DYNAMIC RESPONSE OF A MULTI-SPAN SKEWED BRIDGE WITH SEAT TYPE ABUTMENTS TO MODERATE GROUND MOTIONS

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ABSTRACT

Skewed bridges are irregular structures due to the geometry of the deck and bents. The performance of instrumented skewed bridges during moderate and strong earthquakes provides an opportunity to evaluate their seismic response in realistic conditions. This paper presents the analysis of the strong motion data recorded at the Second Northern Freeway located in Taiwan (TCUBAB). TCUBAB is a three-span, skewed reinforced concrete bridge with discontinuous girders and seat type abutments. Since the installation of the instrumentation, the bridge has experienced two strong motion events, the September 1999 Chi-Chi Earthquake (M, 7.6) and the October 1999 Chiayi Earthquake (M, 6.4). Data from instrumented skewed bridges with seat type abutments is very scarce, so this case offers a unique opportunity to examine the performance of these structures during seismic events and their response in terms of rotational and lateral demands. In this paper, a description of the recorded strong motions events is presented first, then the frequencies of vibration, the modes of vibration and the modal dampings are identified using frequency domain techniques. In addition, the effects of skewness in the acceleration and displacement demands of the deck, piers and abutments are discussed. This paper improves the understanding of the seismic response of skewed bridges with seat type abutments. This understanding contributes to have a better assessment of the seismic demands that skewed structures will undergo and to the development of displacement based design methods for these structures.

Keywords: Instrumented Bridges, Skewed Bridges, Seat Type Abutments, Strong Motion.

1. INTRODUCTION

Skewed bridges are classified as irregular structures due to the geometry of the deck and bents. Seismic damage in past earthquakes and analytical studies suggest that skewed bridges tend to rotate during earthquakes. This problem is especially relevant in multi-span skewed bridges with seat type abutments in which the rotations can increase the probability of superstructure unseating. Data obtained from instrumented bridges offers a realistic approach to study the performance of skewed bridges and a number of authors have conducted studies for skewed bridges with integral or semi-

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integral abutments [1,2,3]. However, the performance of instrumented skewed bridges with seat type abutments during moderate or strong earthquakes has not been reported and needs further investigation.

The Second Northern Freeway (TCUBAB) located in Taiwan is a three-span skewed bridge with discontinuous girders that has undergone the September 1999 Chi-Chi earthquake (M_s=7.6) and the October 1999 Chiayi earthquake (M_s=6.4). Although lightly skewed (13 degrees), the bridge is symmetric and heavily instrumented, including sensors at the pile caps, piers, abutments and deck girders. Data available from instrumented skewed bridge with seat type abutments is very scarce, so this case offers a unique opportunity to examine the performance of skewed bridges during seismic events and their response in terms of rotational and lateral demands.

This paper identifies the dynamic properties of the bridge and discusses the displacement and acceleration demands at different locations on the deck. These analyses provide evidence to understand the displacement profiles and the rotational sensitivity of the deck. The pier drift as well as the longitudinal displacements at abutments joints are also studied. These analyses provide an idea of the type of response exhibited whether linear elastic with no structural damage or nonlinear due to the gaps at abutments or structural damage.

2. BRIDGE DESCRIPTION AND STRONG MOTION INSTRUMENTATION

The Second Northern Freeway (TCUBAB) on the Hsinchu System Interchange is located in Taiwan and is composed by two concrete bridges with a skew angle of 13 degrees (Figure 1). Each bridge is 89.07m long, 15.25 m wide, and has three spans with seat type abutments. Each superstructure consists of a concrete deck slab supported on four 1.80 m deep, discontinuous prestressed U-girders. Each substructure consists of two pier bents, which are 2 m in diameter and approximately 8 m in height. The foundations consist of concrete pile footings with pile caps.

Discontinuous girders are typical on Taiwanese bridges. In order to prevent longitudinal unseating of the superstructure during seismic events, the deck diaphragms at the ends of TCUBAB are anchored to the abutment backwalls, however it has thermal expansion joints on the deck slab at both ends. To prevent transverse unseating, the TCUBAB has internal shear keys at bents and abutments. A summary of the bridge characteristics is given in Table 1.

