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Dynamic Behavior Of Skewed Bridge Compared to Normal Bridge

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Abstract
Highway bridges are among the most crucial elements of the transportation system, therefore continuous operation is required even in the wake of strong to major earthquakes. When the mass and geometry of a bridge are constant, a skewed bridge is more susceptible to higher damage compared to a normal bridge. This paper presents the effects of skew in the multi-span continuous concrete bridge. Nonlinear behavior is concentrated at the top and bottom of pier because the pier is the most important component of the bridge. A Series of non-linear static (Pushover) analyses is performed to compare median values for bridges bridge for different damage states established by (Hazus MH 2.1, 2003). The paper presents variation of the the displacement, drift capacity, and displacement ductility of the bridge for different skew angles.

Keywords
skew bridge, pushover, damage states, drift capacity, displacement ductility

1. Introduction

Bridges are important structure in transportation and it provides crucial contact between two regions. These structures are subjected to large forces during an earthquake event. The consequences of this can be little damage to extensive damage to bridge structures. Nepal is regarded as an earthquake-prone region since it is located in the subduction zone of two plates, the Indian Plate and the Eurasian Plate. At a rate of 25 mm per year, the Indian plate is advancing toward the Eurasian plate. These tectonic plates store a significant amount of strain energy from their movement, which is released as an earthquake when the plates break. Therefore, there is a strong possibility that large earthquakes can occur for an average of 100 years.

Skew bridges are bridges that are built obliquely from abutment to abutment. The skew angle refers to the inclination of the center line line of traffic with respect to the normal to the centre line of the obstructions. These bridges are often encountered in highway design when the geometry cannot accommodate straight bridges and are chosen when road alignments are not perpendicular to the river. Perpendicular approaches to the river in such cases can add extra cost in lengthening the approach road and sometimes and sometimes even cannot be possible due to settlement. Pounding of deck against abutment in direction of decreasing skew causes length supported by the abutment to shorten, which causes the deck to have a tendency to drop off the support at the acute corners caused by planar rigid body rotation. The highway system's bridges are crucial for supply routes and rescue efforts following a disaster. Skewed bridges are more vulnerable than straight bridges because of the impact of the combined reaction of transverse and longitudinal modes.[1][2] The forces operating on bent columns, such as axial force, vertical shear, torsion, and bending moment about the vertical axis of the bridge section, increase as the skew angle increases.[3]

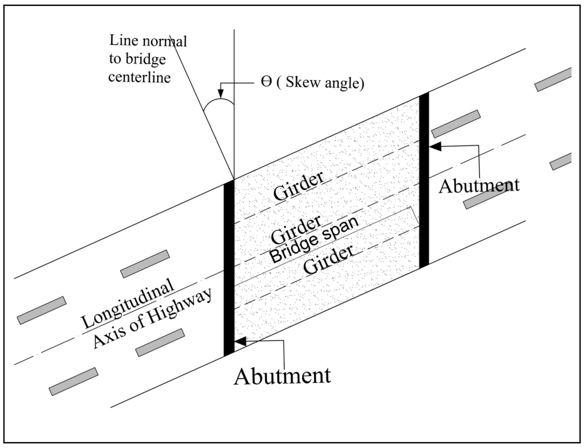

Figure 1: Plan of Skew Bridge

2. Modeling and Analysis

Modeling the bridge is a crucial process that includes the definition of material properties, the geometry of the bridge, assigning loads, and so on. Modeling is done using CSI Bridge v24 which is commercial FEM software specializing in the design and analysis of bridge structures.Pushover analysis is static analysis procedure using non linear technique, is performed to evaluate the capacity of the bridge.

2.1 Bridge Geometry

The sample bridge is based on [4] and [5]. A three-span bridge is considered with a center span of 18.29 meters and two approach spans of 13.41 meters. The ratio of maximum span to approach span is close to 1.4. The Bridge is Multispan Continuous Concrete I-Girder Bridge (MSCC-IG). The Bridge consists of two bents per column with 2 columns per bent. The column is 6.7-meter-tall and 0.92m in diameter with 24 numbers of #11 reinforcement bars. The column has #4 bar stirrups spaced at 10 cm center to center. The cap beam is a rectangular cross-section of 0.762 m x 1.143 m and the deck is supported on 7 numbers of standard I girders equally spaced.

