SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

INVESTIGATION OF THE BEHAVIOUR OF SMALL-SCALE BRIDGE MODELS USING SHAKE TABLE TESTS

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ABSTRACT

The boundary conditions of a structure affect its behavior under seismic loading. Such boundary conditions in a bridge include superstructure to substructure fixity and geometric configurations such as skew and curvature of the deck. Although some research has been carried out to identify the effects of these properties on the seismic behavior of bridges, such investigations for the most part remain analytical, with a few instances including experimental testing. Previous 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. This can be attributed to coupling between rotational and transverse modes of the bridge, followed by pounding between the deck segments and also between the deck end and abutments.

A number of shake-table tests have been carried out on two small-scale model bridges to investigate this behavior. Both of these models are representative of two-bay concrete bridges, the first one having no skew angle and the second one having a skew angle of 35 degrees. The models consist of deck and pier elements which have been assembled using post-tensioned threaded bars with different levels of post-tensioning force. They have then been subjected to sinusoidal motions on the shake table.

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 center of mass and center 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

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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.

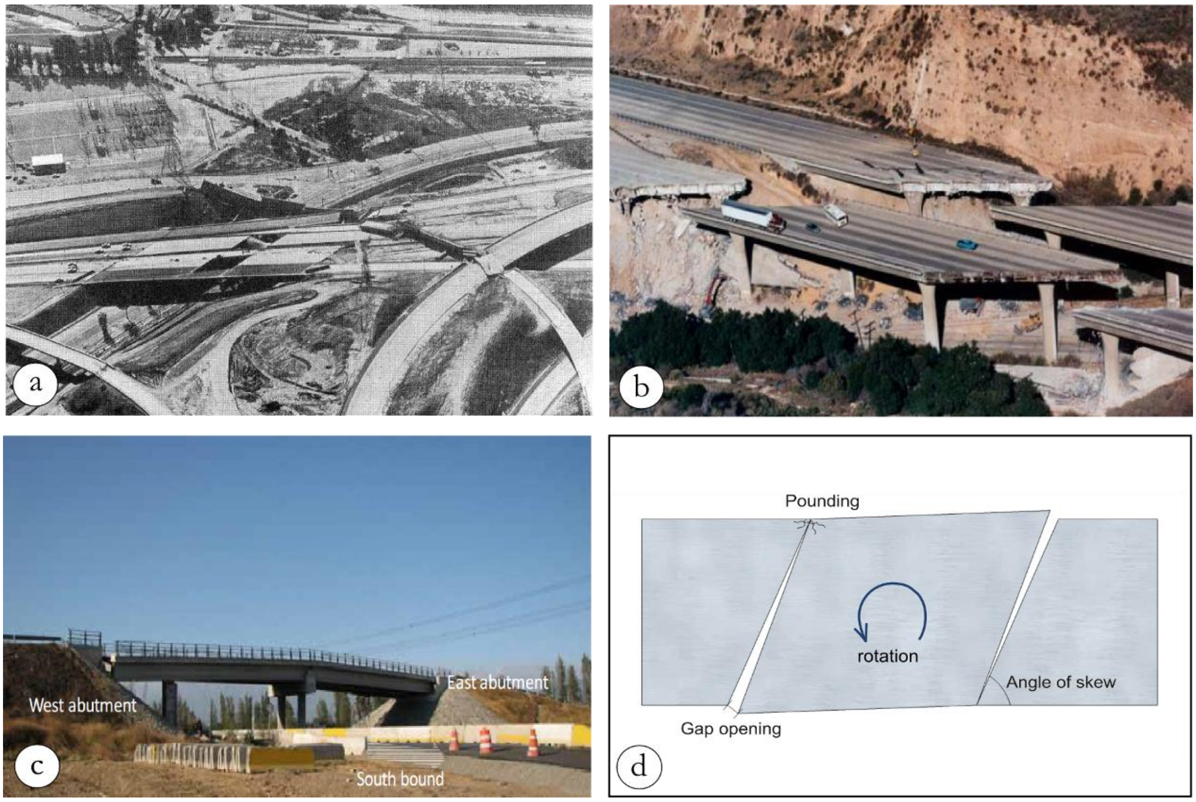

Figure 1. a) Damage to the Foothill-Boulevard crossing in the 1971 San Fernando earthquake (Wood & Jennings 1971); b) Damage to the Gavin Canyon underpass in the 1994 Northridge earthquake (U.S. Department of Transportation ITS Joint Office, 2002); c) : Damage to the Rancagua bypass in the 2010 Maule, Chile earthquake (Elnashai et al. 2010); d) Rotation of bridge deck under seismic loading as a result of skew

TESTING DETAILS

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 Fraude 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 λ=1/30 and mass by a factor of λ2=(1/30)2 The difference between the mass and dimension scaling factors neccessitated 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).

