Endurance Time Analysis of skewed slab-on-girder bridges: The significance of the excitation angle

Homayoon E. Estekanchi¹, Esmaeil Ghaffari² and Ali Haghani-Baei³

Abstract

In this paper the influence of excitation angle on the Endurance Time (ET) analysis of skewed slab-on-girder bridges is studied. The excitation of the structure due to critical angle leads to the maximum seismic responses that are sometimes significantly higher than the average. The modeled bridges are slab-on-girder type which 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 the structures cover a broad range of hazard levels. The results provide some insight for choosing multiple excitation angles in such a way that balances computational costs and retains acceptable accuracy for practical design purposes. Sensitivity of life cycle cost (LCC) to skewness is also studied.

Keywords: Slab-on-girder bridge, Seismic analysis, Endurance Time method, Skewed bridge, Critical excitation angle, Life Cycle Cost analysis

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 the skewed bridges experienced more damage than straight ones with regular geometry [1, 2]. The response of the skewed bridges by considering the flexural and torsional deformations, due to the vertical component of the ground motion and the effect of the deck rigidity is also studied [3, 4]. The effect of skew angles on the behavior of concrete three-span bridges has been studied with pushover, linear, and nonlinear time history analyses, and the maximum relative drift ratio is determined [5]. In 2012, Kaviani et al. [6] examined the seismic behavior of short-span concrete skewed bridges. They showed that for these type of bridges, responses such as columns drift ratios are higher than those of similar but straight bridges (zero-skew). Also, by investigating the effect of various bridge geometry 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]. 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 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 earthquake accelerograms. The angle of exerted earthquake accelerogram, which conduct maximum responses, is called the critical excitation angle. They showed that the critical responses depends on the earthquake record, the skew angle, and the span length. They also indicated that using the SRSS

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method by applying a paired time history record simultaneously in only longitudinal and transverse directions is not conservative and also the 100/30 and 100/40 rules cannot 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 in nonlinear dynamic analysis of bridges. By significantly reducing the computational effort, ET analysis can pave the way towards 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 needed in conventional dynamic procedures such as IDA [9]. ET method provides a framework to practically solve the problem and has the advantage of reducing computational costs beside acceptable precision in predicting of responses.

2. Analysis

2.1. Endurance Time Method

Endurance Time method is a time history-based analytical method using intensifying predefined accelerograms for seismic evaluation of structures. This method was invented by Estekanchi et al. by inspiration from exercise test applied in medicine [10]. Considering a hypothetical shaking table experiment, if a predefined intensifying acceleration function is exerted on the structure, endurance time was defined as the time at which the structure reaches its limit state of choice [11]. Conceptually, the structure which endures longer, is assumed to have a better performance. In Error! Reference source not found., 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 ETA series are provided for 3D analysis, meaning that each of the three ETA20in01-03 are matched to three components of ground motion set. ETA20in series is optimized in such a way that also provides more reliable responses in nonlinear range. More information is available through the website of ET method [13].

{insert Figure 1.}

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

In ET method, each analysis time represents a seismic intensity. Since using time as a seismic intensity parameter is not convenient, time is usually mapped into a desired intensity measure (IM) using an intermediate parameter. IMs such as PGA, return period, spectral acceleration in fundamental period of 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, correlated to time in ET analysis. The function of time mapping to seismic hazard return period depends on the period of structure. Mirzaee mapped time in ET method into 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 to return period, following method is implemented: First, the hazard curve for several structural periods were extracted in 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 annual rate of exceedance. Presently, for each structural period, the area under the obtained spectrum from hazard curve is calculated from 0.2 till 1.5 times of the mentioned period and is called A_{21.5RS}. 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 an ETAF can be produced for the timing of 0.00 till 8.00 seconds. Next, for each structural period, the area under 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 $A_{215RS}$ and $A_{215ET}$ 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. 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 equivalent to a time in ET analysis is obtained. For instance, for a structure with 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.

