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Invited Paper

Endurance time analysis of skewed slab-on-girder bridges: The significance of the excitation angle

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Critical excitation angle;
Life-cycle cost analysis.

Abstract. In this paper, the influence of the excitation angle on the Endurance Time (ET) analysis of skewed slab-on-girder bridges is studied. The excitation of the structure due to the critical angle produces maximum seismic responses that are sometimes significantly higher than the average. The modeled bridges are of slab-on-girder type that are typically used as highway bridges. The bridge models have skew angles of 0, 15, 30, 45, and 60 degrees. The ET excitations exerted on structures cover a broad range of hazard levels. The results provide some insight with regard to choosing multiple excitation angles so as to balance computational costs and retain acceptable accuracy for practical design purposes. Sensitivity of Life-Cycle Cost (LCC) to skewness is also studied.

1. Introduction

Bridges whose alignment is not perpendicular to the underway are called "skewed bridges". The San Fernando 1971 and Northridge 1994 earthquake reports showed that skewed bridges experienced more damage than straight ones with regular geometry [1,2]. The response of skewed bridges by considering flexural and torsional deformations due to the vertical component of the ground motion and the effect of the deck rigidity was also studied [3,4]. The effect of skew angles on the behavior of concrete three-span bridges was studied with pushover, linear, and nonlinear time history analyses, and the maximum relative drift ratio was determined [5]. In 2012, Kaviani et al. [6] examined the seismic behavior of short-span concrete skewed bridges. They showed that, for these types of bridges, responses such as columns' drift ratios are higher than those of similar, yet straight, bridges (zero-skew). Further, by investigating the effect of various bridge geometries and ground motions, it was observed that bridges with larger skew angles would have a higher probability of collapse.

The principal seismic excitation direction is not directly addressed in AASHTO [7]. The assumption of the longitudinal axis of the bridge along the traffic lanes as the principal seismic excitation direction is conventional among bridge designers and, thus, the transverse axis becomes the second principal direction. However, skewed bridges can experience a state of vibration that is not merely in longitudinal and transverse directions. Therefore, straight bridges cannot represent a complete representation of the seismic behavior of all bridges.

Maleki and Bisadi examined the effect of ground motion direction on seismic responses of skewed bridges. They discussed the linear behavior of a single-span slab-on-girder bridge for three different earth-

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quake accelerograms. The angle of exerted earthquake accelerogram, which conduces maximum responses, is called the critical excitation angle. They showed that critical responses depend on the earthquake record, the skew angle, and the span length. In addition, they demonstrated that the application of the SRSS method by using a paired time history record simultaneously in only longitudinal and transverse directions was not conservative, and 100/30 and 100/40 rules could not be safe enough to be recommended for analysis [8].

In this paper, the effect of the angle of ET excitation on the responses of a three-span slab-on-girder bridge with different skew angles is evaluated. ET analysis can be very beneficial for nonlinear dynamic analysis of bridges. By significantly reducing the computational effort, ET analysis can pave the way for practical dynamic optimization, Life Cycle Cost (LCC) analysis, risk analysis, and value-based seismic design of bridges. These concepts are practically inapplicable due to the huge computational effort required in conventional dynamic procedures such as IDA [9]. The ET method provides a framework to practically solve the problem and has the advantage of low computational costs and acceptable precision in predicting responses.

2. Analysis

2.1. Endurance time method

Endurance time method is a time history-based analytical method that intensifies predefined accelerograms for seismic evaluation of structures. This method was invented by Estekanchi and Vafai. and inspired from exercise tests applied in medicine [10]. Considering a hypothetical shaking table experiment, if a predefined intensifying acceleration function is exerted on the structure, endurance time is defined as the time at which the structure reaches its limit state of choice [11]. Conceptually, the structure that endures longer is assumed to have a better performance. In Figure 1, the schematic presentation of ET analysis method is shown.

Endurance Time Acceleration Functions (ETAFs) are synthetic accelerograms produced in such a way that for any time window from zero to a specific time, their response spectrum matches a considered template spectrum. Among various ETAFs developed, *ETA20in* is an ETAF series whose template spectrum matched average spectrum of far-field strong ground motions recorded on stiff soil (FEMA440 [12]). *ETA20in* ETAF series is provided for 3D analysis, meaning that each of the three *ETA20in*01-03 is fitted to three components of the ground motion set. *ETA20in* series is optimized in such a way that provides more reliable responses in a nonlinear range. More information is available on the website of ET method [13].

