

Seismic performance of skew bridge with friction type rubber bearings

K.Y. Liu¹, K.C. Chang², C.H. Lu³ and W.C. Cheng⁴

¹ Associate Research Fellow, Center for Research on Earthquake Engineering(NCREE)/Taipei, Chinese Taiwan

² Professor, Dept. of Civil Engineering, Taiwan University/Taipei, Chinese Taiwan

³ Ph.D Student, Dept. of Civil Engineering, Taiwan University/Taipei, Chinese Taiwan

⁴ Master, Dept. of Civil Engineering, Taiwan University/Taipei, Chinese Taiwan

Email: kyliau@ncree.org.tw

ABSTRACT:

The seismic response of the skew bridges with rubber bearing is studied. In Taiwan, simply-supported PCI bridges are widely used with rubber bearing pads as a supporting system. It is common seen that, during the construction practice, the rubber bearing pads have been laid on the cement mortar-made bearing pads without any details of bolting design. This kind of arrangement potentially allows rubber bearing to slide, so as the superstructure when the earthquake occurs. In addition, bridges are usually being skewed to provide transportation service, requiring a further investigation of seat width to avoid falling of the superstructure. In this study, firstly, a series of friction coefficient was conducted. Furthermore, a scale-down skew bridge model has been constructed to perform the shaking table test. According to the experimental results, the inertial forces from superstructure can be reduced because of the sliding-induced isolation effect. The analytical program, SAP2000N was used to simulate the experimental results, and it has been shown the numerical model can well predict the displacement demand. Based on the parametric study, finally, the study will discuss the bridge behaviors with different skew angles.

KEYWORDS:

skew bridge, rubber bearing, friction coefficient, shaking table test

1. INTRODUCTION

A devastating earthquake with a magnitude of 7.6 struck the central region of Taiwan in the early morning of September 21, 1999. It was known as the 921 or Chi-chi earthquake (NCREE 1999). There are approximately 1,100 highway bridges spread on the provincial and county routes in the region. Major catastrophe occurred especially in Taichung and Nantou counties. About 90 percent of the bridges escaped from serious damage. The extents of bridge damages are relatively minor when compared to those observed in the 1994 Northridge earthquake and 1995 Kobe earthquake. It was observed that the friction-sliding mechanism of rubber bearings played a critical role to limit the seismic load transfer to the bridges' columns. Most of the bridge damages appeared to be caused by the movement of superstructure and separation of thermal expansion joints due to sliding or failure of the bearings, with the exception of seven bridges collapsed due to large fault displacements which crossed indirectly to the bridges. It was also observed that the number of bridge column damage was surprisingly small. Chang et al. (Chang et al 2004) developed a bridge model to simulate slide-friction of rubber bearings, impact effect between shear key and girder, and plastic hinge at the end of the columns, providing well simulation on a bridge that was damaged in the Chi-Chi Earthquake. Since most of the bridges in the damaged area caused by Chi-Chi earthquake were designed without ductile detailing, it may be in contrast to the current seismic design concept emphasizing the design of plastic hinges. Besides, damages of skew bridges were also found in the Loma Prieta earthquake (M7.0) in 1989, Northridge earthquake (M6.7) in 1994, Kobe earthquake (M7.2) in 1995. However, studies of skew bridge with rubber bearing are seldom discussed. Besides, considering the route selection, engineers may face to design a skew bridge rather than a regular or straight bridge in some occasions. For example, the bridge which is across the river often has no choice but to make a column bent inclined to the axis of the superstructure. Therefore, this paper presents the experimental study (Cheng 2008) on seismic performance of skew bridge with friction/sliding RB bearing (steel-reinforced

elastomeric bearing) and PTFE-RB bearing (steel-reinforced elastomeric bearing coated on a thin PTFE material). The friction coefficient test was carried out first to get friction coefficient of RB bearings and PTFE-RB bearings on the surface of cement mortar, concrete, and steel plates. Two scaled bridge model was utilized in the shaking table test to understand the influence of sliding behavior of bearings on a straight and skew bridge, respectively. The force equilibrium relationship between inertial force and base shear was verified from the test results, helping to build up reasonable analytical models to perform the parametric study. The analytical program, SAP2000N, have been used to simulate the experimental results and demonstrated good accuracy in predicting the displacement demand of the skew bridge. Based on the parametric study, finally, the study will discuss the bridge behaviors with different skew angles and input directions of time histories.