Table 1. Dimensions of original and scaled bridge model elements

Model	Deck mm^2	Pier Section mm^2	Pier Height mm	Cap Beam mm^3	Mass (kg)
Original	28000×10350	1800×1800	3900	10350×2000×2000	6700
Scaled	925×350	65×65	390	350×65×65	758

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.

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 0.225fy,pt) 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.

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). number.

Table 2. Properties of small-scale bridge specimens

Specimen	Deck Material	Scale Factor	Skew Angle	Scaled Mass (kg)	Deck PT (kN)	No. of Tests
Non-skew	Concrete	1/30	0	800	10, 20	28
Skew	Steel	1/30	35˚	800	0, 5, 10, 20	56

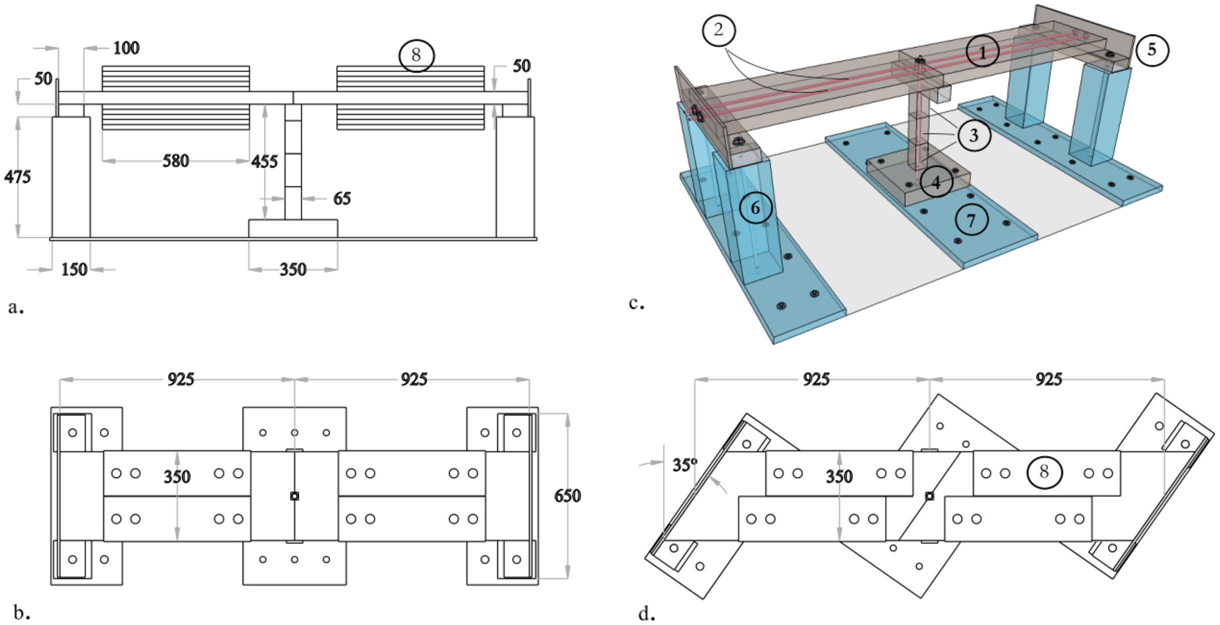

Figure 2. a) Elevation view of non-skew model; b) Plan view of non-skew model; c) Elements consisting the models 1) Decks, 2) Post-tensioning rods, 3) Pier blocks, 4) Foundation, 5) Abutments 6) Support columns (rigid), 7) Connection plates to shake table, 8) Extra weight plates; d) Plan view of skew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