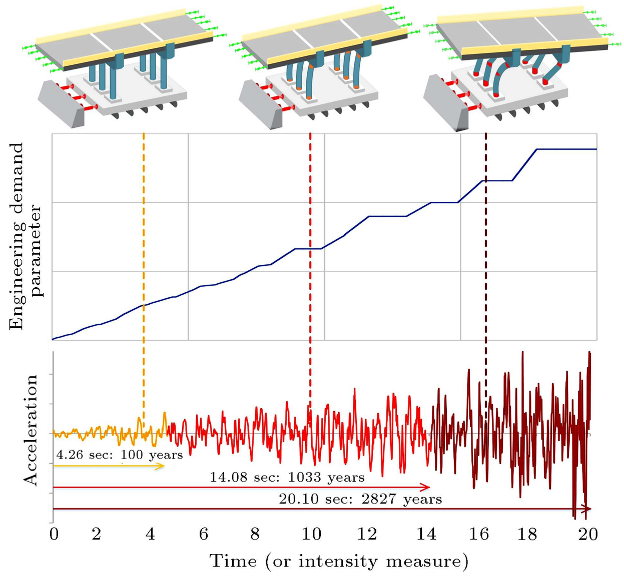

Figure 1. The schematic presentation of the ET analysis method .

2.2. Scaling method and the concept of hazard levels in ET method

In the ET method, each time analysis represents a seismic intensity. Since using time as a seismic intensity parameter is not convenient, time is usually mapped into the desired Intensity Measure (IM) with an intermediate parameter. IMs such as PGA, return period, spectral acceleration in a fundamental period of a structure, the annual rate of exceedance, and the similar ones can be used [14]. In this article, the seismic hazard return period is used as the parameter of seismic intensity, which correlates with time in ET analysis. The function of time mapped into the seismic hazard return period depends on the period of a structure. Mirzaee et al. mapped time by ET method into the seismic hazard return period [14]. As mentioned before, in this study, to analyze the models, *ETA20in* series is used. To map time in ET analysis into the return period, the following method is implemented: first, the hazard curve for several structural periods was extracted from a region in Berkeley, United States (zip code 94704) for a site on soil type C from USGS website [15]. Next, by using interpolation and extrapolation, the hazard curves were produced for other periods (0.01 sec step). The hazard curve for each structure with a specific period is the connector of acceleration spectrum and the annual rate of exceedance. Presently, for each structural period, the area in the obtained spectrum from hazard curve is calculated within 0.2 till 1.5 times of the mentioned period and is called A_{215RS}. On the other hand, since the ETAFs are intensifying, for every time in an ETAF, an acceleration spectrum can be produced. For example, a spectrum of ETAFs can be produced in 0.00 to 8.00 seconds. Next, for each structural period, the area in the ET spectrum within 0.2 to 1.5 times of each structural period can be calculated, which is called A_{215ET}. Obviously, the annual rate of exceedance is the inverse of earthquake return period. Next, by comparing A_{215RS} with A_{215ET} and equating them for every structural period, the mapping between time in ET analysis and earthquake return period is obtained. In Eq. (1), a sample matrix, A_{RP}, is presented for this transformation:

$$A_{RP} = \begin{array}{c} \\ \\ \text{ET analysis time (s)} \end{array} \begin{array}{c} \\ \vdots \\ 5.00 \\ \vdots \\ 10.00 \\ \vdots \\ 17.00 \\ \vdots \end{array} \overset{\displaystyle T(\mathrm{s}) \atop \cdots\ 1.00\ \cdots\ 3.00\ \cdots\ 5.00\ \cdots}{\begin{bmatrix} & \vdots & & \vdots & & \vdots & \\ \cdots & 220 & \cdots & 187 & \cdots & 83 & \cdots \\ & \vdots & & \vdots & & \vdots & \\ \cdots & 490 & \cdots & 422 & \cdots & 408 & \cdots \\ & \vdots & & \vdots & & \vdots & \\ \cdots & 1108 & \cdots & 878 & \cdots & 868 & \cdots \\ & \vdots & & \vdots & & \vdots & \end{bmatrix}}. \quad (1)$$

In this matrix, rows correspond to time in ET analysis, and columns correspond to the structural period. Therefore, for a structural period, an earthquake return period equal to time in ET analysis is obtained. For instance, for a structure within a period of 1.00 second under an earthquake with a return period of 490 years, the ET analysis time for a specific ETAF is equal to 10.00 seconds, and vice versa.

2.3. 3D analysis using ET method

$ETA20in$ series, similar to real accelerograms, has three components of X, Y, and Z. To determine the maximum response of the structure in the analysis, the horizontal components of ETAF should be placed at various angles relative to the principal axes of the structure.

In this case, AASHTO [7] does not require rotating the excitation angle with respect to the principal axes of the structure; as observed, it is not necessary to find a critical excitation angle. In this research, the effect of the excitation angle is examined.

