

Nonlinear Seismic Response of Skewed Slab-Girder Highway Bridges

Shrirang Tande¹ and Payal Bhosale²

¹Professor, Department of Civil Engineering, ADCET, ASHTA, Maharashtra, India

²Assistant Professor, Department of Civil Engineering, ADCET, ASHTA, Maharashtra, India

Abstract— Skewed highway bridges exhibit complex structural behavior under seismic loading due to geometric asymmetry. This study investigates the nonlinear seismic response of single-span slab-girder skew bridges with skew angles ranging from 0° to 60°. A finite element-based approach is adopted to evaluate the influence of skew angle, span length, and aspect ratio on structural response parameters such as axial force, shear force, torsion, and bending moments. Response spectrum analysis is carried out using an advanced structural analysis program. The results demonstrate that both skew angle and aspect ratio significantly influence bridge response, with torsional effects becoming more pronounced at higher skew angles. The findings provide useful insights for the seismic design and analysis of skew bridges.

Index Terms— Skew bridges, seismic response, finite element analysis, skew angle, aspect ratio, torsion

I. INTRODUCTION

Bridges are critical components of transportation infrastructure and must be designed to withstand seismic forces. The 1971 San Fernando earthquake marked a turning point in understanding the seismic vulnerability of bridge structures, particularly skewed bridges, which exhibited significant rotational and torsional behavior.

Unlike straight bridges, skew bridges possess geometric irregularity, resulting in complex load distribution and coupled bending–torsion response. Traditional elastic analysis methods are often insufficient to capture these effects accurately.

In skew bridge decks, bending does not occur purely along longitudinal or transverse directions but rather along inclined axes connecting obtuse corners. This leads to interaction between flexural and torsional responses, making analysis more challenging.

The present study aims to evaluate the nonlinear seismic response of skew bridges by considering the effects of Skew angle, Span length and Aspect ratio using finite element modelling and response spectrum analysis.

II. ANALYSIS OF SKEW HIGHWAY BRIDGES

In the seismic analysis of a single-span skew bridge, a single-mode analysis approach is employed. This method assumes that the seismic effects can be represented by an equivalent static horizontal force acting on an individual frame in either the longitudinal or transverse direction. The magnitude of this force is evaluated based on the natural period of a single-degree-of-freedom (SDOF) system and the response spectra prescribed by relevant seismic design codes.

The single-mode SDOF approach, commonly referred to as the equivalent static analysis, constitutes the most fundamental form of seismic analysis. It is particularly suitable for bridge structures whose dynamic response is predominantly governed by a principal translational mode of vibration. Under such conditions, complex bridge systems can be reasonably idealized as SDOF models. For example, a two-span bridge supported by a single column may be simplified using this approach. The dynamic response of the system subjected to ground motion is described by the standard equation of motion for an SDOF system.

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g \text{ ----- (1)}$$

The influence of geometric asymmetry on bridge behavior under seismic loading is of primary concern, especially in skew bridges. In this study, three numerical models with varying geometric configurations are considered to evaluate this effect. The bridge deck plays a crucial role in defining the

structural response, particularly in the presence of asymmetry. Key parameters governing the deck geometry include the skew angle and aspect ratio.

The aspect ratio is further defined through two parameters, namely the span-to-width ratio (L/B) and the spacing-to-span ratio (S/L). The study investigates the response of bridge decks by systematically varying these parameters, along with skew angles, to assess their influence on seismic performance.

III. NUMERICAL EXAMPLES

To evaluate the influence of various parameters on the seismic response of skewed bridges, a series of analyses is carried out on single-span slab-girder bridges ranging from short to long spans. Span lengths of 8 m, 16 m, 24 m, and 32 m are selected as representative cases. All bridge models are analyzed with a constant deck width of 8 m while varying the span length. The geometry of the bridge deck is illustrated in Fig. 1, whereas the corresponding finite element models of the skewed bridges are presented in Fig. 2 and Fig. 3.

The analysis is performed using a finite element program developed by Computers and Structures, Inc. (2000). Each node in the model is assigned two translational degrees of freedom (U_x and U_y) and one rotational degree of freedom (U_θ). Since the cross frames and lateral load-resisting components of the superstructure are assumed to remain elastic under seismic excitation, a response spectrum analysis is adopted.

The geometric properties of the bridge are defined as follows: the thickness of the cast-in-situ deck slab is 250 mm; the center-to-center spacing of longitudinal girders is 2.5 m; the spacing of cross girders is 2.0 m; and the overall span-to-depth ratio is maintained at 15. The clear roadway width is 7.5 m, and the width of the edge beam is 500 mm, with its stiffness assumed to be equal to that of the slab.

The effective right spans considered for analysis are 8 m, 16 m, 24 m, and 32 m, with skew angles of 0° , 15° , 30° , 45° , and 60° examined for each case.