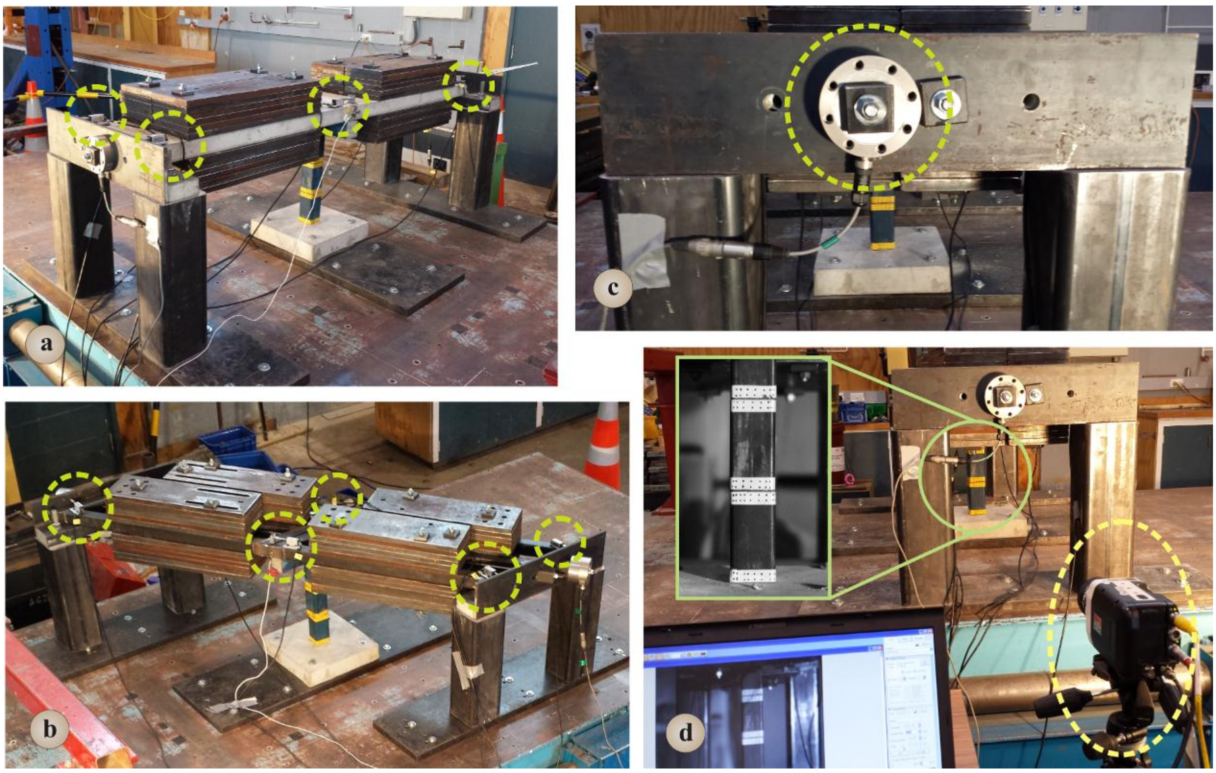

Figure 3. a) Non-skew model on shake table with LVDT sensors; b) Skew model on shake table with LVDT sensors; c) Load cells measuring post-tensioning force in PT rods in the deck; d) Camera recording rocking of pier

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 2. Properties of sinusoidal shake table inputs

Frequency (Hz)	3	5	7	10
Displacement (mm)	5~25	3~10	5~8	0.5~3.5

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.