3. Bridge model

In the present work, a three-span simply supported slab-on-girder concrete bridge with different skew angles is modeled. The deck is modeled by shell elements, and the beams are modeled as frame elements. The AASHTO I-girders are placed on elastomer bearings with linear behavior. The elastomer stiffness is equal to 2162 kN/m in longitudinal and transverse directions and is 694419 kN/m in the vertical direction.

In this study, it is assumed that abutments are generally stiffer than elastomers in the transverse direction, and since these two springs are modeled in series, the softer spring (elastomer) dominates the total stiffness of bearings [16]. In addition, in the longitudinal direction, stiffness of abutment and soil is much higher than elastomers, which are all in series; therefore, the spring stiffness is governed by the elastomer stiffness. A 50-mm gap between deck and abutment is considered and modeled as an element with negligible stiffness untill closing the boundary; very high stiffness is observed afterwards. In practice, after closing the gap, the stiffness of abutment in the longitudinal direction affects the bridge behavior.

As can be seen in Figure 2, the bridge is a three-span structure, which is 15.00 m long and has two

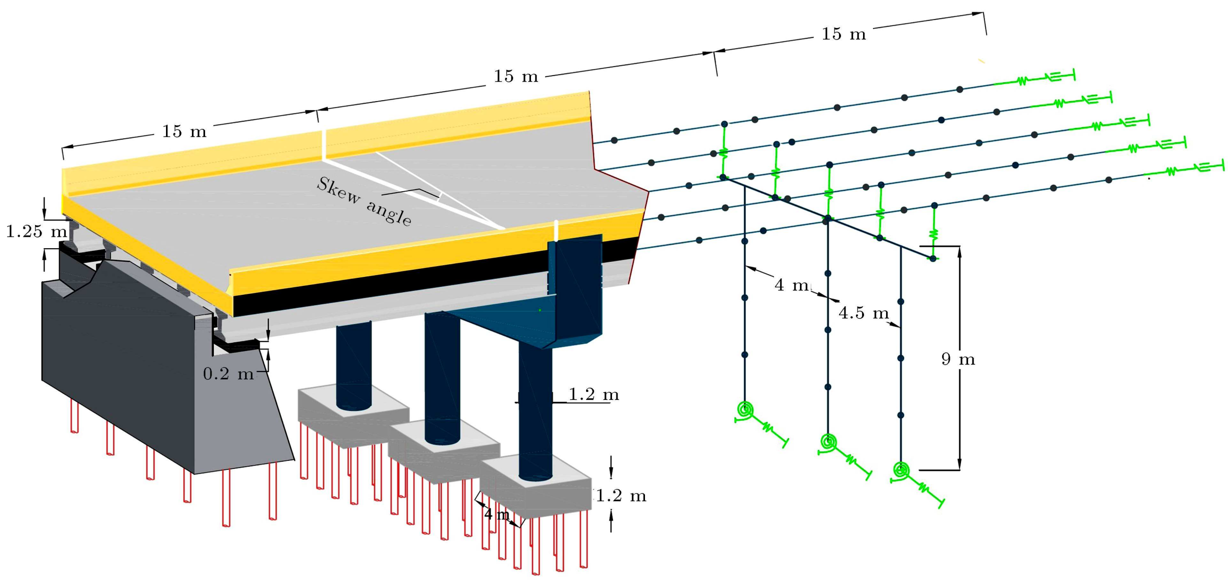

Figure 2. 3D view of a typical slab-on-girder concrete skewed bridge model.

bents, each with three columns. Above the columns, the pier cap beam characterized by 1.20 m depth, 1.00 m width, and 12.00 m length is modeled, and it connects columns to one another. Due to the presence of this beam, the behavior of bridge pier in the transverse direction is the frame behavior. Meanwhile, the pier behavior in the bridge longitudinal direction is cantilever behavior.

According to AASHTO [7], three global seismic design strategies can be applied. In this work, seismic strategy Type I (ductile substructure with essentially elastic superstructure) is assumed. This category includes conventional plastic hinging at the end of columns [17]. Therefore, at the top and bottom of each of six columns presented in the model, a fiber plastic hinge is allocated.

The modeled bridge is displayed in Figure 2, and skew angles of 0, 15, 30, 45, and 60 degrees are considered. As mentioned earlier, $ETA20in$ series including three sets of acceleration functions with three components are exerted on the bridge, and the results of each hazard level for every set of $ETA20in$ are obtained. Finally, to reduce the error and dispersion, an average is obtained from the responses of the analysis by three sets of $ETA20in$, and the average value is used as the response.

The results at 4 hazard levels corresponding to return periods of 100, 475, 1033, and 2475 years are the focus of this study. In ET method, the exertion of acceleration function on the structure at any specific time corresponds to the occurrence of an earthquake at a specific hazard level (return period). By considering the time window from 0.00 to 4.26 sec, an accelerogram equivalent to a return period of 100 years is obtained; by considering an ETAF in a time window from 0.00 to 14.08 sec, an accelerogram with a return period of 1033 years is obtained. In Table 1, based on the structural period of each model (different skew angles), for selected return periods, the equivalent time of ETAF is presented [18].