2. FRICTION COEFFICIENT TEST

2.1. Test specimen and setup

Figure 1 shows the test setup of the friction coefficient test. The size of bearing specimens are determined due to (1) minimal height of 15mm can only be provided by the manufactory and (2) consistent width of 150mm for same specimens to be used in the shaking table test. So, the size of the bearing specimen is 150mm×150mm×15mm. The Hardness IRHD material and shape factor of the rubber is 60 and 3.75, respectively. One SS400 shim plate is placed inside of the bearing. Based on the test requirements for rubber bearings in Chapter 18, AASHTO (AASHTO, 2002), a total of 12 cases shown in Table 1 was performed to get friction coefficient of two types of bearing (RB and PTFE-RB in Figure 2-3) on two different surfaces (material: cement mortar, steel in Figure 4-5) with four sliding velocities (1.06, 50, 150 and 300 mm/sec). In each test, the bearing clamped by the restrain plates on the top beam, shown in Figure 6, was forced to slide on the prefixed blocks, either made by cement mortar or steel, within 14 cycles. The target displacement for horizontal actuator is 60 mm in both positive and negative direction, providing a sufficient friction length to develop sliding mechanism. The constant normal force around 4MPa for each bearing was applied by two vertical hydraulic actuators, while shear and friction force were measured through two load cells under a loading beam. The relative displacement was recorded by a temposonic sensor to compare to the data from horizontal actuator.

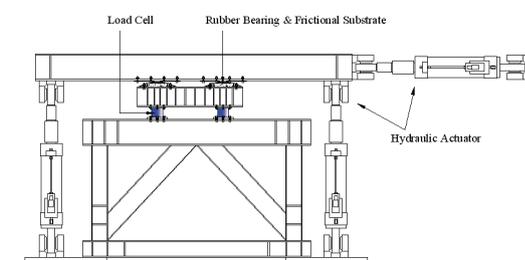


Figure 1 Test setup of the friction coefficient test



Figure 2 RB bearing



Figure 3 PTFE-RB bearing



Figure 4 Cement mortar block



Figure 5 Concrete block with steel plate



Figure 6 Installation of bearing

2.2. Test results and Discussions

Force and displacement curves for all cases are shown in Figure 7. During the test, it has been found that the friction force rapidly decreases after first cycle and is getting smaller and smaller as increasing the number of cycles. There is no doubt that long accumulated sliding distance will wear bearing surface and smoothen the

surface of cement mortar or steel with some residue rubber attached. The friction coefficient was determined according to ISO 15113 (ISO 2005). Since friction force is unstable in the first three cycles and affected in the last three cycles by the horizontal actuator before stopping the test, it is suggested to neglect those six cycles to obtain the coefficient with respect to cycles. Therefore, the maximum, minimum, and average friction coefficients for each case are listed in Table 1.

Table 1 Summary of the friction coefficient test results

Group	Friction surface	Case	Velocity (mm/sec)	Friction coefficient		
				Maximum	Minimum	Average
RB	cement mortar	1	1.06	0.378	0.346	0.358
		2	50	0.299	0.248	0.267
		3	150	0.229	0.169	0.192
		4	300	0.231	0.168	0.193
	steel plate	5	1.06	0.417	0.371	0.388
		6	50	0.536	0.422	0.467
		7	150	0.477	0.359	0.409
		8	300	0.498	0.386	0.434
PTFE-RB	steel plate	9	1.06	0.130	0.101	0.112
		10	50	0.175	0.138	0.152
		11	150	0.193	0.158	0.171
		12	300	0.213	0.172	0.188

