Investigation of the behaviour of small-scale bridge models using shake table tests

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ABSTRACT: The skew angle of a bridge is an important boundary condition that affects its behaviour under seismic loading. Although some research has been carried out to identify these effects, such investigations for the most part remain analytical with a few instances including experimental testing. In an effort to understand the effects of skew on the seismic behaviour of bridges, a number of shake table tests have been performed on a skew and a non-skew bridge model and the results have been compared. These small-scale models are representative of two-bay short-span concrete bridges and consist of precast deck and pier elements which have been assembled using threaded bars. The results of the tests show that although the amount of deck rotation is not higher in the skew deck, this rotation is non-symmetric and may lead to unseating of the deck. It is also discussed that the results of these tests can be used in the design of ‘controlled rocking’ connections in precast bridge structures.

1 INTRODUCTION

Skew bridges are those in which the supports and superstructure are located at an angle relative to the longitudinal axis of the bridge. Such bridges are commonly constructed to accommodate geometric and space constraints. Although widely used, these types of bridges have proven to be susceptible to severe damage during earthquakes due to unseating of the superstructure (Priestley et al. 1996), as can be seen in a number of examples shown in Figure 1. Although the static and dynamic behavior of skew bridges have been investigated by various researchers, these investigations for the most part remain analytical (Maragakis & Jennings 1987, Dimitrakopoulos 2011, Kaviani et al. 2012) with a few instances including laboratory testing (Meng et al. 2004, He et al. 2012).

Previous analytical research and also investigations carried out on affected bridges after a seismic event show that skewed decks have a tendency to rotate in the plane of the deck and in the opposite direction of the skew (Figure 1-d). This behavior can be attributed to coupling of the rotational and translational modes of the deck, which in turn occurs as a result of eccentricity between the centre of mass and centre of stiffness in the span. In the event of an earthquake this coupling causes a slight rotation in the deck, however the obtuse corner will be binded to the adjacent deck or abutment whereas the acute corner will further rotate under cyclic transverse response. This unsymmetric rotation may eventually result in unseating of the deck.

The present experimental study aims to investigate the effects of skewness on the dynamic response of bridges. To this end two small-scale models representative of simply supported short-span concrete bridges commonly built in New Zealand were constructed in the laboratory and subjected to a number of sine wave motions on a shake table. The models were constructed using precast steel and concrete blocks connected together using threaded rods. The response of the models was recorded in the form of gap opening in the decks and pier, acceleration of the deck and also post-tensioning force in the threaded rods connecting the decks. The following discusses the design, construction, instrumentation and testing of the bridge models and interpretation of the results.
2 TESTING DETAILS

2.1 Model details and construction

The bridge models were chosen to represent two-bay short-span concrete bridges typically built in New Zealand. The original unscaled models were designed for a 1000 year return period in accordance to the guidelines in NZTA Bridge Manual v3 (NZ Transport Agency, 2004). The superstructure was chosen in accordance with NZTA research report No. 364 (NZ Transport Agency, 2008) to be a Super-T Bridge precast concrete deck. The base pier section was designed using the CUMBIA software (Kowalsky & Montejo 2004).

After designing the full-scale models, the dimensions were then scaled by a factor of 1/30 in order to meet the limitations incurred by the size of the shake table. Scaling of the model was carried out using Cauchy and Froude similitude requirements. A scaling factor of 1 was used for the modulus of elasticity, stress, strain and acceleration whereas dimensions were scaled by a factor of \( \lambda = 1/30 \) and mass by a factor of \( \lambda^2 = (1/30)^2 \). The difference between the mass and dimension scaling factors necessitated the addition of 730kg to the scaled models which was added in the form of steel plates attached to the decks. The dimensions of the original and scaled model can be seen in Table 1 (Mazza et al. 2013).