The response of a structure for a specific hazard level is the maximum response of ET analysis for the predetermined equivalent time window. For example, according to Table 1, for a structure with a period of 0.83 sec, the maximum responses of ET analysis from 0.00 to 4.26 sec are equivalent to the responses of analysis of the same structure for an earthquake set scaled to a return period of 100 years based on the predefined hazard curves.

4. Results

After analyzing the bridges by the ET method, the maximum drift ratio and the maximum normalized base shear at every seismic hazard level in longitudinal and transverse directions will be obtained by each model. In addition, the SRSS of responses of longitudinal and transverse directions is computed. This procedure is repeated for the bridges with skew angles of 0, 15, 30, 45, and 60 degrees by ET analysis in seismic hazard return periods of 100, 475, 1033, and 2475. As a sample, the responses of a hazard level of a 1033-year return period related to the bridges with various skew angles are presented. Figure 3(a) illustrates the effect of bridge skew angle on the drift ratio of a central node on the bridge deck for a 1033-year return period. According to Figure 3(a), at skew angles of 30 degrees, the drift ratio in the longitudinal direction is minimum. In addition, the SRSS of drift ratios for the mentioned skew angle is also minimum among all skew angles. The SRSS of drift ratios at a skew angle of 30 degrees has a 24% reduction relative to the straight bridge (zero-skew). Figure 3(b) displays that the changes in the skew angle exert considerable effect on base shear. According to Figure 3(b), at a skew angle of 30 degrees in the longitudinal and 60 degrees in the transverse directions, the normalized base shear is lower than other states. In addition, the SRSS of normalized base shears for the skew angle of 30 degrees is minimum among all skew angles. The SRSS of normalized base shears at a skew angle of 30 degrees undergo a 10% reduction relative to the straight bridge. The maximum base shear has been observed at a skew angle of 45 degrees. Moreover, the

Table 1. The equivalent time in ETAFs at the considered hazard levels for various skew angles.

Skew angle (degree)	Period (s)	Mode	ET equivalent time (sec)			
			RP* = 100	RP = 475	RP = 1033	RP = 2475
0	0.85	Long.**	4.26	10.33	14.06	19.29
15	0.83	Long.	4.26	10.31	14.04	19.22
30	0.86	Long.	4.26	10.34	14.07	19.30
45	0.88	Long.	4.26	10.34	14.08	19.35
60	0.92	Long.	4.27	10.33	14.14	19.44

*RP: Return Period in year;

**Long.: Longitudinal direction, the cantilever behavior of pier.

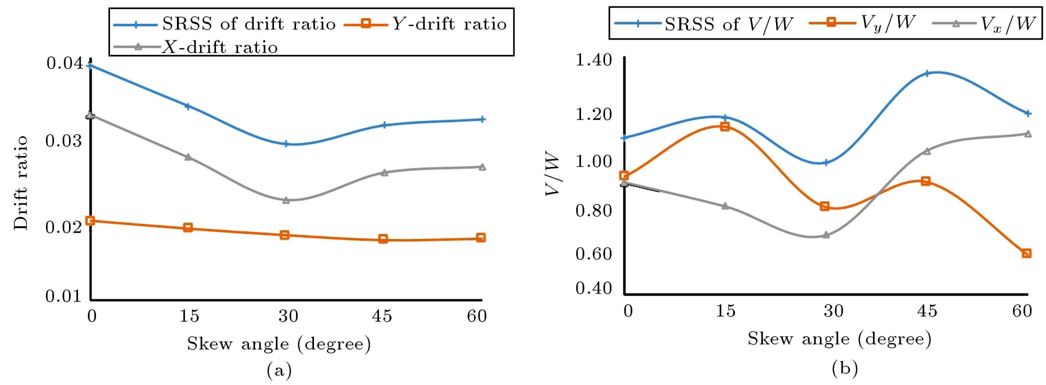

Figure 3. Responses of bridges with various skew angles for the 1033-year earthquake: (a) Longitudinal, transverse, and SRSS directions of the column drift ratio and (b) longitudinal, transverse, and SRSS directions of normalized base shears.

normalized base shear in this state is 24% greater than the base shear in the straight bridge.

Figure 4 shows the results of the SRSS of the drift ratios and that of the normalized base shears for ET analysis at times that are equivalent to the earthquakes with return periods of 100, 475, 1033, and 2475 years, and then they are compared. These figures complete the aforementioned explanations about the bridge responses in the 1033-year earthquake for all other return periods, and it is shown that the above results are also observed at other hazard levels. It should be noted that, in this section, the ETAFs are exerted only in longitudinal and traverse directions of the bridge, and the results are obtained only for the single state where ETAFs are not rotated.