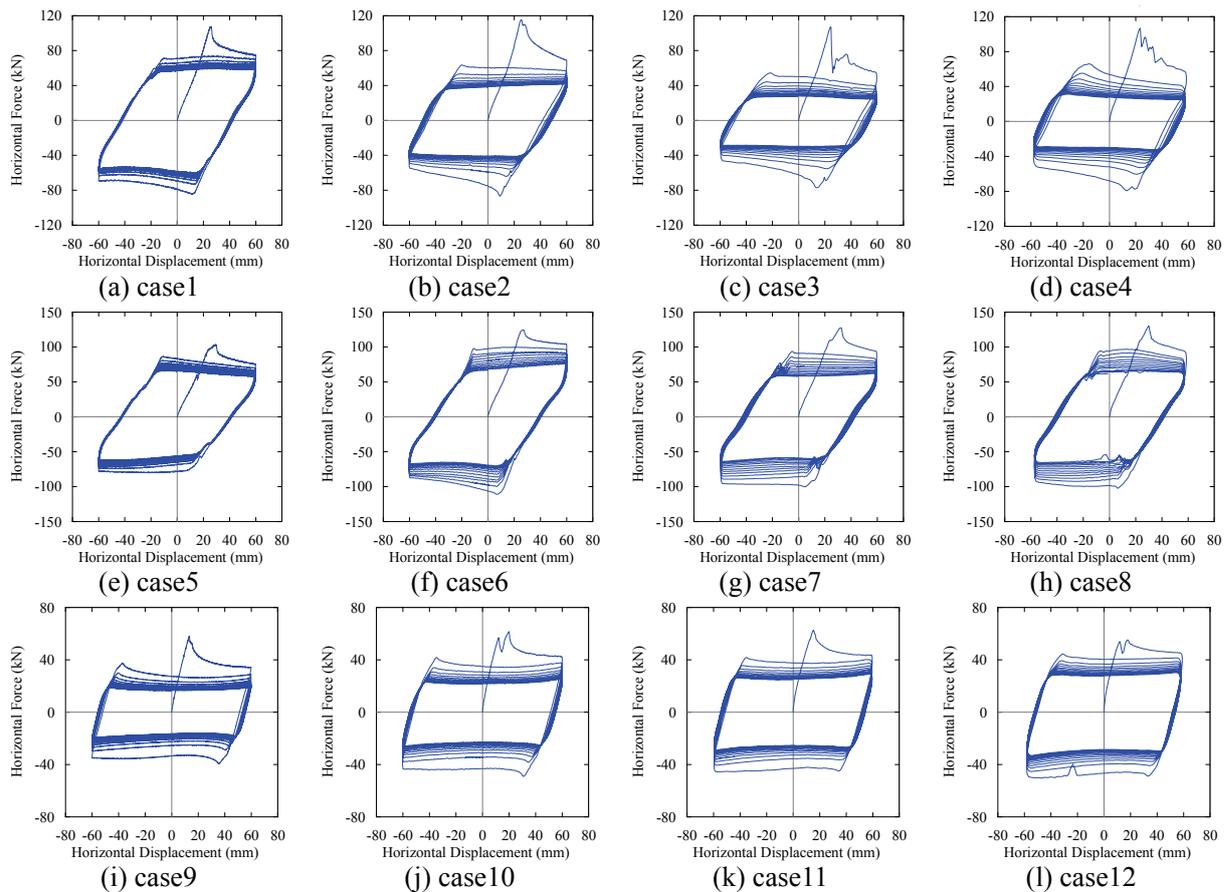


Figure 7 Hysteresis curve of the friction coefficient test

From Figure 5, the initial stiffness represents the elastic shear stiffness of the bearing and the unloading stiffness is as same as the initial one. Consequently, owing to the contribution of the rubber in the elastic range, the hysteresis loop for both RB and PTFE-RB bearing are a parallelogram shape rather than a pure rectangular loop.

Moreover, in comparison of reaction coefficient on different surfaces, this value on the cement mortar is smaller than the one on the steel plate. To reflect the construction practice of unbolted bearings, a range from 0.2 to 0.4 for the friction coefficient is more realistic than using a single value. As for the PTFE-RB, the friction coefficient from 0.1 to 0.2 can be obtained based on the test results.

3. SHAKLING TABLE TEST

3.1. Test specimen and setup

Shaking table tests were conducted to get realistic dynamic performance from two 1/7.5 scale-down simply-supported bridge models with rubber bearings, shown in Figure 8 and 9, a straight and a skew bridge model, respectively. Based on the definition of a complex bridge, which should be examined through dynamic analysis method (MOTC 2000), the skew angle is 20 degree. The superstructure is 10.67 tons and consists of concrete slabs, two girders and four diaphragms, supported by two rectangular hollow-section steel bents. The column bents were designed to remain elastic. Figure 10 shows the design drawings of the bridge. The bearings used in this test are as same as in the friction coefficient test, including RB and PTFE-RB bearings. Besides, in order to compare the sliding behaviors between two different boundary conditions (B.C), as shown in Figure 11, both RB-RB cases which represent a semi-fixed B.C, and PTFE-RB cases which are like a roller-hinge B.C, were performed with peak ground acceleration (PGA) levels from 0.1g to 0.7g. The south bent may use RB or PTFE-RB bearing, depending upon the cases; while the north bent was equipped with RB bearing only. The input ground motion along the longitudinal direction of the bridge model is record in east-west direction of 1941 El Centro earthquake. Both time-history and response spectrum normalized to 1.0g are given in Figure 12. Regarding to the instrumentation plan, acceleration on the superstructure, relative displacement of the bearing, and surface strains at the end of the columns were measured.

Test schedule for the shaking table test

Bridge model	Bearing arrangement (South end - North end)	Peak input ground acceleration of El Centro earthquake (g)
Skew	RB - RB	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7
	PTFE - RB	
Straight	PTFE - RB	