\[
\begin{bmatrix}
\cdots & 1.00 & \cdots & 3.00 & \cdots & 5.00 & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
5.00 & \cdots & 220 & \cdots & 187 & \cdots & 83 & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
10.00 & \cdots & 490 & \cdots & 422 & \cdots & 408 & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
17.00 & \cdots & 1108 & \cdots & 878 & \cdots & 868 & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\end{bmatrix}
\]

(1)

2.3. 3D analysis using ET method

ETA20in series, similar to real accelerograms, has three components of X, Y, and Z. For finding the maximum response of structure in the analysis, the horizontal components of ETAF ought to be exerted in various angles relative to the principal axes of the structure.

In this case, AASHTO [7] does not require to rotate the excitation angle in respect to the principal axes of the structure and states it is not necessary to find the critical excitation angle. In this research, the effect of 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 having linear behavior. The elastomer stiffness in longitudinal and transverse directions is equal to 2162 kN/m and in vertical direction is 694419 kN/m.

In this study, it is assumed that in transverse direction, abutments generally are stiffer than elastomers and since these two springs are modeled in series, the softer spring (elastomer) is dominated on the total stiffness of bearings [16]. Also 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 till closing the boundary and after that by very high stiffness. In practice after closing the gap, the bridge behavior is affected by the stiffness of abutment longitudinal direction.

As can be seen in Error! Reference source not found., the bridge is a three-span structure each 15.00 m long and has two bents that each of them has three columns. Above the columns, the pier cap
beam having 1.20 m depth, 1.00 m width, 12.00 m length is modeled and connects the columns to one another. Due to the presence of this beam the behavior of bridge pier in transverse direction is frame behavior. Meanwhile, the pier behavior along 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 six columns presented in the model, a fiber plastic hinge is allocated.

The modeled bridge is displayed in Error! Reference source not found., and skew angles of 0, 15, 30, 45, and 60 degrees are considered. As mentioned earlier, ETA20in series which include three sets of acceleration functions with three components are exerted on the bridge and the results related to each hazard level for every set of ETA20in will be obtained. Finally, to reduce the error and dispersion, an average is obtained from the responses resulted from analyzing by three sets of ETA20in and the average value is used as the response.

{insert Figure 2.}

The results at 4 hazard levels corresponding to return periods of 100, 475, 1033, and 2475 years will be focused on in this study. In ET method, exerting acceleration function on the structure till any specific time corresponds with exerting an earthquake with a specific hazard level (return period). By considering the time window from 0.00 to 4.26 seconds, an accelerogram equivalent to a return period of 100 years is obtained and considering an ETAF in a time window from 0.00 to 14.08 seconds, an accelerogram with return period of 1033 years is obtained. In Error! Reference source not found., 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 Error! Reference source not found., for a structure with a period of 0.83 sec, the maximum responses of ET analysis from 0.00 to 4.26 sec is 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.

{insert Table 1.}

4. Results

After analyzing the bridges by 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 in each model. In addition, the SRSS of responses of longitudinal and transverse directions are computed. This procedure was 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 1033 years return period related to the bridges with various skew angles is presented. Error! Reference source not found. (a) illustrates the effect of bridge skew angle on drift ratio of a central node on the bridge deck for a 1033-year return period. According to Error! Reference source not found., (a), at skew angles of 30 degrees drift ratio in longitudinal direction is the 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 skew angle of 30 degrees has 24% reduction relative to the straight bridge (zero-skew). Error! Reference source not found. (b) displays that the changes in the skew angle have considerable effect in base shear. According to Error! Reference source not found., (b), at skew angles of 30 degrees in longitudinal and 60 degrees in transverse direction the normalized base shear is lower compared to 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 skew angle of 30 degrees has 10% reduction relative to the straight bridge. The maximum base shear was observed at the skew angle of 45 degrees. Moreover, normalized base shear in this state is 24% greater than the base shear in the straight bridge.
Error! Reference source not found. shows the results related to the SRSS of the drift ratios as well as the SRSS of the normalized base shears for ET analysis at times which are equivalent with the earthquakes having return periods of 100, 475, 1033, and 2475 years and they are compared. These figures complete the aforementioned explanations about the bridge responses in 1033-year earthquake for all other return periods and it shows that the above results are also observed in 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 Error! Reference source not found. considering the rotation of one of column plastic hinge, in most of cases the responses of bridges with higher skew angles are more than those of the lower skew angles in all return periods. These reinforce the idea that skewed bridges are more vulnerable than straight ones in all hazard levels. It can be a sign of vulnerability of skewed bridges in comparison to straight ones in all hazard levels.