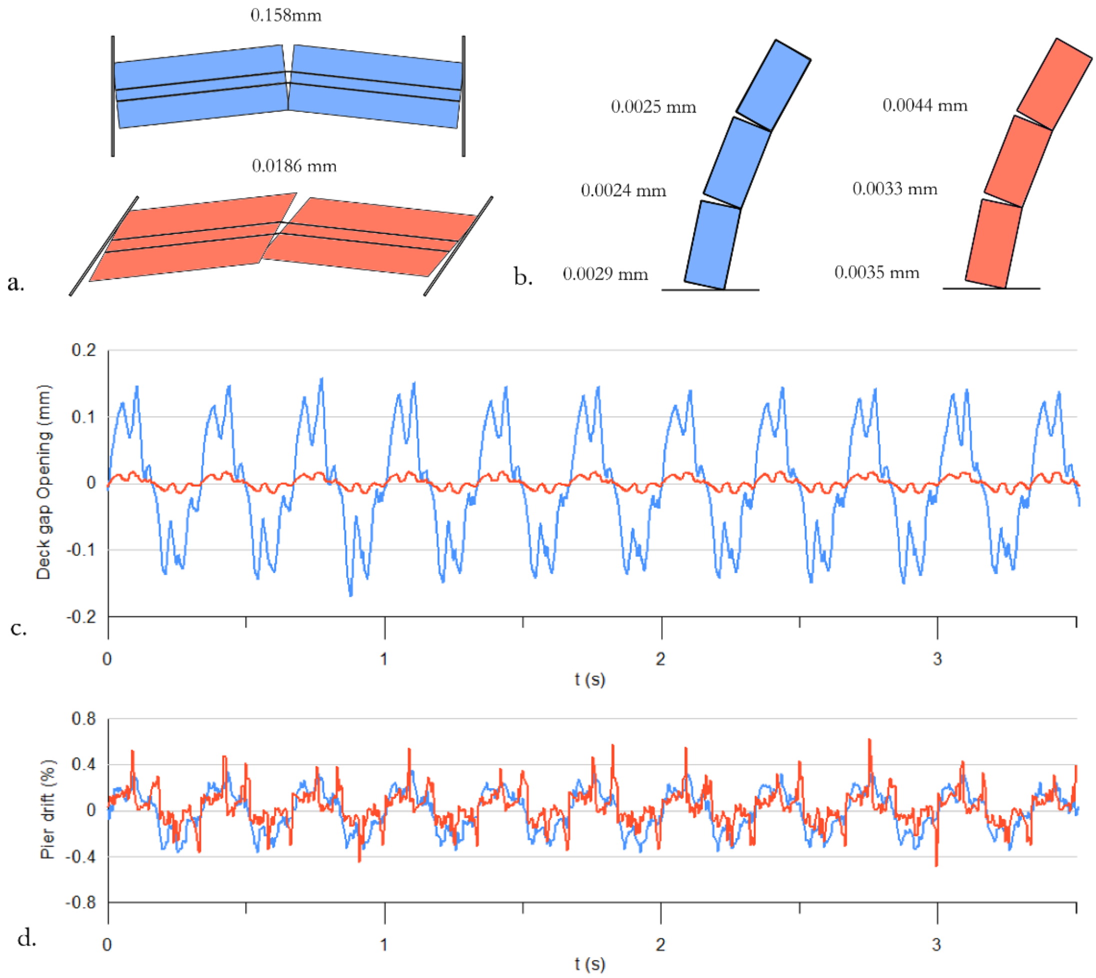

Figure 4. Values of gap opening resulting from a sine wave input of 3Hz and 0.9g. a) Max. gap opening between two decks; b) Max. gap opening in piers; Plot of gap opening of deck in the time domain; d) Plot of pier drift in the time domain

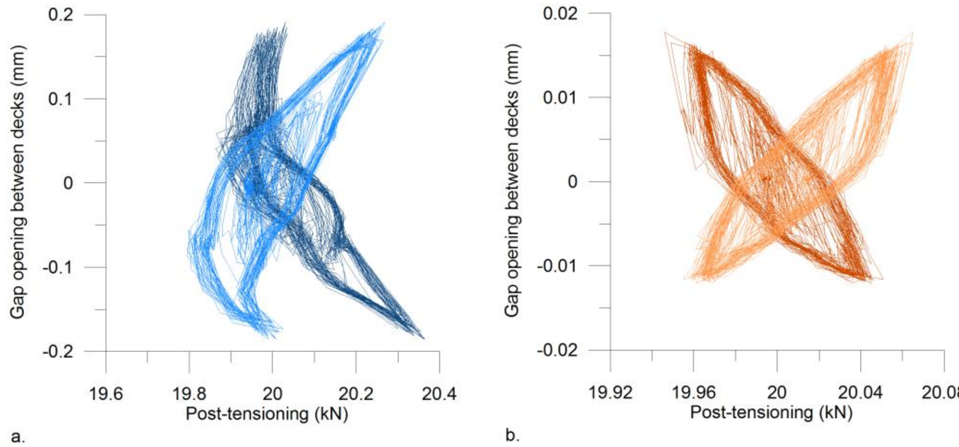

Figure 5. Variation of gap opening vs. post-tensioning force in rods connecting the decks in a) Non-skew & b) Skew models, resulting from a sine wave input of 5Hz and 10mm

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 occuring 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.