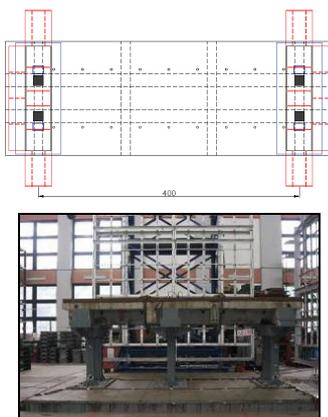


Figure 8 regular bridge model

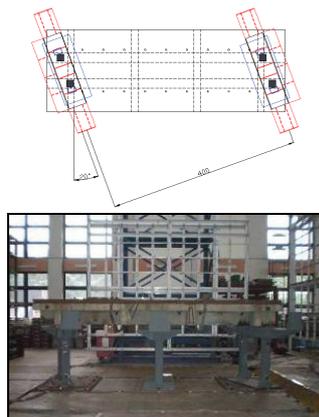


Figure 9 skew bridge model

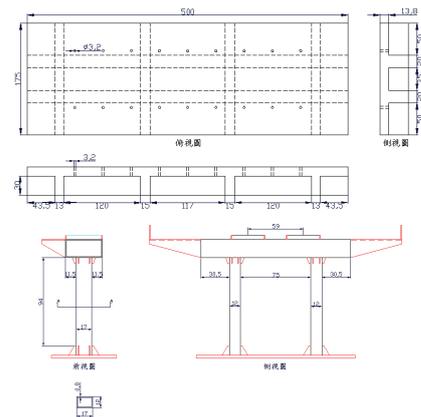
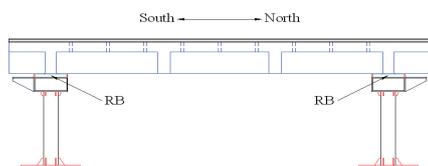
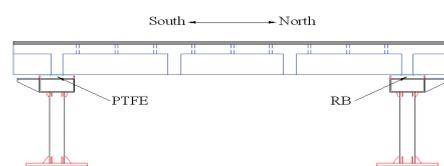


Figure 10 design drawings

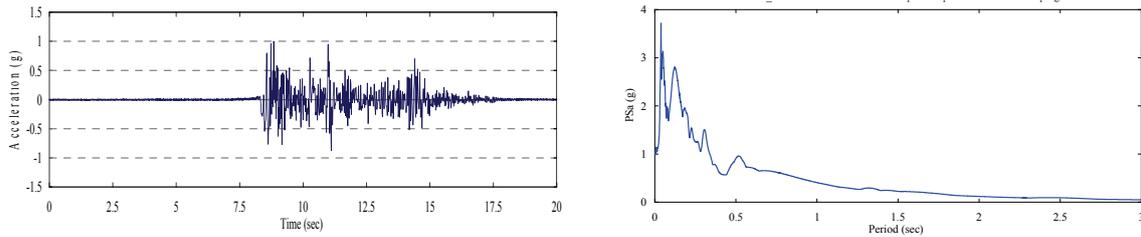


(a) RB-RB case



(b) PTFE-RB case

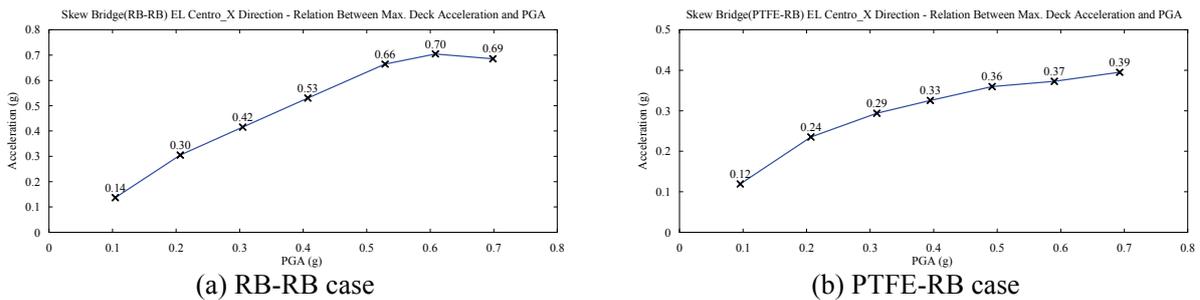
Figure 11 Arrangement of bearings



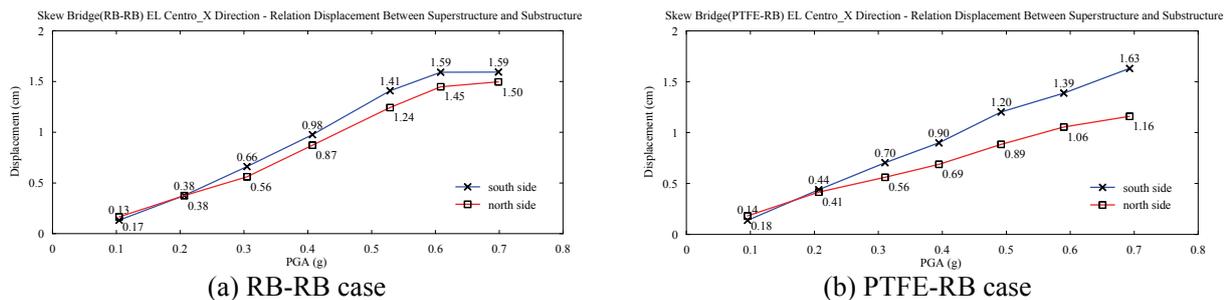
(a) Time history (b) Response spectrum
 Figure 12 Input ground motion of EL-Centro earthquake (PGA normalized to 1.0g)