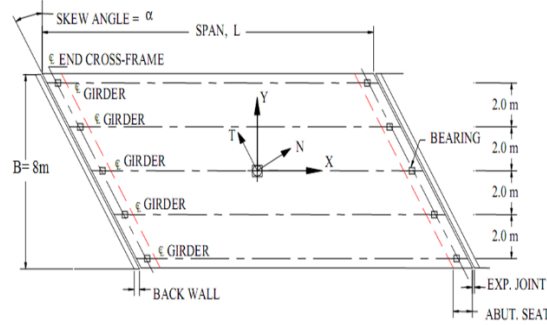


Fig.1: Typical Skewed Bridge Plan

IV. FINITE ELEMENT MODELLING

The deck slab is modeled using rectangular shell elements, while the girders are represented by frame elements that are connected to the shell elements at each node. The girder ends are assumed to be free to rotate but are restrained in the vertical direction. This modeling approach effectively captures the contribution of the girders' weak-axis moment of inertia to the overall stiffness of the superstructure under transverse loading.

In the longitudinal direction, the girder ends are connected to spring elements that simulate the lateral stiffness of elastomeric bearings. A single-span straight bridge configuration is considered to investigate the influence of skew angle on the seismic response of the structure. The analysis is carried out for four different span lengths, namely 8 m, 16 m, 24 m, and 32 m.

The bridge response is primarily influenced by the aspect ratio and the variation in skew angle. For the right (non-skewed) bridge configuration, the aspect ratio (B/L) is initially equal to unity; however, as the span length increases, the aspect ratio correspondingly decreases.

