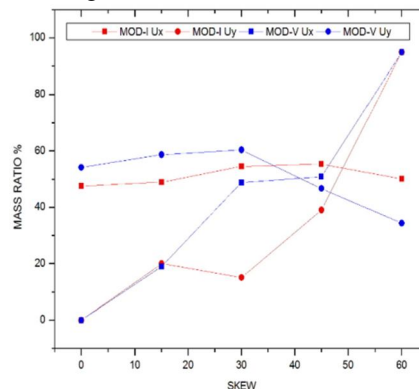


Fig. 4. Mass Participation ratio

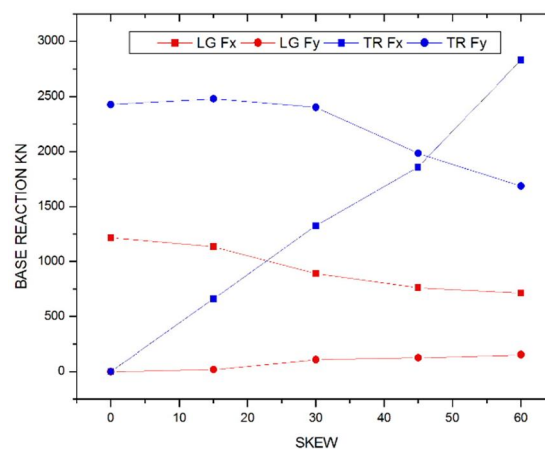


Fig. 5. Base Reaction

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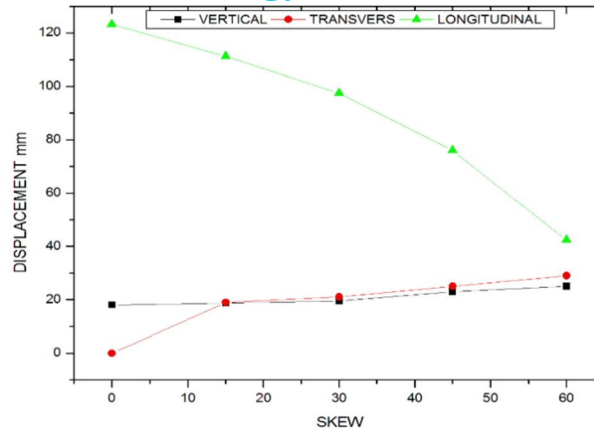


Fig. 7. Deck Displacement-EQ applied along X direction

From the Fig 7 & Fig 8, the deck displacement when the earthquake force is applied along x direction the longitudinal displacement decrease while the transverse displacement increases, and vice versa for when earthquake force applied along y direction. But the vertical displacement of bridge deck remains almost same for force applied along x direction while increases rapidly for y direction. And also from the Fig 9, the deck rotation increases with the skew with the rapid increase when the force is applied along y direction. Thus it seems that when the force is applied along y direction the deck displacement changes rapidly.

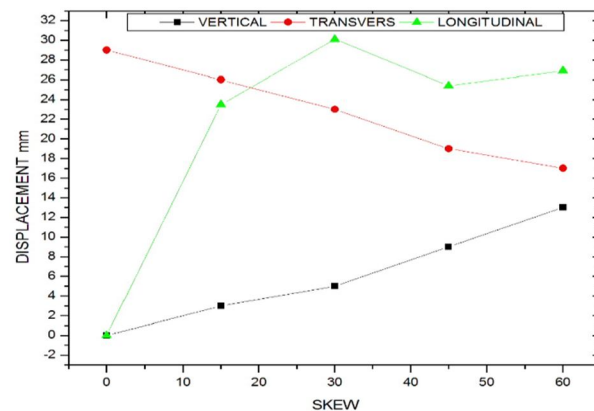


Fig. 8. Deck Displacement-EQ applied along Y direction

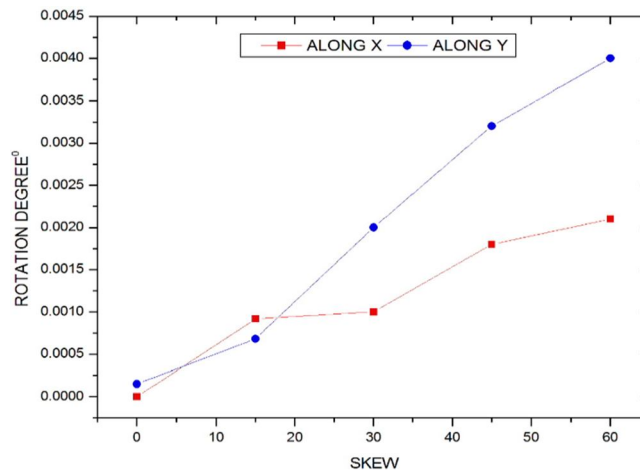


Fig. 9. Deck Rotation

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## V. CONCLUSIONS

The effect of skew angle on a multi span steel girder bridge is presented in this paper. A ground motion, compatible with design acceleration spectrum is applied in the longitudinal direction and transverse direction of the bridge. The maximum skew angle of  $60^\circ$  as recommended in codes and specification (e.g., AASHTO, 2000) is considered in the analysis. Some of the seismic responses of the bridge discussed are: modal stiffness, time period, base shear, deck displacement and bearing and bent column 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 multi span steel-girder 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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