3.2. Test result

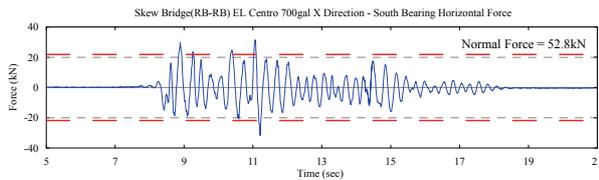
Figure 13 illustrates the test results of peak acceleration on the superstructure with respect to PGAs. The obtained acceleration is not proportional to the PGA, not only in RB-RB case or PTFE-RB case, representing the influence of sliding effect on the global performance. Especially, the trend of the line in Figure 13(b) is getting flat with a turning point around 0.2~0.3g. Although received same input ground motions, the accelerations in PTFE-RB case are smaller than in RB-RB case, indicating that an isolation effect is apparent when utilizing a bearing with small friction coefficient. The global structure response, particularly the force demand of the column, can be reduced due to a sliding mechanism. However, the relative displacement between superstructure and substructure is increasing. In Figure 14 (b), the obtained displacement showed no difference between two locations before PGA of 0.2g, but after that, the displacement at south bent with PTFE-RB is increasing and the displacement ratio between south and north bent is greater than 1.5. In contrast, the displacement demands at both bents in Figure 14 (a) are similar due to using same type of RB bearing to require a semi-fixed boundary condition. So, the structure performance was significantly affected by the bearing system, corresponding to a low or high friction coefficient, and the arrangement of bearings to make a specified constrain on the boundary. So far, friction coefficient of rubber bearing was often determined through static tests under very slow velocity. However, for bridge subjected to the earthquake excitation, the coefficient from a dynamic test, such as a shaking table test, is more realistic to describe the sliding phenomena. As shown in Figure 15, the base shear forces, which are sum of two column forces at either north or south side bent, were divided by the weight of the superstructure to determine the friction. The PGA in Figure 15 is 0.7g, and the bridge was moved according to the recorded videos. Clearly, it is due to the sliding effect that an upper and lower bound of shear forces can be identified. The friction coefficient for RB bearing and PTFE-RB bearing is around 0.4 and 0.2, respectively, close to the test results obtained in the friction coefficient test with the speed at 300mm/sec.



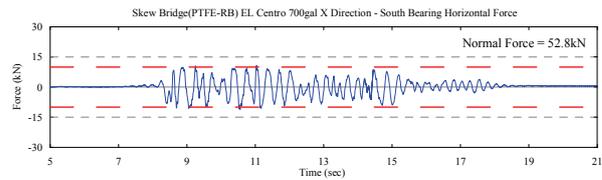
(a) RB-RB case (b) PTFE-RB case
 Figure 13 Peak acceleration on the superstructure



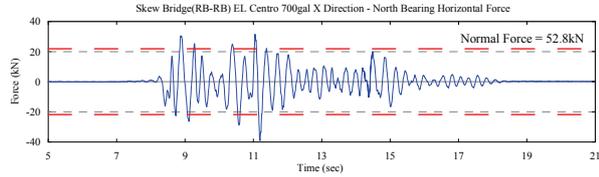
(a) RB-RB case (b) PTFE-RB case
 Figure 14 Maximum relative displacement between superstructure and column bent



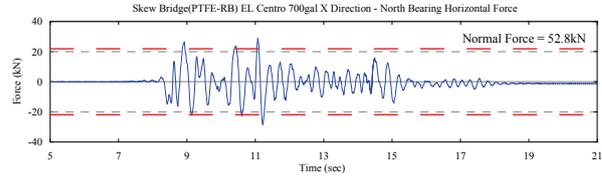
(a) RB-RB case (south side)



(c) PTFE-RB case (south side)



(b) RB-RB case (north side)



(d) PTFE-RB case (north side)

Figure 15 Column shear forces with PGA of 0.7g

3.3. Analytical simulation

Based on the structure information, both skew and straight models shown in Figure 16 and 17 were established in SAP200N (CSI 2002) to compare the structure performance with experimental results. In order to simulate the sliding behavior of the rubber bearing, the friction-pendulum element (Wen 1976) was utilized with proper friction coefficient given from either friction coefficient test or shaking table test. Only the bearing is considered a nonlinear element with elastic shear stiffness determined by the shear modulus, area and height of the rubber, and a constant friction coefficient of 0.4 for RB bearing, as well as 0.2 for PTFE-RB bearing. In Figure 19, the analytical models can well predict the time history of the acceleration in the cases of 0.1g, 0.4g and 0.7g, respectively. Not only the results from straight bridge model but the skew bridge models show good accuracy.