5. Critical excitation direction

For straight bridges, the bridge longitudinal and transverse directions are usually considered as the principal axes and usually accelerograms are only exerted on structure in these directions. It means that the direction of accelerogram input is 0 or 90 degrees. However, the maximum responses for the bridges specially skewed bridges do not necessarily occur in these angles. For each earthquake, there is a specific angle of excitation which makes the maximum responses. This angle is called the critical angle of excitation. In this section, the direction of exertion of ET accelerogram is examined to find the critical excitation direction. As mentioned before, ETA20im01-03 as the ETAFs are exerted on the bridge in various angles, each one has three components in X, Y and Z directions. The ETAFs are initially exerted in 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 exerted on the structure and ET analysis is done. This pattern is continued up to 180 degrees angle relative to the initial longitudinal and transverse directions. Since the bridges in this study have a center of symmetry, this also covers 360 degree results.

Error! Reference source not found. shows the average responses of aforementioned ETAFs in 1033 years 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 the normalized base shear in X and Y directions and also the SRSS of normalized base shears in the two mentioned directions.

It is illustrated in Error! Reference source not found. that the critical angle of bridge with various skew angle is different from one another. Based on the figures for return period of 1033 years it can be observed that for the SRSS of drift ratios the critical responses for the straight bridge (zero-skew) occurs at excitation angle of 150 degrees. While, for the model with 60 degrees skew, the critical excitation angle is 70 degrees. For other skew angles, the critical excitation angle is between these 70 and 150 degrees.
For a model with skew of 60 degrees, the drift ratio in transverse direction is much higher than the straight bridge. In addition, for the case of the drift ratio in longitudinal direction the straight bridge experience the maximum response.

To compare the responses, using the SRSS of results in 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 were extracted by using the graphs. In Error! Reference source not found., the critical excitation angles for four return periods are displayed which are obtained based on SRSS of drift ratios of longitudinal and transverse directions. It can be seen that for straight bridge the critical excitation angle for all considered hazard levels are the same. For skewed bridges, the critical angle varies in different hazard levels (e.g. for a model of 60° skew angle the critical excitation angle is between 70 to 110°). Therefore, analyzing a model only in two directions of 0 and 90° is not conservative.

In order to meet the design requirements as well as limit the calculation costs, the critical responses of structure in analysis with different excitation angle steps were extracted. Error! Reference source not found. shows the responses for various excitation angle steps and also their deviations based on the results of complete analysis with 10 degrees excitation angle steps.

{insert Figure 7.}

{insert Figure 8.}

Error! Reference source not found. 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. The Error! Reference source not found. (a) states that for a 100-year return period the selection of excitation angle step has a significant effect on the responses. For the 15°-skew bridge, 90° excitation angle step leads to a 20% error with respect to 10° 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 refers to the costs resulting from earthquakes that may occur during lifetime of the bridge. Initial cost is the construction cost of a new structure and is related to the materials and labor cost for the construction of the bridge. Based on the literature, as shown in Lots of indirect cost components can be defined. Indirect costs are those which 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 simplify, the average indirect costs will be assumed to be 13 times of the direct damage repair cost which is estimated to be on the order of 5-20 in other studies [20].