![Figure 1 The Second Northern Freeway (TCUBAB) in Taiwan](image)
Table 1 Characteristics of the Second Northern Freeway (TCUBAB)

<table>
<thead>
<tr>
<th>Bridge Type</th>
<th>Length (m)</th>
<th>Spans No.</th>
<th>Spans Lengths (m)</th>
<th>Width (m)</th>
<th>Clearance (m)</th>
<th>Skew Angle (degrees)</th>
<th>Substructure Type</th>
<th>Superstructure Type</th>
<th>Foundation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin</td>
<td>89.02</td>
<td>3</td>
<td>29.51-30-29.51</td>
<td>15.25</td>
<td>8.00</td>
<td>13</td>
<td>multi-column-frames (ϕ = 2.0 m)</td>
<td>seat type</td>
<td>discontinuous – U girders</td>
</tr>
</tbody>
</table>

The strong motion instrumentation in Taiwan is monitored by the Central Weather Bureau [4]. TCUBAB is instrumented with 29 strong motion accelerometers installed at different locations: free field (3), pile caps (8), abutments (6), pier caps (6), deck girders (3) and lateral barriers (3). As indicated in Figure 2 most sensors are placed in such a way that the “x direction” (longitudinal) is along the centerline of the bridge and the “y direction” (transverse) is perpendicular to this direction.

Figure 2 TCUBAB – Strong Motion Instrumentation
3. STRONG MOTION DATA

The instrumentation at the Second Northern freeway (TCUBAB) recorded the accelerations from the two strong motion events that hit Taiwan in 1999: The Chi-Chi earthquake and the Chiayi earthquake. The September 21 Chi-Chi earthquake ($M_s=7.6$, depth 7 km) was caused by a major thrust fault along the western foothills of the central Taiwan [5]. TCUBAB is located at 110 km North from the epicentre (Figure 3a). According to the free field data (Channels 1 and 2), the dominant direction of the motion was in the S-N azimuth. The response spectrum for this direction (CH 2) is presented in figure 3b. The peak ground acceleration is 0.13g and the dominant frequencies are 0.39, 1.17 and 1.95 Hz.

The October 22 Chiayi earthquake ($M_L=6.4$, depth 17.7 km) is the result of a reverse thrust fault located 55 km south-west from the epicentre of the Chi-Chi earthquake [6]. The dominant trace of the motion is in the S-N azimuth. The response spectrum for this direction is shown in figure 3b. The peak ground acceleration is 0.09g and the dominant frequencies are 0.97, 1.56 and 2.14 Hz.

![Epicentre and Response Spectra](image)

(a) Epicentre and Magnitude  (b) Response Spectra

Figure 3 Recorded Earthquakes

Large coseismic displacements were recorded at different sites during the Chi-Chi earthquake in Taiwan. However, TCUBAB is located outside the fault plane of the earthquake [7] and near fault effects such as coseismic displacements are not expected. For instance, the station M379, which is the closest GPS station located at 8 km from the bridge, recorded displacements in the east, north and vertical direction of 0.8, 4.5, and 4.5 cm, respectively [8]. In addition, according to the author’s knowledge, no damage has been reported for this bridge. The closest bridge with significant damage is the Shin Wei bridge, which is located 50 km south-west of TCUBAB [5]. As a result, no permanent displacement and an elastic structural response is expected for TCUBAB.

4. MODAL IDENTIFICATION

The instrumented points at the pier caps and abutments in the transverse and longitudinal direction (channels 12, 13, 15, 16, 18, 19, 21, 22) were used to identify the damping ratios and natural frequencies of the modes of vibration excited by the recorded ground motions. In this way, two frequencies of vibration at 2.24 and 2.93 Hz were identified by using the Enhanced Frequency Domain
Decomposition (EFDD) technique available in the program Artemis [9]. The damping ratios estimated was 6.3 % for the Chi-Chi earthquake and 4.3 % for the Chiayi earthquake.

The plan views of the corresponding modes of vibration with the bridge deck represented as a line are shown in figure 4. The mode profiles identified are consistent with the profiles expected for a skewed bridge with discontinuous girders and illustrate a predominant direction of the modes perpendicular to the skew angle. These results are similar to those obtained by Catacoli et al [10] using ambient vibration tests. In addition, rigid body motions at 0.39 Hz for the Chi-Chi earthquake and at 0.97 Hz for the Chiayi earthquake were identified; these motions are associated to the dominant frequency of each ground motion.

![Figure 4 TCUBAB – Modes of Vibration Predominantly Excited](image)

**5. ACCELERATION AND DISPLACEMENT DEMANDS**

**5.1. Bridge Superstructure**

The peak accelerations of the deck were 0.6g (Ch 24) for the Chi-Chi earthquake and 0.35g (Ch 27) for the Chiayi earthquake. The Fast Fourier Transformations (FFT) of the recorded accelerations for both earthquakes at different locations on the superstructure and the transfer functions between them are shown in figure 5 and 6. The dominant frequencies at the east abutment (Ch 13) and the pier cap 1 (Ch 16) during the Chi-Chi earthquake are 0.39 and 2.34 Hz. For these frequencies the transfer function between the two locations has a magnitude of one and a phase angle of approximately zero radians, indicating that accelerations at these points are in phase and have almost the same amplitude. Similar results are observed for the Chiayi Earthquake.