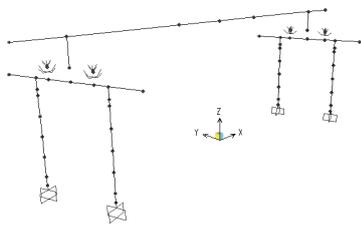


Figure 16 Skew bridge model

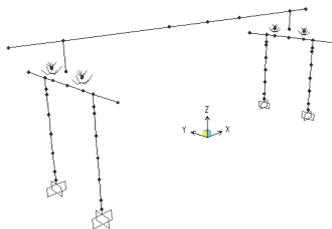


Figure 17 Straight bridge model

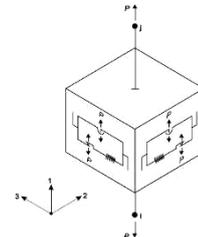
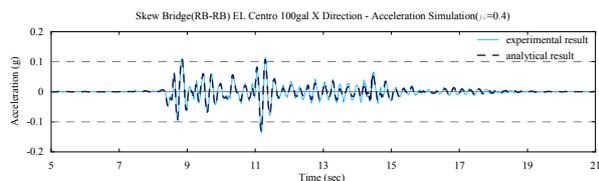
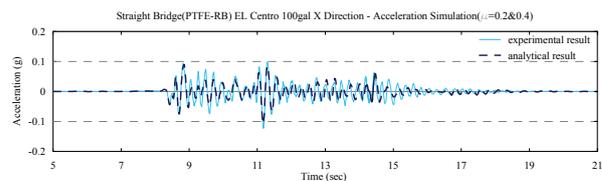


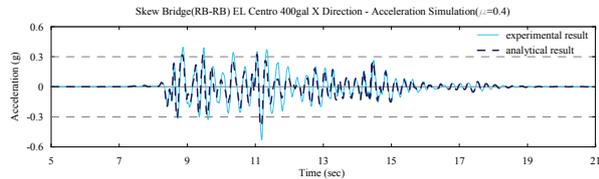
Figure 18 Friction-Pendulum element



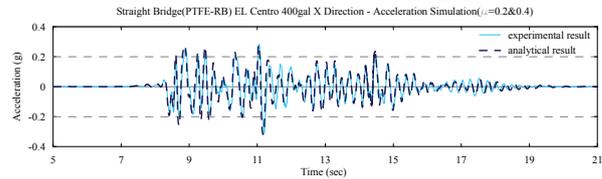
(a) RB-RB case (Skew bridge, 0.1g)



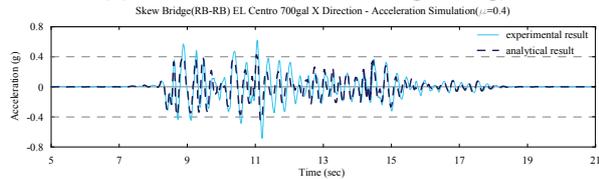
(d) PTFE-RB case (Straight bridge, 0.1g)



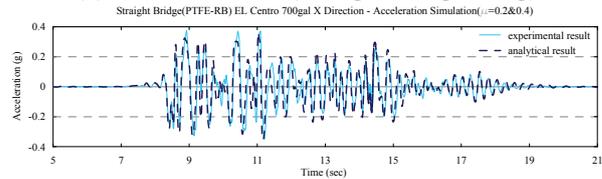
(b) RB-RB case (Skew bridge, 0.4g)



(e) PTFE-RB case (Straight bridge, 0.4g)



(c) RB-RB case (Skew bridge, 0.7g)



(f) PTFE-RB case (Straight bridge, 0.7g)

Figure 19 Comparison of deck acceleration between analytical and experimental results

Like results in Figure 19, the comparisons regarding to displacement in skew and straight model with three PGA levels are also shown in Figure 20. Though the time history results of displacement are not so as good as acceleration, ie., in Figure 20 (f) the analytical residual displacement is larger than the test data; however, the peak response was capable of predicting the maximal response, helping engineers to confirm the safety of unseating length based on the design code.

