ISBN 978-93-84422-57-8
Proceedings of 2015 International Conference on Disaster Management in Civil Engineering (ICDMCE'2015)
Phuket, Thailand, October 1-3, 2015, pp. 8-13

Seismic Behaviour of Unskewed Two Bridge Pier under In-Plane Lateral Cyclic Loading

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Abstract: *Nowadays, the earthquake phenomenon is a natural disaster for Southeast Asia Region which causes loss of assets, casualties and the government needs to recover all the losses after the earthquake. One of the expensive infrastructures to rebuild is the bridge. Most of the bridges in Malaysia are not fulfilling the requirement of the Basis Design Earthquake (BDE) and Maximum Considered Earthquake (MCE) under the Performance-Based Earthquake Engineering (PBEE). Consequently, this research provides some evidences on the seismic performances and damages of unskewed bridge under in-plane lateral cyclic loading. A one-third scale of semi integral bridge together with post-tensioning on both bridge piers were designed, constructed and tested in the heavy structural laboratory. Experimental results show that ultimate in-plane lateral load of the bridge is 186 kN at ultimate displacement of 33.8mm. Visual observations on the damages such as hairline cracks and spalling of concrete cover were occurred at top and bottom of column. The equivalent viscous damping for first cycle is higher than second cycle and the calculated ultimate displacement ductility is 3.38. It can be concluded that this type of bridge will survive under minor earthquake and did not survive under severe or great earthquakes.*

Keywords: *seismic performances, in-plane loading, ductility, ultimate displacement, equivalent viscous damping*

1. Introduction

Almost all the bridges in Malaysia which were built in the last 30 years did not consider the seismic load except for Second Penang Bridge [1]. Some of the bridges were collapsed due to severe or strong earthquake such as the collapse of Oakland Bay Bridge on 1989 with magnitude of the Loma Pieta Earthquake of 7.1 Richter scale [2]. The strong earthquake was making the side of bridge shifts to the east and caused the bolts of bridge to shear off then some part of the bridge collapsed. Past earthquake records showed that the damage induced in the bridges can take many forms depending on the ground motion, site conditions, structural configuration and specific details of bridge. Damage within the superstructure has rarely been the primary cause of collapse. Most of the severe damage to bridges has taken three forms such as the bridge deck did not seating at in-span hinges or simple supports because of inadequate seat lengths or bearing capacity, brittle failure of column due to deficiencies in the percentage of reinforcement bars, reduction in shear capacity and inadequate ductility and unique failures in complex structures [3].

Hitherto, there are a lot of research have been performed on the bridges subjected to dynamic and cyclic loading. In both the static and dynamic loading regimes, significant sources of resistance not typically relied upon in bridge pier design have been identified and quantified through comparisons of numerical modeling results and physical test data [4]. It is also very important to validate between the theoretical values and experimental results for proving that the theory can be used to design and model the structures under different kinds of loads [5]. In order to avoid any damages to bridge piers and reinforced concrete buildings during strong earthquake, the Damage Avoidance Design (DAD) philosophy can be adopted during design and construction stages [6,7,8,9]. This concept was introduced by Mander and Cheng [6] through conducting experimental work of two-column bridge pier and tested under in-plane lateral cyclic loading. The precast columns are expected to

rock on the pile cap or foundation beam surface to accommodate large seismically induced deformations. The lateral forces are resisted by vertical dead load at pier top and post-tensioned steel inside the columns. Indeed, this research is conducted to determine the seismic behavior of rocking multi-column pier under in-plane lateral cyclic loading which has been designed using the British Standard (BS 8110).

2. Materials and Method

A one-third specimen of unskewed bridge with two piers was constructed in Heavy Structural Laboratory, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia. Ready mixed concrete with compressive strength (f_{cu}=30 MPa) was poured into the foundation beam, column and pile cap formwork. The characteristic yield strength of longitudinal reinforcement bars (f_y=460 MPa) and mild steel of shear reinforcement bars (f_{yv}=250 MPa) were utilized for preparation cages for foundation beam, pile cap and two bridge columns. The diameter of longitudinal reinforcement bars were 20mm, 16mm, 12mm and 10mm. The ultimate strength for post-tensioned tendons to clamp two bridge piers with pile cap and foundation beam is f_{pu}=1860 MPa.

Figure 1 represents the side view of the conceptual prototype semi integral bridge together with capping beam and foundation beam. The one-third scale of semi integral bridge has one foundation beam (3155x1000x400mm), two bridge piers with diameter 333mm and height of 1882mm attached to one pile cap (3155x616x500mm) on its top. The designed stage, construction and testing of this specimen was carried out in the heavy structural laboratory. Once the compressive strength of concrete achieved the target designed, it is ready to be tested under in-plane quasi-static lateral cyclic loading after all the equipment and instruments are calibrated.