Additional elements used to support the scaled models were the foundation block which was not scaled from the original model (due to lack of participation in dynamic behavior), abutments and their supporting columns. These elements were connected the base plate and shake table using threaded rods forming a rigid support structure. The base plate was in turn connected to the shake table using bolts.
Table 1. Dimensions of original and scaled bridge model elements

<table>
<thead>
<tr>
<th>Model</th>
<th>Deck mm²</th>
<th>Pier Section mm²</th>
<th>Pier Height mm</th>
<th>Cap Beam mm³</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>28000×10350</td>
<td>1800×1800</td>
<td>3900</td>
<td>10350×2000×2000</td>
<td>6700</td>
</tr>
<tr>
<td>Scaled</td>
<td>925×350</td>
<td>65×65</td>
<td>390</td>
<td>350×65×65</td>
<td>758</td>
</tr>
</tbody>
</table>

Two sets of decks, the first non-skew and the second with a skew angle of 35° were constructed and mounted on the substructure system. This skew angle was chosen to represent typical skew angles in highway bridges which range from 30° to 60° (Buckle et al. 2012, Dimitrakopoulos 2011). All elements were constructed as concrete-filled RHS sections to avoid crushing of the concrete during dynamic excitation, with the exception of the non-skew decks and the foundation block. Due to excessive crushing of the concrete non-skew decks during the first series of tests, the skew deck was constructed using rectangular steel sections. Details of the scaled models can be seen in Figure 2. The constructed models mounted on the shake table can be seen in Figure 3.

The bridge elements were precast and then assembled using grade 8.8 D22 threaded rods (Figure 2-c). Plastic ducts were placed inside the elements during the pouring of concrete to allow for the placement of these post-tensioning rods. Different post-tensioning levels were used for rods in different locations. Both rods connecting the decks and abutments were post-tensioned to the same level that ranged from 0kN to 20kN (equivalent to 0.225f_{pt,y}) during different sets of testing, whereas the rod connecting the pier segments to the foundation, cap beam and deck had zero post-tensioning. The rods connecting the abutment columns to the base plate and shake table were post-tensioned to the maximum value possible to prevent movement of these elements and provide a rigid support frame. Further details of these arrangements can be seen in Table 2.

Table 2. Properties of small-scale bridge specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Deck Material</th>
<th>Scale Factor</th>
<th>Skew Angle</th>
<th>Scaled Mass (kg)</th>
<th>Deck PT (kN)</th>
<th>No. of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-skew</td>
<td>Concrete</td>
<td>1/30</td>
<td>0</td>
<td>800</td>
<td>10, 20</td>
<td>28</td>
</tr>
<tr>
<td>Skew</td>
<td>Steel</td>
<td>1/30</td>
<td>35°</td>
<td>800</td>
<td>0, 5, 10, 20</td>
<td>56</td>
</tr>
</tbody>
</table>

Figure 2. a) Elevation view of non-skew model; b) Plan view of non-skew model; c) Elements consisting the models 1) Decks, 2) Post-tensioning rods, 3) Pier blocks, 4) Foundation, 5) Abutments 6) Support columns (rigid), 7) Connection plates to shake table, 8) Extra weight plates; d) Plan view of skew model.
2.2 Measurements and measuring devices

Two methods were used simultaneously for measuring the displacement of the models during the tests. In the first method, 6 LVDT sensors were placed in the corner of the decks to measure the amount of gap opening between the decks and the decks and abutments (Figure 3-a & 3-b). The second method consisted of using a high-speed camera (1000 fps) to record the rocking movement of the pier blocks. The pier blocks were marked at the edges using distinct points (Figure 3-d) and the recordings were afterwards processed using a MATLAB-based computer code (Hedrick 2008). A load cell was attached to each post-tensioning rod in the deck to measure the amount of post-tensioning force during the test (Figure 3-c).