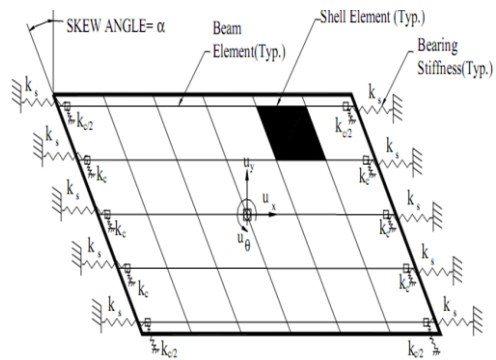


Fig.2: Typical Finite Element Model of a Bridge

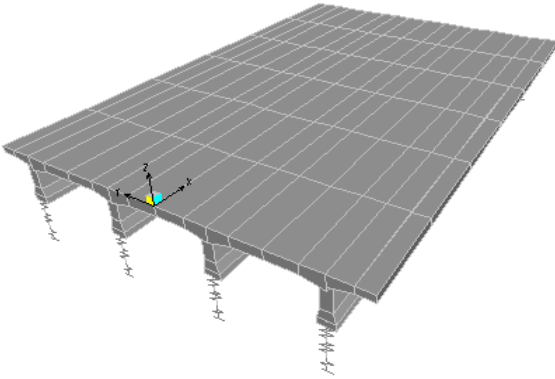


Fig.3: Extrude Model of Straight Bridge

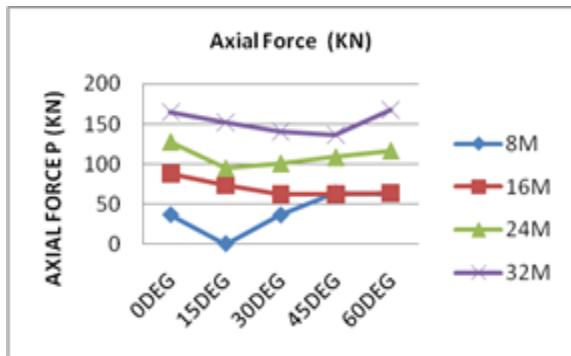


Fig.4 (a): Axial force

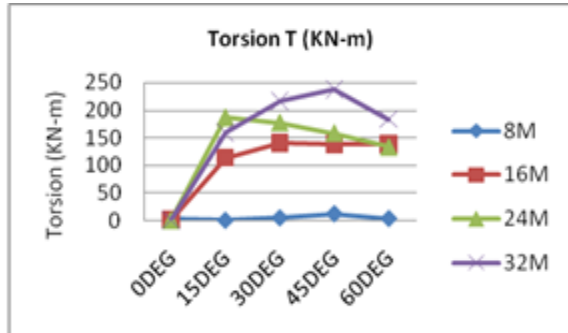


Fig.4 (b): Torsion

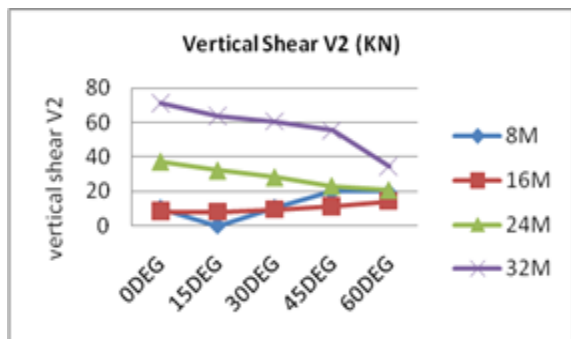


Fig.4 (c): Vertical Shear

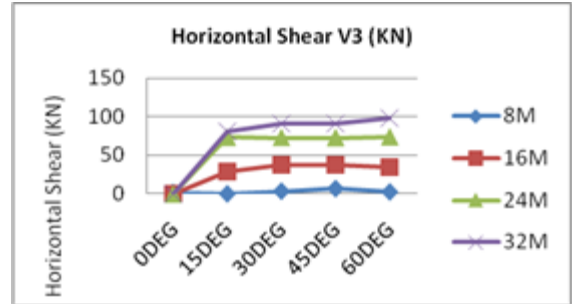


Fig.4 (d): Horizontal Shear

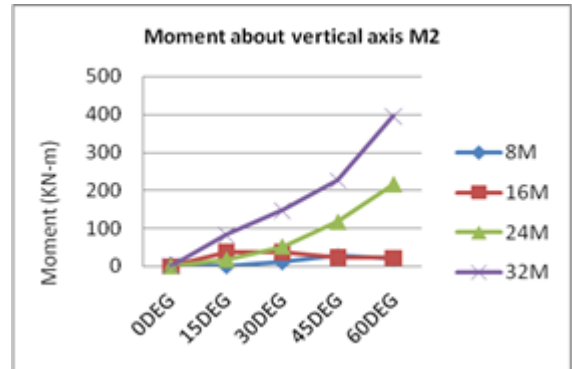


Fig.4 (e): Moment about Vertical Axis

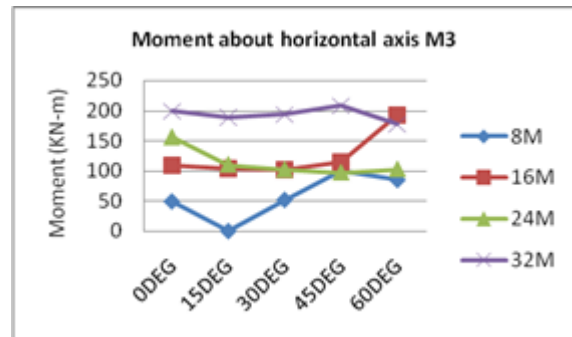


Fig.4 (f): Moment about Horizontal Axis

V. DISCUSSION OF RESULTS

An analytical investigation has been carried out on single-span skewed slab-girder bridges with span lengths ranging from 8 m to 32 m and skew angles varying from 0° to 60°. The results presented in Tables 1–3 and Fig. 4(b) indicate that the torsional forces developed in the 8 m span bridge are comparatively lower than those in longer spans for all skew angles. This observation highlights that the aspect ratio plays a significant role in governing the development of torsional moments in skewed bridges.

From Fig. 4(c), it is observed that the variation in vertical shear force for 8 m and 16 m spans is minimal

across different skew angles. However, as the unsupported span increases to 24 m and 32 m, a noticeable reduction in vertical shear is observed. Fig. 4(d) demonstrates that the horizontal shear force is negligible for a straight bridge (0° skew angle), but increases sharply up to a skew angle of 15° , beyond which it continues to increase gradually for all span lengths.

Fig. 4(e) shows that the moment about the vertical axis is relatively small for straight bridges and increases progressively with an increase in skew angle. In contrast, Fig. 4(f) indicates that the moment about the horizontal axis is initially high and exhibits only minor variations with changes in span length and skew angle.

The study evaluates bridge response for different aspect ratios, namely 1.0, 0.5, 0.33, and 0.25, with skew angles varying from 0° to 60° in increments of 15° . The results reveal that the aspect ratio is inversely proportional to the bridge deck response, whereas the skew angle is directly proportional to the structural response. Traditionally, skew angle alone has been considered the primary parameter governing bridge behavior, and it is generally assumed that skew effects are negligible for angles less than 15° . However, this assumption is valid only when the bridge width is relatively small compared to the skew span. Recent insights indicate that both skew angle and aspect ratio—particularly the ratio of skew span to right width—are critical parameters in accurately assessing skew effects.

The influence of aspect ratios L/B and S/L , in conjunction with skew angle, on the structural behavior of bridges has also been examined. Here, L represents the skew span (measured along the free edge), B denotes the right width, and S is defined as the projected deck span between obtuse-angled corners along the span direction. It is observed that skew effects are insignificant when $S/L \geq 0.75$. For $0.5 \leq S/L < 0.75$, skew effects become moderate and must be considered in design, whereas for $S/L < 0.5$, skew behavior becomes dominant across the entire deck.