Figure 2 shows the actual size of the specimen after finish curing and painting with white colour for the bridge piers, pile cap and foundation beam. Post-tensioned tendons were applied to both bridge piers in the compressive force from top of the pile cap so that the columns gain their strength and stiffness before start testing the specimen. A total number of six LVDTs were installed at right hand side of the specimen for measuring the lateral displacements/ deformation of the columns and uplift of the foundation beam when in-plane cyclic loading applied to the specimen. The first LVDT1 was placed at center of capping beam, three along one side of bridge pier and two were placed on top of the foundation beam. A total number of 12 strain gauges were glued to the longitudinal reinforcement bars located at bottom and top of both columns. Strain gauges were used to measure the elongation or compression of bars under tension or compression force.

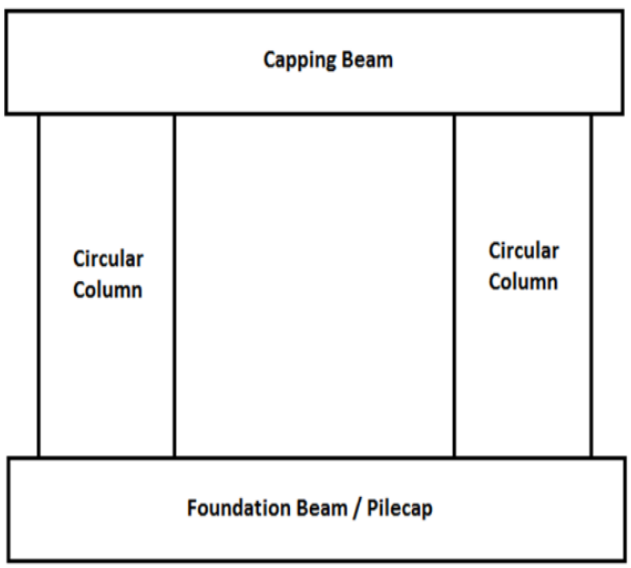

Fig. 1 : Prototype semi integral bridge

Fig. 2: Semi integral bridge model

Subsequently, the specimen was tested using control displacement method where load cell from actuator recorded the applied load along with the target drift imposed to the structure. The specimen was tested at ±0.01%, ±0.1%, ±0.25%, ±0.5%, ±0.75%, ±1.0%, ±1.25%, ±1.5%, ±1.75% and ±2.0% drift. The experimental data such as lateral force, lateral displacement and strain of the reinforcement bars were used to plot the hysteresis loops (load vs displacement) for each LVDT and stress versus strain for each of strain gauge. The

visual observation on the damages of the bridge piers and analysis of the results will be explained in the following section.

3. Visual Observation On The Damages

Figure 3 shows locations of vertical and diagonal cracks which occurred at the bottom and top of the columns when tested up to 1.25% drift. Undoubtedly, a lot of cracks were concentrated at the plastic length closed to column-foundation and column-capping beam interfaces because these areas were located within the plastic hinge zone (PHZ) mechanism.

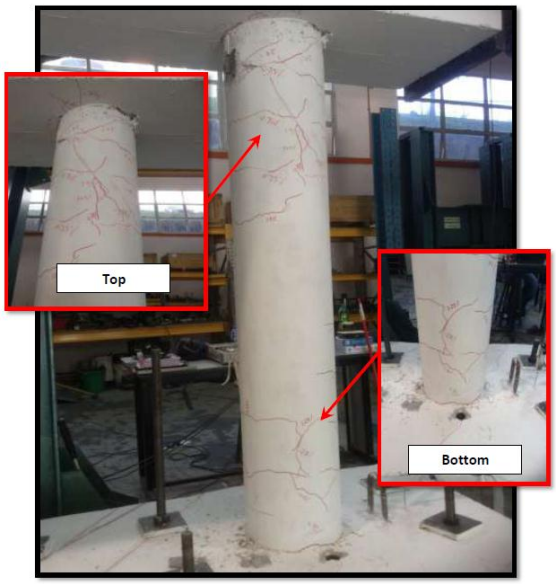

Fig. 3: Cracks observed at top and bottom column

Fig. 4: Spalling of concrete cover at top column

Figure 4 shows the spalling of nominal concrete cover at top of the first column when +1.5% drift was applied to the specimen. The main reasons of the spalling of concrete is due to the insufficient of percentage of transverse and longitudinal reinforcement bars in the concrete, lack of detailing at the plastic hinge length (L_p) and low compressive strength of concrete. Certainly, these factors will influence the amount of unconfined concrete in the column which leads to the failure of concrete and buckling of reinforcement bars.

4. Analysis And Interpretation Of Results

Figure 5 exhibits the overall seismic behavior of bridge piers system under in-plane lateral cyclic loading which also known as hysteresis loops which measured by LVDT1. Herein, the important parameters such as yield lateral load, yield displacement, ultimate load and ultimate displacement which can be obtained from the hysteresis loops are used to calculate the elastic stiffness, secant stiffness, effective stiffness, displacement ductility and equivalent viscous damping. The modeling of hysteresis loops of unskewed bridge piers using HYSTERES program in Ruaumoko 2D can be carried out under different level of earthquake excitations.