According to Figure 5, considering the rotation of one of column plastic hinges, in most of the cases, the responses of bridges with higher skew angles are more than those of the lower skew angles in all return periods, thus reinforcing the idea that skewed bridges are more vulnerable than straight ones at all hazard levels. It can be a sign of vulnerability of skewed bridges in comparison to straight ones at all hazard levels.

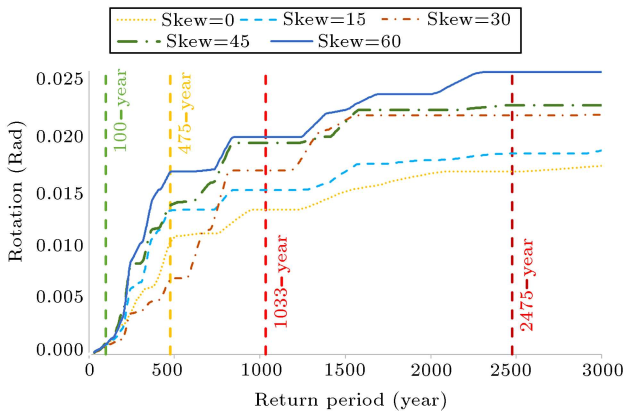

Figure 5. Rotation of a column plastic hinge in different return periods.

5. Critical excitation direction

For straight bridges, the bridge longitudinal and transverse directions are usually considered as the principal axes; usually, accelerograms are only applied to structures in these directions. In other words, the accelerogram input direction is 0 or 90 degrees. However, the maximum responses for the bridges,

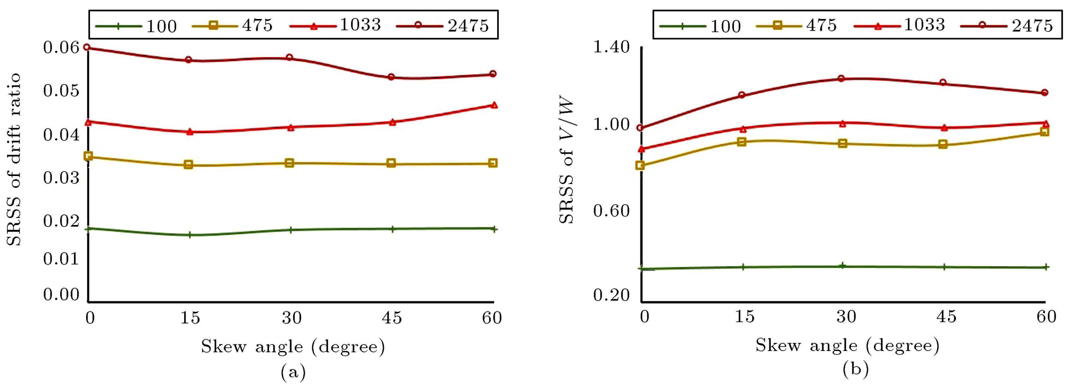

Figure 4. Comparison of the bridges response and various skew angles in four considered earthquake return periods: (a) SRSS of drift ratios and (b) SRSS of normalized base shears.

especially skewed bridges, do not necessarily occur at these angles. For each earthquake, there is a specific angle of excitation that produces maximum responses. This angle is called the critical angle of excitation. In this section, the direction of exerted ET accelerogram is examined to find the critical excitation direction. As mentioned before, $ETA20in01$-03 as the ETAFs are exerted on the bridge at various angles, each with three components in X, Y, and Z directions. The ETAFs are initially exerted on the directions of longitudinal (X), transverse (Y), and vertical (Z) on the structure. Afterwards, by rotations with a step of 10 degrees around the vertical axis, the accelerogram is applied to the structure, and ET analysis is done. This pattern continues up to 180-degree angle in the initial longitudinal and transverse directions. Since the bridges in this study have a center of symmetry, this also covers 360-degree results.

Figure 6 shows the average responses of the aforementioned ETAFs in the 1033-year return period. These figures include drift ratio in X and Y directions as well as the SRSS of drift ratios in two horizontal directions, in addition to the normalized base shear in X and Y directions and the SRSS of normalized base shears in the two mentioned directions.

It is illustrated in Figure 6 that the critical angle of the bridge with various skew angles is different from one another. Based on the figures for a return period of 1033 years, it can be observed that the critical responses for the straight bridge (zero-skew) occur at an excitation angle of 150 degrees for the SRSS of drift ratios. However, for a model characterized by 60-degree skew, the critical excitation angle is 70 degrees. For other skew angles, the critical excitation angle ranges between 70 and 150 degrees.