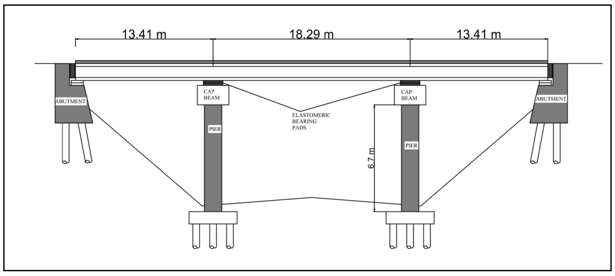

Figure 2: Longitudinal Section of Bridge

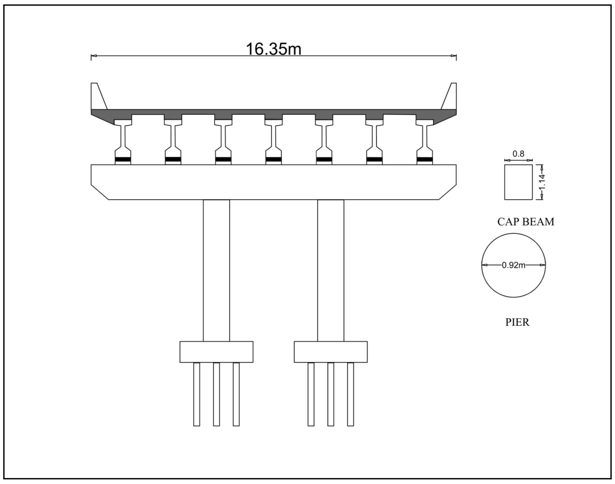

Figure 3: Cross Section of Bridge

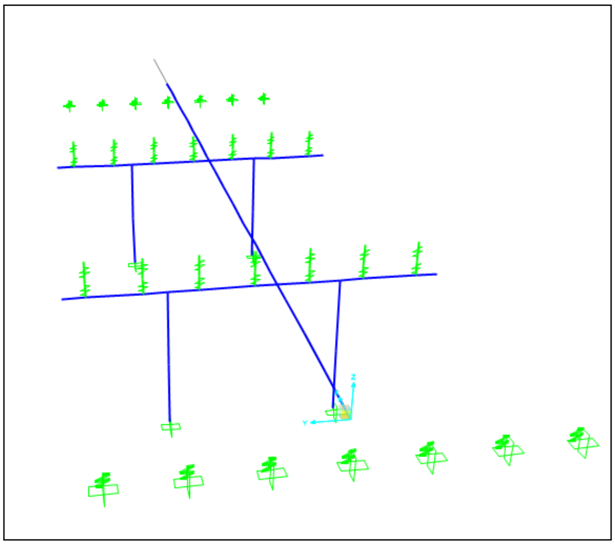

Figure 4: Beam stick FEM model for 0^o

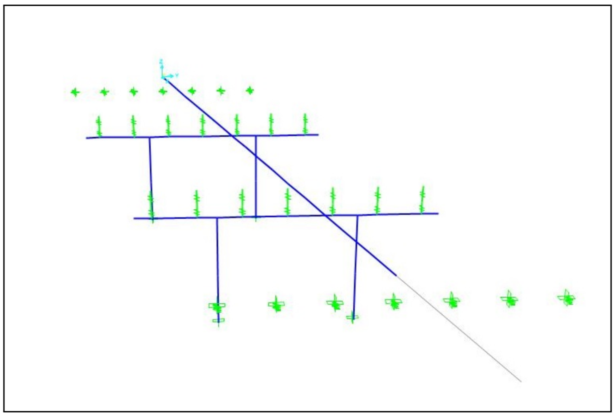

Figure 5: Beam stick FEM model for 15^o

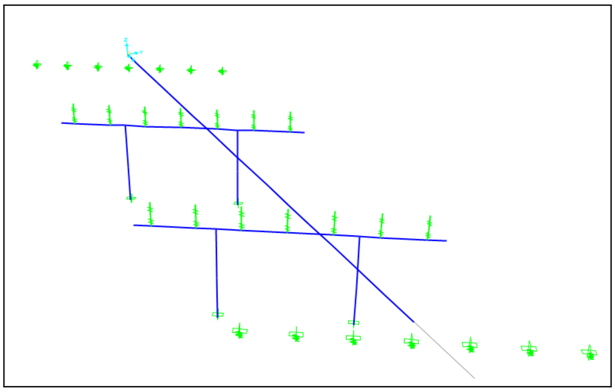

Figure 6: Beam stick FEM model for 30^o

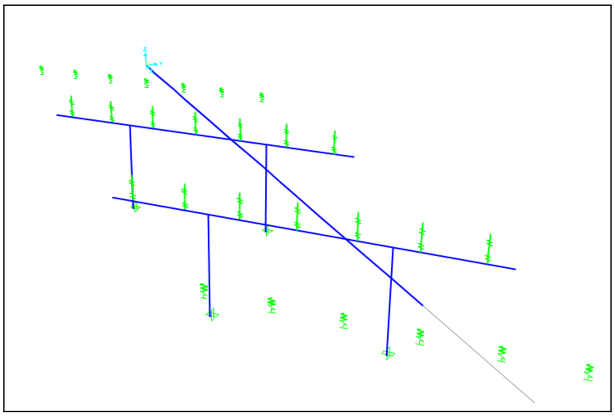

Figure 7: Beam stick FEM model for 45^o

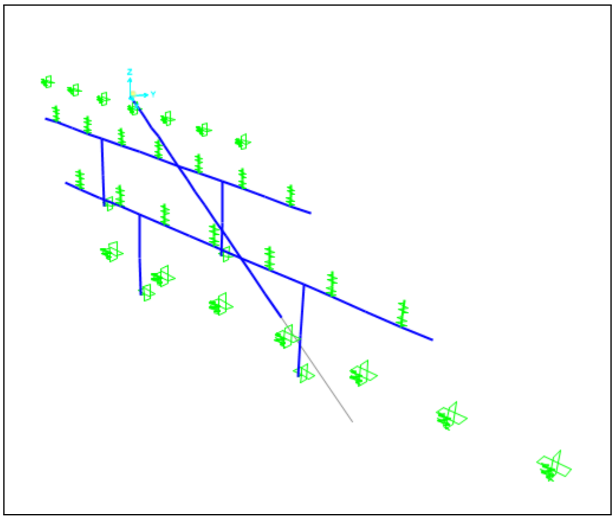

Figure 8: Beam stick FEM model for 60^o

2.2 Finite Element Modeling

The analysis focuses on a three-span continuous RCC bridge with a skew angle that ranges from 0° to 60°. The model of the superstructure is represented by the reduced beam stick model which assumes the superstructure as an elastic element and can capture the behavior of the bridge [6] [7] . When a simple linear elastic models of the bridge is taken into account the analysis that goes along with it will only accurately describe the static and dynamic behaviour of the system if stresses on every component of the bridge stay within their elastic region. Actual force demands on the structure beyond that demand level will differ greatly from the forces and displacements computed by a linear elastic analysis. Such a model will ignore the effects of the surrounding ground according to its level of strain, the cyclic yielding of structural elements, the closing and opening of superstructure joints, the engagement, yielding, and release of restrainers, as well as the complex and nonlinear abutment behavior.[8] . The columns have potential plastic hinges at top of the column where it mounts into the bent beam and at the bottom of the column where it mounts into the pile cap. The pier is divided into two zones, one is an elastic zone and another one is a plastic zone. In idealized cantilever models, plastic hinges are formed at the end of the each segment close to the point of rigidity of the column. The column's curvature gradually increases with height from the inflection point , point with zero moment through fixity point, point with maximum moment.[8].

Although the deck can be treated as indefinitely rigid to withstand pile-top rotation, it's vital to note that due to bond stress, the strain in the dowels does not drop to zero at the pile-deck interface, but progressively decreases over a finite length. It is important to add member at the top of the pile, penetrating a length Lsp into the deck, for proper modeling as mentioned in [9] and [10]

$$L_{sp} = 0.022 * f_{ye} * d_{bl} \tag{1}$$

$$L_{PT} = kH_{con} + L_{sp} \geq 2L_{sp} \tag{2}$$

$$k = 0.2(\frac{f_u}{f_{ye}} - 1) \leq 0.08 \tag{3}$$

Where L_{sp} is Length of Strain Penetration of Member, d_{bl} is dowel-bar diameter, f_{ye} is yield stress H_{con} is the distance from the deck soffit to the point of contra flexure in the pile.