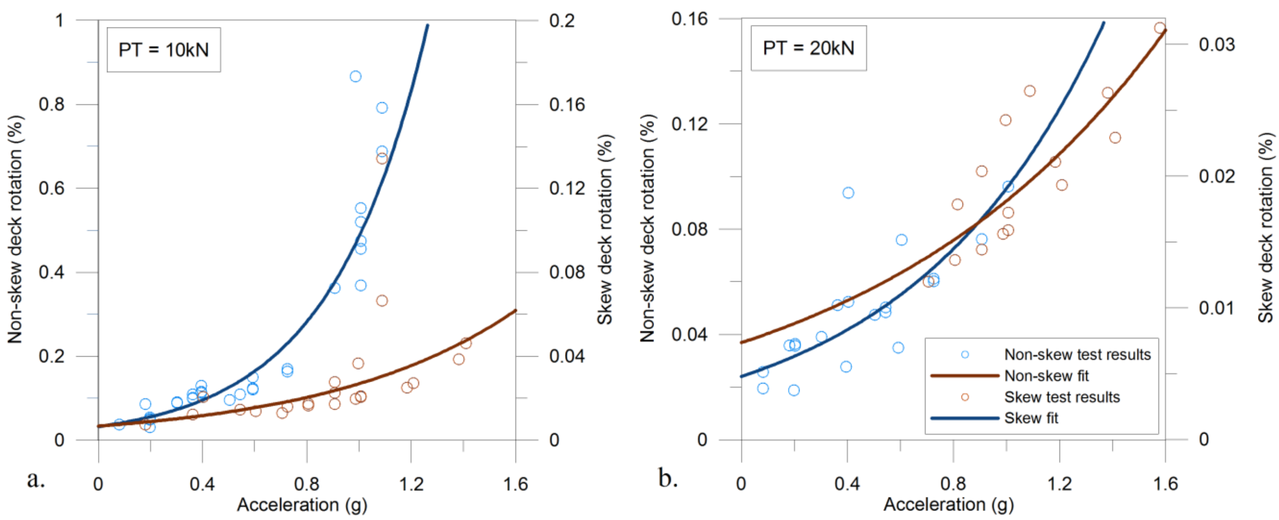

Figure 6. Plots of deck rotations resulting from different shake table inputs in a) 10kN post-tensioning in decks & b) 20kN post-tensioning in decks

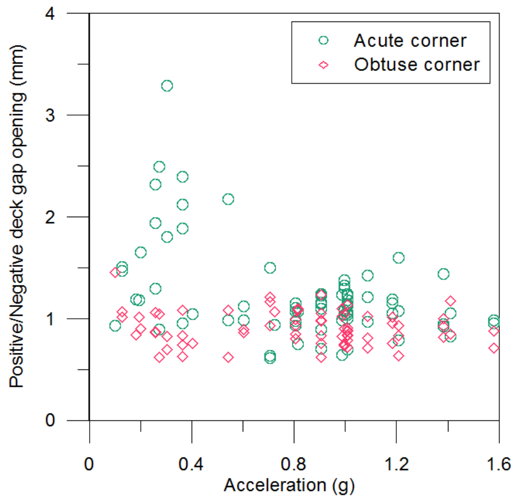

Figure 7. Ratio of positive to negative gap opening in non-skew decks under different shake table inputs. Higher ratios in the acute corners result in an anti-clockwise rotation in the deck

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.

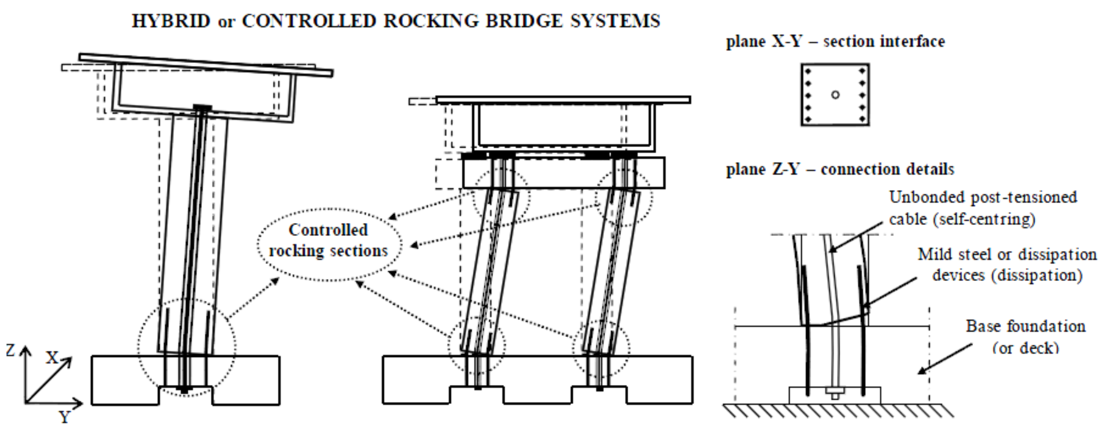

Figure 8. 'Hybrid' or 'controlled rocking' solutions for bridge piers (Palermo & Pampanin 2008)

CONCLUSIONS

This paper presents the results of a number of shake table testings on two small-scale concrete bridges with the aim of investigating the effect of skewness on their dynamic behavior. 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.

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