For a model with a skew of 60 degrees, the drift ratio in the transverse direction is much higher than the straight bridge. In addition, in the case of the drift ratio in the longitudinal direction, the straight bridge experiences the maximum response.

To compare the responses, the application of the SRSS of results in the longitudinal and transverse directions seems to be a logical selection. Therefore, to compare the results, the SRSS of drift ratio and normalized base shear in various models are used. As a result, for each model at various hazard levels, the critical angles are extracted by using the graphs. In Figure 7, the critical excitation angles for four return periods are displayed, which are obtained based on SRSS of drift ratios of the longitudinal and transverse directions. Of note, for the straight bridge, the critical excitation angle for all considered hazard levels is the same. For skewed bridges, the critical angle varies at different hazard levels (e.g., for a model of 60° skew angle, the critical excitation angle ranges from 70 to 110°). Therefore, analyzing a model only in two directions of 0 and 90° is not conservative.

In order to meet design requirements and limit

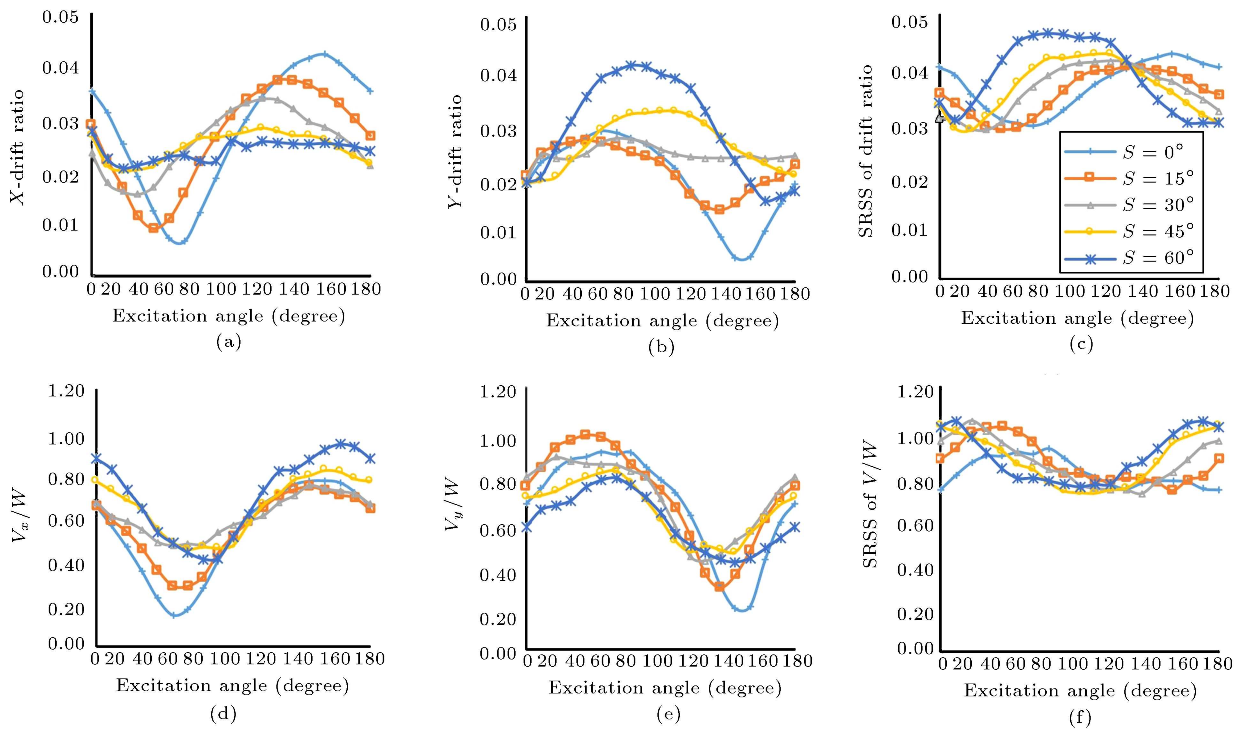

Figure 6. Responses at various excitation angles for a return period of 1033 years: (a) Drift in longitudinal, (b) drift in transverse, (c) SRSS of drifts, (d) longitudinal normalized base shear, (e) transverse normalized base shear, and (f) SRSS of normalized base shears.