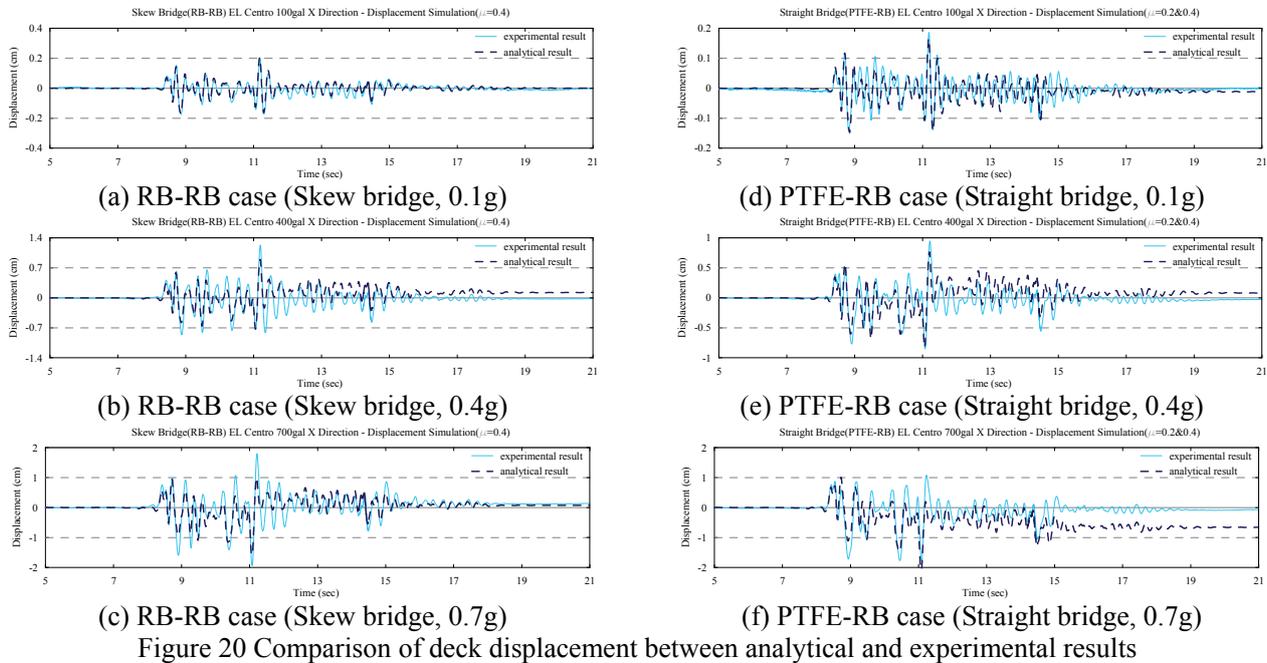
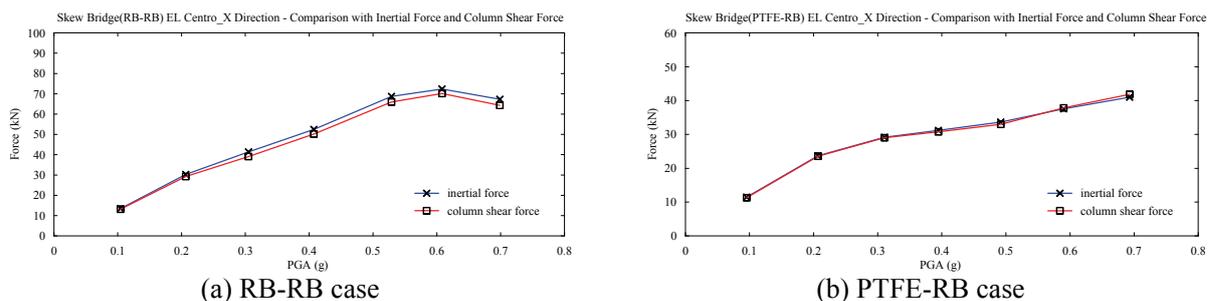


Figure 20 Comparison of deck displacement between analytical and experimental results

3.4. Comparison and Discussion

The shear force of the substructure is resulted from the inertial force of the superstructure, cap-beam and column bents, assumed the damping force is neglectable; hence, these two loads should be identical to each other to make the loading path clearly identified through the bearing system in between. In this study, the contribution of inertial force from cap-beam and column themselves are too small to neglect because of relative small weight compared to the girder. Figure 21 represents the comparison between inertial force of the superstructure and the base shear of the substructure. The inertial force is the product of deck mass and deck acceleration at the time point corresponding to maximal acceleration of the deck; meanwhile, the base shear at the same time point was also calculated. It was found that no matter the superstructure was sliding or not, the force equilibrium relationship is satisfied in both RB-RB case and PTFE-RB case. Therefore, by taking advantage of the accuracy of the analytical model, the force demand of sliding rubber bearing and columns at different PGA levels can be quickly and precisely judged. Besides, the maximal base shear force between skew and straight bridge model are also compared. As shown in Figure 22, though the force of south bent in skew bridge is slightly smaller than the force obtained from straight bridge model (Figure 22 (a)), the trend of two lines almost same. However, if the skew angle is larger than 20 degree, the parametric study results in Figure 23 reveal that the structure behavior is not proportional to the skew angle. Consequently, it is suggested to use suitable bearing elements in the bridge model to get maximal response of a skew bridge.