At the deck girder (Ch 27) the dominant frequencies during the Chi-Chi earthquake were 1.56, 2.34 and 2.93 Hz. The transfer function of this point with respect to the east abutment (Ch 13) indicates that at 1.56 Hz the two locations are vibrating in the same direction; however the transfer function for vibrations at 2.34 and 2.93 Hz has a phase angle of almost $\pi$ radians, which indicates vibrations of the first span in opposite direction at these frequencies. These rotational accelerations are in good agreement with the profiles described by the identified modes of vibration at 2.24 and 2.93 Hz. For the Chiayi Earthquake similar results are observed, but the phase difference at 2.34 Hz is smaller.

A comparison of the relative peaks of the FFT at the deck girder (Ch 27) suggests that the vibrations at 2.34 Hz, which are associated to rotational accelerations of the deck, have higher energy than the vibrations at 1.56 Hz, which are associated to linear accelerations of the deck. This could be an evidence of the rotational sensitivity of the spans of skewed bridges with discontinuous girders.
5.2. Pier Drifts

The accelerations recorded on Pier 1 at the base (CH 4 and 5) and the top (CH 15, 16) were integrated to obtain the pier drift. The integration procedure in frequency domain applied to the relative accelerations in order to obtain the displacements consists of the following steps: 1. Baseline correction and high pass filtering of the signal, 2. Calculate Fast Fourier Transformation (FFT), 3.
Calculate negative FFT divided by frequency squared to obtain displacement in the frequency domain. Use inverse FFT and high pass filtered to obtain relative displacement in time domain.

For the Chi-Chi Earthquake the maximum drift in the transverse direction (0.32 %) is slightly higher than the drift in the longitudinal direction (0.24 %). The dominant frequency of the displacement response of pier 1 is 0.39 Hz (Figure 7). This low frequency, which coincides with the dominant frequency of the recorded ground motion, is associated with a rigid body motion of the bridge. For the Chiayi Earthquake the maximum drifts found are 0.08 % and 0.07 % in the transverse and longitudinal direction, respectively. As in the Chi-Chi earthquake, the displacement is dominated by a frequency of 0.97 Hz which is associated to the dominant frequency of the ground motion.

![Transverse and Longitudinal Drift](image1)

**Figure 7** Drift Demands at Pier 1 during the Chi-Chi Earthquake

### 5.3. Abutment Seats

The amount of longitudinal displacement at the abutments is a key parameter to evaluate the probability of superstructure unseating on seat type abutments bridges, as well as the occurrence of pounding between the abutments and the deck. The longitudinal accelerometers at the abutment (CH 14) and at the deck girder by the abutment (CH 24) were used to evaluate the relative displacements at the abutment seats during the 1999 Chi-Chi and Chiayi Earthquakes. Figure 8a shows that the relative displacement at abutments during both events was very small (< 3mm). One of the reasons for this result is the fact that the deck diaphragms of the bridge are anchored to the abutment's backwalls.

The transfer function of the accelerations illustrates that during both earthquakes the signals at the abutments and at the girders are in phase for the range of frequencies driven the displacements (f < 2 Hz). In addition, the amplitudes of the vibrational components associated to rotational accelerations (2.34 Hz and 2.93 Hz) are higher at the deck’s girder than at the abutments (Figure 8b).
6. CONCLUSIONS

The instrumentation at Second Northern Freeway (TCUBAB) provided a unique opportunity to examine the response of multi-span skewed bridges with seat type abutments. The records from the September 1999 Chi-Chi (PGA=0.13g) and the October 1999 Chiayi earthquake (PGA=0.09g), which produced moderate shaking at the site, were used to evaluate the performance of the bridge in realistic conditions. In terms of deck rotations, the analysis identified rotational accelerations that could potentially produce in-plane rotations of the deck; however these rotations are actually prevented by the internal shear keys of the bridge. The displacement profile during both events predominantly corresponded to longitudinal and transverse rigid body motions of the entire bridge, driven by the dominant frequency of vibration of each ground motion.

The results indicate that the bridge exhibited a linear elastic response in both events. The maximum pier drifts (0.37 %) occurred during the Chi-Chi earthquake and was similar in the longitudinal and transverse directions. The relative displacement at the abutment seats in the longitudinal direction was very small (< 3mm), which is explained by the Taiwanese seismic strategy of anchoring the deck diaphragms and the abutments backwalls to prevent superstructure unseating. The damping ratios estimated was 6.3 % for the Chi-Chi earthquake and 4.3 % for the Chiayi earthquake. This paper helps improve the understanding of the seismic demands that skewed bridges with seat type abutments may undergo and contributes to the development of displacement based design methods for these structures.

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