The calculated value of L_sp from equation 1 is 326 mm. The height of the pier is increased by L_{sp} in the model. The length of the plastic hinge from equation 2 is 862 mm. Fiber hinge of 826 mm is defined in the model on which nonlinear behavior is considered. The bearings of abutment are modeled as free bearing and the bearing of bent is modeled as fixed. The connection between the deck slab and girders is assumed to be of rigid link to ensure proper continuity in model.

2.2.1 Material Properties

The concrete of 34.47 MPa and the rebar is 60 grade rebar with a yeild strength of 415MPa.The properties of confined concrete and unconfined concrete are different. In addition to having stronger strength, confined concrete typically exhibits significantly higher ductility than unconfined concrete. A stress-strain model that distinguishes between the behavior of confined and unconfined concrete is therefore crucial and desirable. Mander's model [11] describes the stress-strain relationship for confined and unconfined concrete. The properties of rebars are obtained from Park's Model.

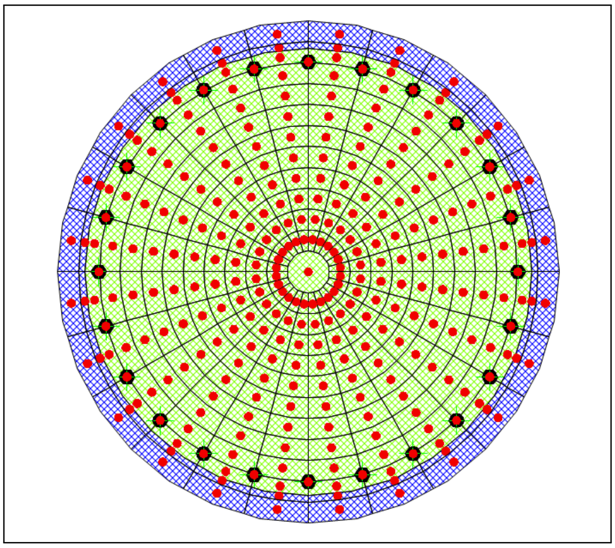

Figure 9: Fiber Layout of Pier Section

2.2.2 Superstructure Modeling

The nonlinear behavior of the superstructure is not considered during the analysis. So, the superstructure including all girders and deck slab is modeled as a single beam element. The connections between bridge components are modeled using a rigid link to ensure proper connections and maintain continuity of the model. The superstructure consists of girders and a deck slab which is modeled as a single beam element. The bearings of abutment are modeled as free bearing and the bearing of bent is modeled as fixed.

2.3 Modal Analysis

Modal analysis determines fundamental dynamic characteristics, such as natural frequencies, damping factors, and mode shapes, and uses them to construct a mathematical model for its dynamic behavior.Using eigenvector analysis, the system's undamped free vibration mode shapes and frequencies are determined. Through these natural modes, the behaviour of the structure may be very easily interpreted. Ritz-vector analysis seeks to discover modes activated by a particular loading. Ritz vectors can surpass eigenvectors when used for response-spectrum and time-history analysis based on modal superposition. [12] As with an increase in skew angle, stiffness of the bridge decreases which increases the natural time period of vibration of the bridge in both longitudinal and transverse directions.

2.4 Non-Linear Static Analysis

The median capacity of a skew bridge for various damage states with respect to predetermined fiber element strain values is determined using damage states for highway systems provided by [13] The damage states for highway system are None damage, Slight damage or Minor damage, Moderate Damage, Extensive damage, and Collapse damage. The qualitative definition is mentioned by [13] and quantitative definition presented by authors [2], [14]. Damage states can be defined in terms of displacement ductility [15].

Drift capacity is defined as maximum allowable drift without collapse where columns can undergo cracking and spalling without collapse. From the definition of damage states [13], the state at which column undergoes degradation without shear failure is identified by displacement in which extreme fiber of core concrete reaches maximum compressive strain.

3. Results and Discussion

3.1 Modal Analysis

The study of dynamic systems with in frequency domain is termed as modal analysis. Modal analysis is needed to comprehend the vibration properties of mechanical structures. It translates vibration signals of excitation and responses observed on a difficult-to-perceive complicated structure into a collection of modal characteristics that can be predicted easily. The natural time period is given by the following equation

$$T_n = 2\pi\sqrt{\frac{m}{k}} \tag{4}$$

As mass is identical for all models, the time period of a structure is inversely its stiffness only ($T_n \propto \frac{1}{k}$).With the increase in skew angle, the stiffness of the bridge decreases which increases the natural time period of vibration of the bridge in both longitudinal and transverse directions.