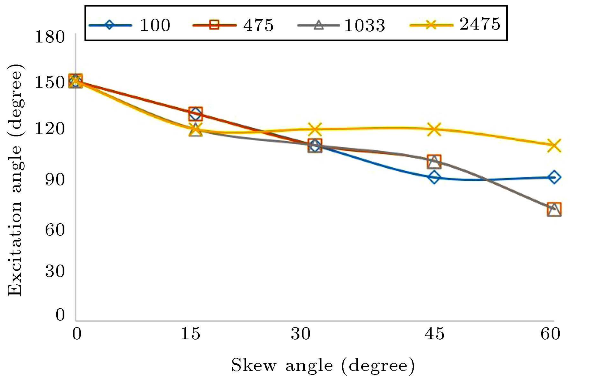

Figure 7. Critical excitation angle of models in different earthquake return periods.

calculation costs, the critical responses of a structure in the analytical process with different excitation angle steps are extracted. Figure 8 shows the responses for various excitation angle steps and, also, their deviations based on the results of complete analysis with 10-degree excitation angle steps.

Figure 8 indicates the error of critical responses of straight and skewed bridges for different excitation angle steps of 45°, 60°, and 90° in all mentioned return periods of 100, 475, 1033, and 2475 years. Figure 8(a) states that, for a 100-year return period, the selection of an excitation angle step has a significant effect on the responses. For a 15°-skew bridge, a 90° excitation angle step leads to 20% error with respect to the 10° angle step, although this error is limited to a maximum of 9% in all other return periods for all skew angles.

6. Life-cycle cost analysis

Life-cycle cost in this study represents the costs that result from earthquakes, which may occur during a bridge's lifetime. The initial cost is the construction cost of a new structure and is related to the materials and labor cost for the bridge construction. Based on the literature, as shown in Table 2, multiple limit states based on bent drift ratio are considered and, for each damage state, a mean damage index, which is the related repair cost, is set [19]. The Total Cost (C_{TOT}) of the structure is defined as the sum of its initial construction cost and the present value of the life-cycle cost C_{LC}, transmitted to the present value by a 3% discount rate over 75 years of bridge lifetime.

$$C_{\mathrm{TOT}} = C_{\mathrm{IN}} + C_{\mathrm{LC}}. \tag{2}$$

Lots of indirect cost components can be defined.

Table 2. Damage states and related drift ratios and damage costs indices [19].

Damage state		Bent drift ratio (%)	Mean damage index
DS1	None	$\Delta \leq 0.6$	0.00
DS2	Minor	$0.6 < \Delta \leq 2.2$	0.03
DS3	Moderate	$2.2 < \Delta \leq 3.6$	0.08
DS4	Major	$3.6 < \Delta \leq 4.9$	0.25
DS5	Complete	$4.9 < \Delta$	1.00

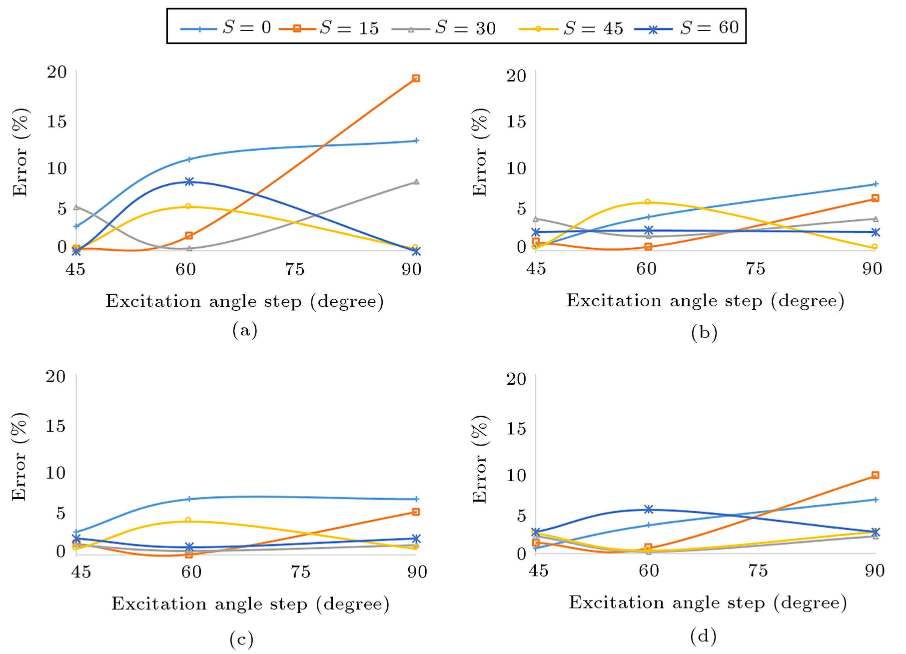

Figure 8. Error in evaluating bridge responses for different excitation steps in comparison with a 10-degree step for all skewed models in different earthquake return periods: (a) 100 years, (b) 475 years, (c) 1033 years, and (d) 2475 years.