multiple limit states according to 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 \( C_{\text{TOT}} \) of the structure is defined as the sum of its initial construction cost and the present value of the life cycle cost \( C_{\text{LC}} \) which are transmitted to present value by use of a 3% discount rate over 75 years of bridge lifetime.

\[
C_{\text{TOT}} = C_{\text{IN}} + C_{\text{LC}}
\]  

(2)

Lots of indirect cost components can be defined. Indirect costs are those which 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 simplify, the average indirect costs will be assumed to be 13 times of the direct damage repair cost which is estimated to be on the order of 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 computing the LCC from the loss curve is discussed in [22]. The ratio of total cost to the initial cost is illustrated in Error! Reference source not found. for different skew angle and 10° step of excitation angle. The mentioned cost ratio for the critical angle is shown in Error! Reference source not found.

As can be seen in figure 10, when full rotational analysis using 10 degrees 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, consequences of irregularity and asymmetry, that can significantly increase the amount of damages, are not included. Further study is needed 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 are considered. Critical excitation angles where studied. The following conclusion can be drawn based on this study:
1. The variation of the maximum normalized base shear as well as 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 to hazard level in addition to the skew angle. On the other hand, for the straight bridge, the critical excitation angle remained the same at all considered hazard levels.
3. The seismic responses of bridges with higher skew angles are in general higher than those with a lower skew angles. This confirms the vulnerability of skewed bridges in comparison to straight ones in 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 lead to 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 angle compared to the 10° step have 11% error. Hence, considering 45° steps is recommended for ET analysis using component wise produced ETAFs such as ETA20in series.

References


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

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

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

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

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

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

**Figure 6.** Responses in various excitation angles for 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

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

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

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

**Figure 10.** Cost components in critical angle for different skew angles (normalized to construction cost)
Figure 1.
Figure 2.
Table 1.

<table>
<thead>
<tr>
<th>Skew angle (Degree)</th>
<th>Period (s)</th>
<th>Mode</th>
<th>ET equivalent time (sec.)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>*RP=100</td>
</tr>
<tr>
<td>0</td>
<td>0.85</td>
<td>**Long</td>
<td>4.26</td>
</tr>
<tr>
<td>15</td>
<td>0.83</td>
<td>Long.</td>
<td>4.26</td>
</tr>
<tr>
<td>30</td>
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<td>Long.</td>
<td>4.26</td>
</tr>
<tr>
<td>45</td>
<td>0.88</td>
<td>Long.</td>
<td>4.26</td>
</tr>
<tr>
<td>60</td>
<td>0.92</td>
<td>Long.</td>
<td>4.27</td>
</tr>
</tbody>
</table>

*RP = Return Period in year  **Long. = longitudinal direction, the cantilever behavior of pier
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.
<table>
<thead>
<tr>
<th>Damage state</th>
<th>Bent drift ratio (%)</th>
<th>Mean damage index</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS 1 None</td>
<td>$\Delta \leq 0.6$</td>
<td>0.00</td>
</tr>
<tr>
<td>DS 2 Minor</td>
<td>$0.6 &lt; \Delta \leq 2.2$</td>
<td>0.03</td>
</tr>
<tr>
<td>DS 3 Moderate</td>
<td>$2.2 &lt; \Delta \leq 3.6$</td>
<td>0.08</td>
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<tr>
<td>DS 4 Major</td>
<td>$3.6 &lt; \Delta \leq 4.9$</td>
<td>0.25</td>
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<tr>
<td>DS 5 Complete</td>
<td>$4.9 &lt; \Delta$</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 9.
Figure 10.
Nomenclature

$A_{215ET}$ Area under the ET spectrum within 0.2 to 1.5 times of each structural period

$A_{215RS}$ Area under the obtained spectrum from hazard curve is 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
Biographies

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