Table 1: Fundamental time period of bridge structures

Mode	0° sec	15° sec	30° sec	45° sec	60° sec
1	0.9031	0.9033	0.9082	0.9298	0.9454
2	0.5302	0.5453	0.5852	0.6135	0.7364
3	0.3999	0.4020	0.4034	0.4060	0.4182
4	0.1340	0.1340	0.1337	0.1333	0.1327

Table 2: Modal Participating Mass Ratio in Longitudinal direction

Mode	0°	15°	30°	45°	60°
1	0.981	0.915	0.734	0.481	0.243
2	0	0	0	0.007	0
3	0	0.067	0.25	0.498	0.746

Table 3: Modal Participating Mass Ratio in Transverse direction

Mode	0°	15°	30°	45°	60°
1	0	0.066	0.247	0.485	0.738
2	0	0	0	0.007	0
3	0.991	0.924	0.741	0.493	0.245

Modal Participating Mass Ratio in Longitudinal direction(U_x) decreases for Mode 1(Translational mode in the X direction) as the skew angle of the Bridge increases. While for Mode 3(Translational mode in the Y direction) it increases with skew angle. With the increase in the skew angle of the bridge, the relative contribution of mass for vibration shifts from Mode 1 to Mode 3 for (U_x) due to a change in geometric properties.
Modal Participating Mass Ratio in Transverse direction (U_y) increases as the skew angle of the Bridge increases for Mode 1. While for Mode 3 it decreases with increase in the angle of skew. With the increase in the skew angle of the bridge, the relative contribution of mass for vibration shifts from Translational mode in the transverse direction to the translational mode in the Longitudinal direction for (U_y) as geometric properties vary with the angle.
For straight bridge the relative contribution in deformation is solely based on first mode however for skewed bridge, the overall deformation is due to relative contribution of longitudinal and transverse modes and both modes should be considered as important.

Table 4: Deck torsion for different Skew angle

SN	Skew Angle	Deck Torsion
1	0	0 KNm
2	15	5.86 KNm
3	30	11.07 KNm
4	45	20.19 KNm
5	60	38.98 KNm

Linear analysis of bridge model under Dead load plus IRC-70 R l loading monitors increase in torsion in beam stick model in a deck of the bridge. As the angle of the skew is increased, the torsion in the deck increases.

3.2 Non-linear Static Analysis

Pushover analysis is done using displacement controlled approach usning fiber hinges. All of the fibers in the sections are initially compressed, and when a lateral force is applied, certain fibers' compressive strain gradually rises while others gradually fall, changing from compressive strain to tensile strain. By observing the strain on the fibers, it is possible to estimate the proper displacement.

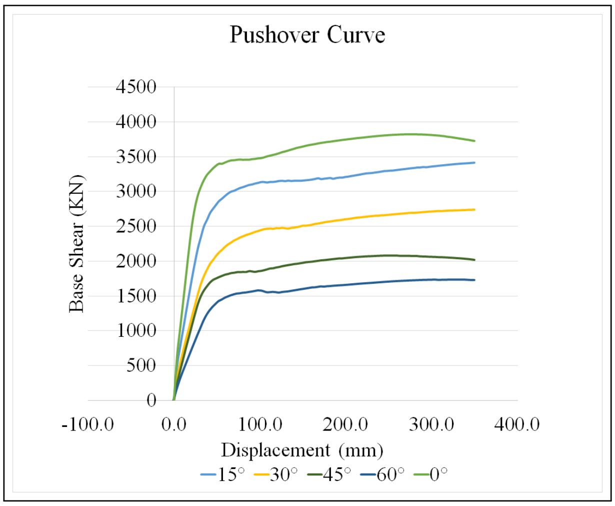

Figure 10: Pushover Curve for different skew angles

The top base shear of bridge is decreasing for increasing skew angle, so lateral load resisting capacity of bridge decreases. Due to this skew bridge cannot perform well in earthquake compared to normal bridge for identical mass and geometry.