In slab bridges where the width is significantly larger than the span, the influence of skew is less pronounced. Consequently, skew effects may be

6. It is concluded that both skew angle and aspect ratio—specifically the ratio of skew span to right width—are critical parameters in accurately

neglected when $L/B \leq 0.5$. Furthermore, if the bridge width exceeds twice the span ($B > 2L$), the structural response is primarily governed by unidirectional bending, and skew effects can be reasonably ignored. For cases where $S/L < 0.5$, it is recommended to adopt beam-and-slab deck systems to enhance torsional rigidity. Alternatively, closely spaced multi-beam decks with cast-in-situ slabs may be employed, particularly where depth constraints exist.

VI. CONCLUSIONS

Based on the analytical results and discussions presented, the following conclusions are drawn:

1. Among the available refined analytical approaches, the finite element method (FEM) is the most comprehensive and versatile technique for both static and dynamic analysis of bridge structures. Although it is computationally intensive and time-consuming, it effectively captures the complex interactions and parameters influencing structural response.
 2. The support reactions at the obtuse corner near the applied load are significantly higher and increase with an increase in skew angle. Conversely, the axial force decreases with increasing skew angle, while torsional moments develop and become more pronounced. For a straight bridge (skew angle = 0°), torsional effects are negligible.
 3. The torsional force is comparatively lower for the 8 m span across all skew angles when compared to longer spans. This indicates that the aspect ratio is a governing parameter in the development of torsional effects in skewed bridges.
 4. The parametric study considering variations in skew angle and aspect ratio reveals that:
 - a. The bridge response is directly proportional to the skew angle.
 - b. The bridge response is inversely proportional to the aspect ratio.
 5. To achieve a reduced structural response, it is recommended that the skew angle be limited to approximately 30° – 40° , and the aspect ratio be maintained close to unity. Additionally, the maximum unsupported span length for single-span bridges should preferably be restricted to 20–25 m.
- predicting and assessing skew effects in bridge structures.

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Table 1: Response of 8m Right Span Bridge

Skew Angle	Axial Force P(KN)	Horizontal Shear V2(KN)	Vertical Shear V3(KN)	Torsion T(KN-m)	Moment @ Vertical Axis M2(KN-m)	Moment @ Horizontal Axis M3(KN-m)
0°	36.495	10.253	1.753	1.9967	5.2491	49.121
15°	0.037	0.01	2.54E-08	5.24E-08	2.53E-08	0.0484
30°	36.171	10.527	3.204	4.7297	10.6922	51.5532
45°	63.768	19.859	6.57	12.2414	27.6759	99.904
60°	62.95	19.605	2.337	3.5126	19.7305	84.5585

Table 2: Response of 16m Right Span Bridge

Skew Angle	Axial Force P(KN)	Horizontal Shear V2(KN)	Vertical Shear V3(KN)	Torsion T(KN-m)	Moment @ Vertical Axis M2(KN-m)	Moment @ Horizontal Axis M3(KN-m)
0°	88.239	8.477	1.99E-06	8.18E-05	2.32E-05	109.644
15°	73.22	8.202	29.181	114.0571	37.9695	103.5072
30°	62.779	9.323	37.001	141.0442	37.6501	101.828
45°	62.079	11.264	37.502	138.5423	23.3528	115.2243
60°	63.368	14.269	34.922	138.3139	22.3957	193.0686

Table 3: Response of 24m Right Span Bridge

Skew Angle	Axial Force P(KN)	Horizontal Shear V2(KN)	Vertical Shear V3(KN)	Torsion T(KN-m)	Moment @ Vertical Axis M2(KN-m)	Moment @ Horizontal Axis M3(KN-m)
0 ⁰	164.903	71.534	5.72E-06	6.55E-05	1.71E-05	199.1271
15 ⁰	152.629	63.733	81.383	159.2679	82.3756	189.2363
30 ⁰	140.857	60.616	90.692	216.59	147.0239	193.8228
45 ⁰	136.445	55.382	90.815	237.6417	226.77	208.2752
60 ⁰	168.269	34.186	98.605	183.3352	396.2877	177.8486

Table 4: Response of 32m Right Span Bridge

Skew Angle	Axial Force P(KN)	Horizontal Shear V2(KN)	Vertical Shear V3(KN)	Torsion T(KN-m)	Moment @ Vertical Axis M2(KN-m)	Moment @ Horizontal Axis M3(KN-m)
0 ⁰	127.376	37.335	2.44E-06	3.23E-05	7.40E-06	155.9825
15 ⁰	95.197	32.233	73.702	187.9955	17.9913	110.3488
30 ⁰	101.11	28.342	73.445	178.3133	51.8545	101.8813
45 ⁰	108.649	23.299	73.337	159.1026	116.7722	96.9551
60 ⁰	116.653	20.908	74.305	133.7408	216.2245	102.4379