(a) RB-RB case (b) PTFE-RB case
 Figure 21 Comparison of inertial force and base shear force in skew bridge model

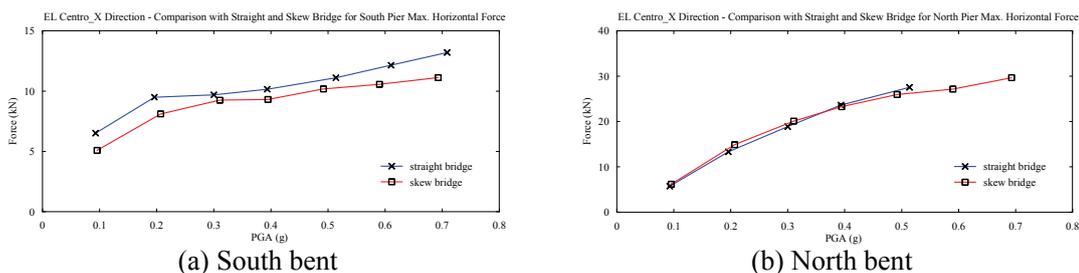


Figure 22 Comparison of maximal base shear force in the longitudinal direction (PTFE-RB case)

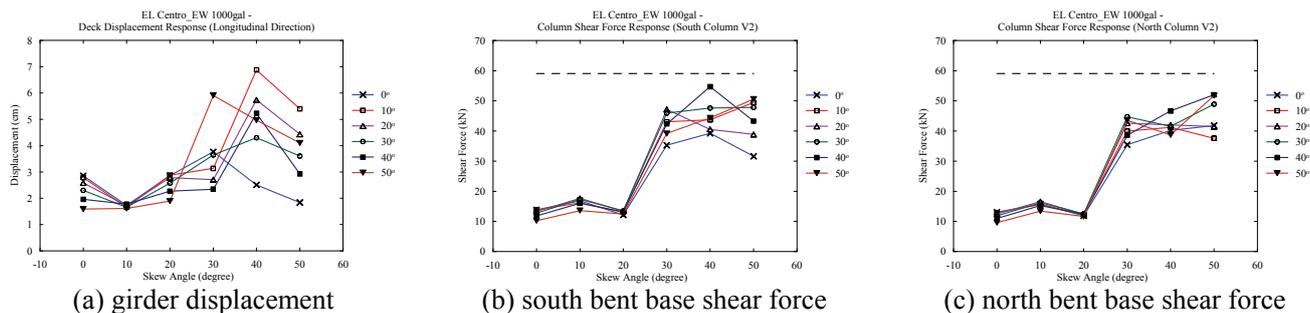


Figure 23 Prediction of maximal response for RB-RB case under different skew angles (PGA = 1.0g)

CONCLUSIONS

This paper aims at discussing the seismic response of the skew bridges with sliding rubber bearings. The construction practices of rubber bearing without any anchor bolts provide a fuse-like mechanism for rubber bearing to slide on the bearing pad and thereafter to reduce the force demand of the column and enlarge the displacement requirement of seat width. Therefore, a series of friction coefficient was conducted first and followed by shaking table tests on two scale-down skew bridge models. According to the experimental results, the friction coefficient for RB and PTFE-RB bearing is 0.4 and 0.2, respectively, considering the influence of high speed may be required in a real seismic event. Beside, the force equilibrium relationship between inertial force and base shear was confirmed experimentally. The analytical models can well predict the structure performance in comparison with the test results, helping to set seat width for the skew bridge. Based on the parametric study, finally, it is suggested to use suitable bearing elements in the bridge model to get maximal response of a skew bridge under seismic excitations.

REFERENCES

- AASHTO. (2002), "Standard Specifications for Highway Bridges, 17th Ed", American Association of State Highway and Transportation Officials, Washington, DC.
- Cheng Wei-Jin. (2008). "Shaking Table Test for Scale Down Skew Bridge Models with Rubber Bearings." Master thesis, Department of Civil Engineering, Taiwan University, Chinese Taiwan.
- Computers and Structures, Inc., (2002). "SAP2000, Integrated Finite Element Analysis and Design of Structures, Analysis Reference Manual," University of California at Berkeley, California, USA.
- ISO. (2005). "Rubber-Determination of Frictional Properties", ISO 15113 INTERNATIONAL STANDARD.
- K.C Chang, K.Y Kuo, K.Y Liu, and C.H Lu. (2004). "On Seismic Retrofit Strategies of Highway Bridges - Experiences Learned from Chi-Chi Earthquake", 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, Paper No. 639, 2004
- Center for Research on Earthquake Engineering(NCREE). (1999). "Reconnaissance report of the 921 Chi-Chi Earthquake for bridges and transportation facilities," Report No. NCREE -99-055, Taipei, Chinese Taiwan.
- Wen Y.K. 1976. Method for Random Vibration of Hysteretic Systems. Journal of the Engineering Mechanics Division, ASCE, 102(EM2).