Table 5: HAZUS Damage State Definition

Damage states	Qualitative Definition [13]	Quantitative Definition	Strain	Remarks
Slight/ Minor Damage	Minor spalling of column	First Reinforcement yield displacement	0.002069	At extreme Rebar
Moderate Damage	Spalling in column	Maximum compressive strain at cover concrete εc_0	0.002481	At extreme fiber of cover concrete
Extensive Damage	Column degradation without collapse	Maximum Compressive strain at core concrete $\varepsilon_c = 0.002(1+5(\frac{f'_{cc}}{f_{cc}})-1)$	0.004308	At extreme fiber of Core concrete
Complete Damage	Column collapsing	Ultimate compressive strain at core concrete $\varepsilon_c = 0.004 + \frac{1.4\rho_s f_{yh}\varepsilon_{su}}{f'_{cc}}$	0.01188	At extreme fiber of Core concrete

3.3 Damage States

The qualitative definitions in HAZUS [13] are taken into consideration while creating the quantitative definition. The slight damage state is defined as the first yielding of extreme fiber reinforcing steel in the cross-section of bridge piers. Quantitatively, moderate damage is defined as the maximum compressive strain at the extreme fiber of cover concrete and that is estimated from equations in the tables for extreme core concrete, respectively. The definition of extensive and complete damage is determined by the extreme core concrete fiber's ultimate compressive strain, as determined by equations in the table as presented by authors [2] [14].

The displacement of the top of the pier for the first yield of extreme rebar with tensile strain 0.002069 was 21 mm for a straight bridge which increases to 31.5 mm for an increase in skew angle from 0° to 60°. Quantification of damage states are presented in table 6 to 10

Table 6: Quantification of Damage state for 0°

Damage State	Displacement (mm)	Displacement Ductility	Median Displacement Ductility
Slight	21	1.00	1.42
Moderate	38.5	1.83	2.50
Extensive	66.5	3.17	5.42
Collapse	161	7.67	7.67

Table 7: Quantification of Damage state for 15°

Damage State	Displacement (mm)	Displacement Ductility	Median Displacement Ductility
Slight	21	1.00	1.67
Moderate	49	2.33	3.58
Extensive	101.5	4.83	8
Collapse	234.5	11.17	11.17

Table 8: Quantification of Damage state for 30°

Damage State	Displacement (mm)	Displacement Ductility	Median Displacement Ductility
Slight	28	1.00	1.5
Moderate	56	2.00	3
Extensive	112	4.13	6.5
Collapse	252	9.00	9

Table 9: Quantification of Damage state for 45°

Damage State	Displacement (mm)	Displacement Ductility	Median Displacement Ductility
Slight	31.5	1.00	1.39
Moderate	56.00	1.78	2.39
Extensive	94.5	3.00	4.5
Collapse	189.00	6.00	6.00

Table 10: Quantification of Damage state for 60°

Damage State	Displacement (mm)	Displacement Ductility	Median Displacement Ductility
Slight	28	1	1.4375
Moderate	52.5	1.875	2.625
Extensive	94.5	3.375	5.25
Collapse	199.5	7.125	7.125

The displacement of the top of the pier increases for slight damage, moderate damage, and extensive damage state when the angle of skew is increased up to 45° . Although when the angle of skew is increases from 45° to 60° the displacement decreases. The displacement of the top pier for collapse damage state increases up to 30° and decreases up to 60°