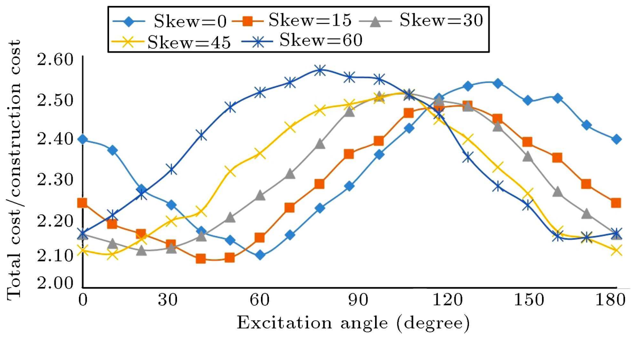

Figure 9. Total costs for different skew angles and excitation angles (normalized to construction cost).

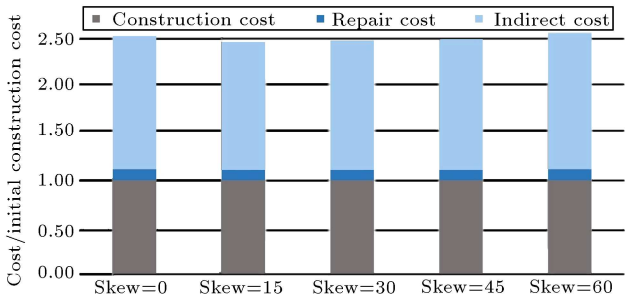

Figure 10. Cost components at a critical angle for different skew angles (normalized to construction cost).

Indirect costs are those that are indirectly related to damage such as traffic divert losses, environmental losses, etc. Direct costs are the costs of repair or replacement of the structure due to structural damage. In order to make simplifications, the average indirect costs are assumed to be 13 times the direct damage repair cost, estimated to be approximately 5-20 in other studies [20].

To calculate the LCC, the area of loss curve should be computed. Loss curve can be readily obtained from ET curve, as explained in [21], and the LCC computation from the loss curve is discussed in [22]. The ratio of the total cost to the initial cost is illustrated in Figure 9 for different skew angles and 10° step of excitation angle. The mentioned cost ratio for the critical angle is shown in Figure 10.

As can be seen in Figure 10, when full rotational analysis using 10-degree step angels is used, skewness does not significantly change the total cost. However, it should be noted that all bridges in this study have a center of symmetry. Therefore, the consequences of irregularity and asymmetry that can significantly increase the amount of damage are not included. Further study is required in order to derive a broader conclusion regarding the effect of skewness on seismic damage and LCC of skewed highway bridges.

7. Conclusions

The objectives of this study were to evaluate the effects of excitation angle on the endurance time analysis of skewed bridges. Different hazard levels were considered. Critical excitation angles were studied. The following conclusion can be drawn based on this study:

1. The variation of the maximum normalized base shear and the maximum drift ratios of bents for different excitation angles are considerable at all skew angles;
2. For the skewed bridges, the critical excitation angle is dependent on the hazard level in addition to the skew angle. On the other hand, for the straight bridge, the critical excitation angle remains the same at all considered hazard levels;
3. The seismic responses of bridges with higher skew angles are in general higher than those with lower skew angles. This confirms the vulnerability of skewed bridges in comparison to straight ones at all hazard levels;
4. There is a significant scatter in the critical excitation angle at different skew angles. Therefore, analyzing a model only in two perpendicular directions of 0° and 90°, as proposed by typical design codes, does not necessarily produce maximum responses;
5. Employing excitation angles of 0°, 45°, 90°, and 135° produced results that are only 5% less than those from 10° steps on average. If the excitation angles are reduced to three angles of 0°, 60°, and 120°, the predicted responses at critical angles compared to the 10° step have an error rate of 11%. Hence, considering 45° steps is recommended for ET analysis using component-wise produced ETAFs such as $ETA20in$ series.

Nomenclature

$A_{215\text{ET}}$	Area under the ET spectrum in 0.2 to 1.5 times of each structural period
$A_{215\text{RS}}$	Area under the obtained spectrum from hazard curve calculated from 0.2 till 1.5 times of the mentioned period
AASHTO	American Association of State Highway and Transportation Officials
A_{RP}	Matrix which relates ET time, structural period, and earthquake Return Period
ASCE	American Society of Civil Engineers
C_{IN}	Initial construction cost
C_{LC}	Life Cycle cost
C_{TOT}	Total cost
DS	Damage State
ET	Endurance Time method
ETA	Endurance Time Analysis

ETAF	Endurance Time Acceleration Function
FEMA	Federal Emergency Management Agency
IDA	Incremental Dynamic Analysis
IM	Intensity Measure
LCC	Life Cycle Cost
PGA	Peak Ground Acceleration
RP	Return Period
SRSS	Square Root of the Sum of the Squares

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