2.3 Shake table input

Shake table input was chosen to satisfy both shake table limitations (acceleration, displacement, velocity and frequency input) and non-destructive testing objective. A series of sine waves were selected according to this criteria with the properties shown in Table 3.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>5~25</td>
<td>3~10</td>
<td>5~8</td>
<td>0.5~3.5</td>
</tr>
</tbody>
</table>

3 TEST RESULTS

The results of the tests can be divided into three categories; gap opening and rotation of the decks, gap opening and drift of the piers, and post-tensioning level of the rods connecting the decks. A schematic
view of the gap opening in the decks and piers can be seen in Figure 4. Figure 4-c and 4-d show a time-history variation of the gap opening in the time domain resulting from a sine wave of 3Hz and 25mm.

Figure 4. Values of gap opening resulting from a sine wave input of 3Hz and 0.9g. a) Max. gap opening between two decks; b) Max. gap opening in piers; Plot of gap opening of deck in the time domain; d) Plot of pier drift in the time domain

Figure 5. Variation of gap opening vs. post-tensioning force in rods connecting the decks in a) Non-skew & b) Skew models, resulting from a sine wave input of 5Hz and 10 mm

Figure 6 shows plots of the maximum values of deck rotation (taken as the average of the two decks) in the skew and non-skew deck with two levels of post-tensioning under a number of sine wave
motions with different accelerations. It can be seen that the maximum rotations occurring in the skew bridge is much lower than the corresponding value in non-skew decks. This difference can be attributed to the restraining effect of the post-tensioning rods in the deck. However as can be seen in Figure 7, the ratio of positive to negative gap opening in the acute corners of the skew decks is higher than the corresponding value in the obtuse corners. This difference indicates an in-plane rotation of the skew decks in the counter-clockwise direction.

Figure 6. Plots of deck rotations resulting from different shake table inputs in a) 10kN post-tensioning in decks & b) 20kN post-tensioning in decks

Figure 7. Ratio of positive to negative gap opening in non-skew decks under different shake table inputs. Higher ratios in the acute corners result in an anti-clockwise rotation in the deck

4 FUTURE DIRECTION

This research was aimed at clarifying the effects of skewness on the dynamic response of bridges. One of these effects was the observed difference between the amount of gap opening in non-skew and skew bridges under seismic excitation. This gap opening plays a significant role in the design of certain types of connections which are known as ‘hybrid’ or ‘controlled rocking’ connections. In these low-damage connections precast concrete blocks are connected using post-tensioning tendons and dissipative devices are placed at the locations of gap opening (Figure 5). The post-tensioning provides a self-centering property to the connection, and the dissipation devices dissipate energy which would otherwise create plastic hinges in the structure. Implementation of this type of connections in bridge
piers has been studied previously (Palermo et Al 2007, Marriott et Al 2009, Pollino et al. 2007) and is to be further developed for use in bridge decks at the University of Canterbury. The results obtained from the experiments presented herein can be used as a reference point for a future quasi-static testing on a 1:3 scale bridge with a similar configuration i.e. using precast concrete elements and post-tensioning.

Figure 8. ‘Hybrid’ or ‘controlled rocking’ solutions for bridge piers (Palermo & Pampanin 2008)

5 CONCLUSION

This paper presents the results of a number of shake table tests on two small-scale concrete bridges with the aim of investigating the effect of skewness on their dynamic behaviour. The models which consisted of a skew and non-skew specimen were representative of two-bay short-span concrete bridges typically built in New Zealand. The full-scale models were designed in accordance with New Zealand standards and scaled down to accommodate limitations of the shake table. The scaled specimens were tested dynamically using a number of sine wave motions with a range of frequencies and amplitudes. The results showed that although skewness did not increase the amount of gap opening, it caused unsymmetric rotation in the decks in the direction of decreasing skew. This rotation can result in unseating of simply-supported bridge spans. In cases where the input motion to the shake table was similar, the results showed a similar value of pier drifts in the two specimens. Finally the results of these experiments could be applied to implementing low-damage hybrid connections in bridges, especially bridge superstructures.

REFERENCES


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