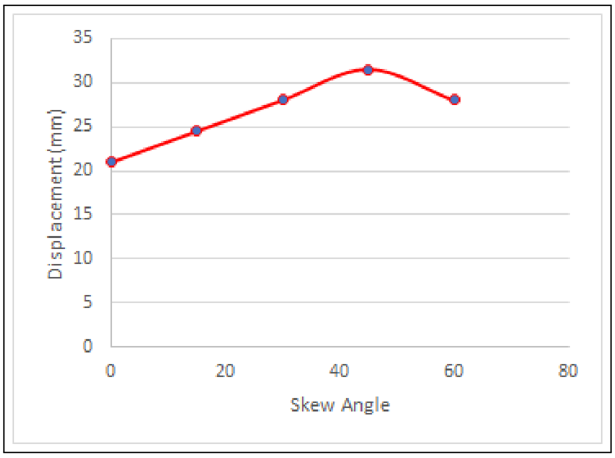

Figure 11: Pier top displacement for Slight Damage

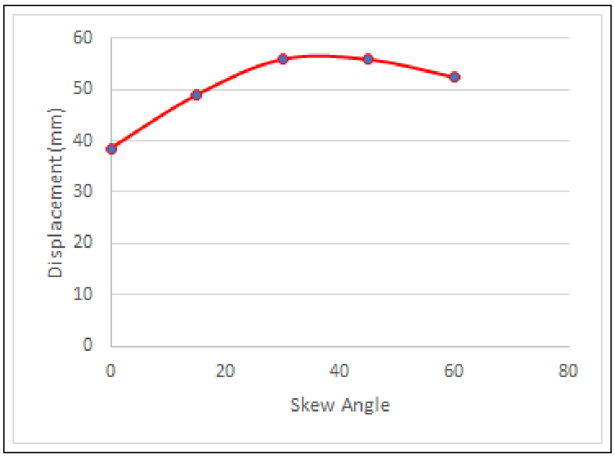

Figure 12: Pier top displacement for Moderate Damage

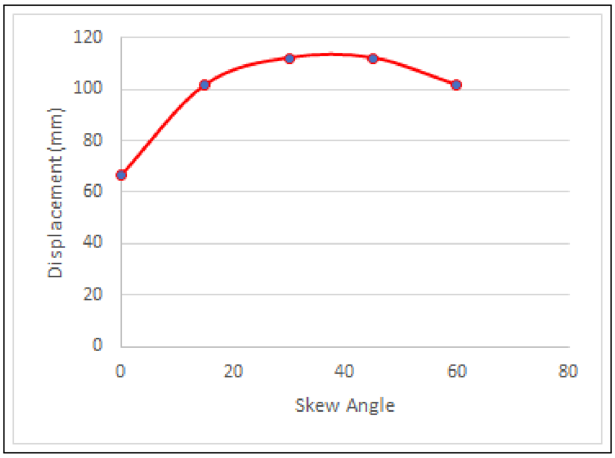

Figure 13: Pier top displacement for Extensive Damage

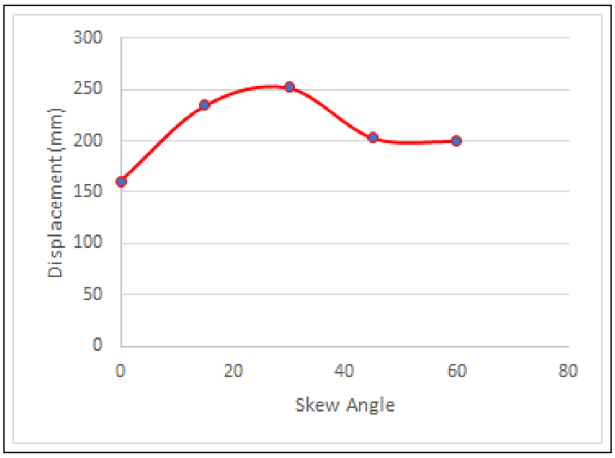

Figure 14: Pier top displacement for Collapse Damage

The displacement for damage state evaluated by looking strain values of different fibers. It is observed that with change in angle of skew the fiber that attains critical strain also changes. The area of pier which suffer major damages due to earthquake changes with change in skew angle.

4. Conclusion

Through a pushover analysis, the performance of a reinforced concrete bridge was examined. The major conclusion of this research work is

1. Fundamental time period of vibration in longitudinal direction increases from 0.90312 secs to 0.945406 with an increase in skew angle from 0 degree to 60 degrees respectively.

2. Fundamental time period of vibration in transverse direction increases from 0.39990 secs to 0.41820 with an increase in skew angle from 0° to 60°.

3. The drift capacity increases from 66.5mm to 115.5 with an increase in skew angle from 0° to 45° and decreases 115.5mm to 101.5 mm with an increase in skew angle from 45° to 60°.

4. The transverse displacement in global direction for slight, moderate and extensive damage increases for increase in skew angle up to 45 degree and then decreases with increase in angle upto 60 degree. While for complete damage it decreases from 30 degree.

5. The capacity of the bridge decreases significantly due to the rise in skew angle.

6. Torsion in the deck due to Gravity load and vehicle load increases from 0 to 38.98 KNm with an increase in skew angle from 0° to 60° and effect of torsion cannot be neglected in skewed bridge as in straight bridge during analysis.

7. The major deformation in skewed bridge is due to the combined response of two modes while it was due to same mode in straight bridges.

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