Figure 6 shows backbone of lateral strength versus lateral displacement for each drift. Initially, lateral load increase linearly with lateral displacement under elastic limit and become nonlinear behavior under plastic range. The yield lateral load can be determined by taking 75% of ultimate load (F_y=0.75F_{ult}). Eventually, the specimen reaches the ultimate load (F_{ul}=186.42 kN) at 1.5% drift with ultimate displacement ($\Delta_{ult} = 33.8mm$). Consequently, F_y = 0.75*186.42=140kN. By projecting the vertical line downward to meet the x-axis, the yield displacement is Δ_y=15mm. This value can be used to determine stiffness, ductility and equivalent viscous damping.

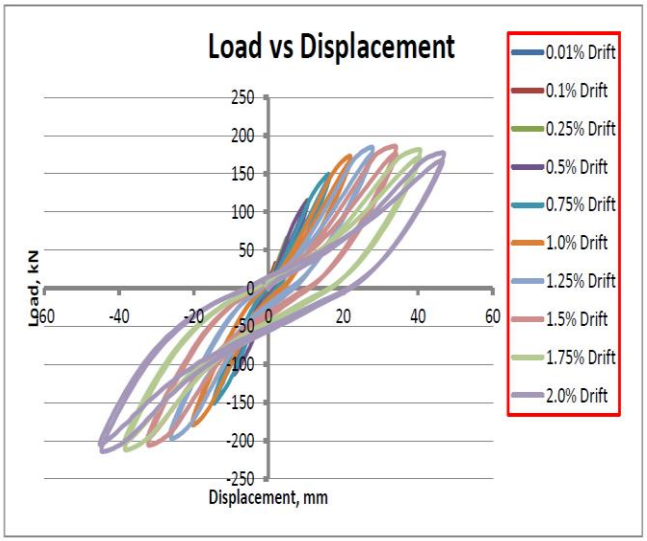

Fig. 5: Hysteresis loops of the first column

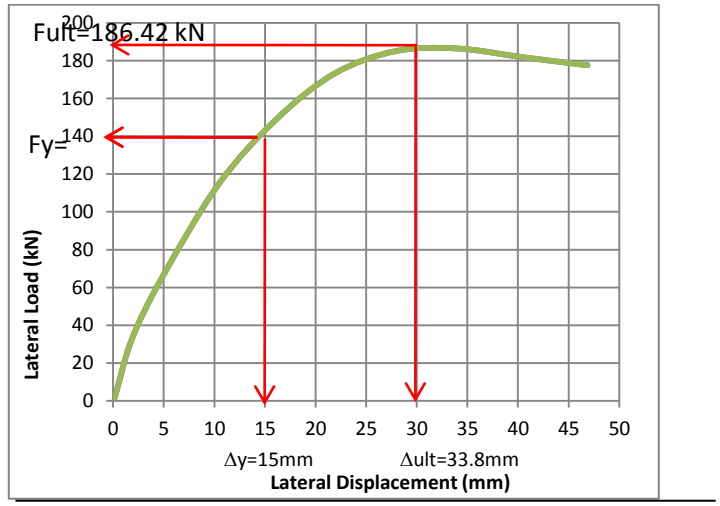

Fig. 6: Lateral force versus displacement

Figure 7 shows the profile of lateral displacement versus % of drift. The experimental testing was started at 0.01% drift with displacement of 0.16mm in pushing direction and -0.16mm in pulling direction. The specimen was tested with increment of 0.25% drift starting from 0.25%, 0.5%, 0.75%, 1.0%, 1.25%, 1.5%, 1.75% and finally 2.0% drift. The final displacements at 2.0% drift are 46.88mm in pushing and -45.14mm in pulling. Table 1 tabulated the maximum lateral load and maximum lateral displacement for LVDT 1 under pushing and pulling directions. Figure 8 shows the amount of energy dissipated during the experimental work during first by plotting the equivalent viscous damping versus time for each drift. Undoubtedly, the equivalent viscous damping behaves slightly linear with respect of the drift up to 2.0% drift. Normally, the equivalent viscous damping of the first cycle is higher than second cycle because a lot of energy is required to resist the lateral capacity of the bridge piers especially at elastic limit with bigger elastic stiffness.

TABLE I: Maximum lateral load and maximum lateral displacement

Drift (%)	Maximum Lateral Load (kN)		Maximum Lateral Displacement (mm)	
	Pushing	Pulling	Pushing	Pulling
0.01%	1.69	-2.53	0.16	-0.16
0.1%	32.51	-23.63	1.84	-1.36
0.25%	65.5	-64.90	4.86	-4.16
0.5%	114.92	-112.76	10.46	-9.16
0.75%	149.35	-151.15	16.2	-14.66
1.00%	173.22	-179.46	21.9	-20.34
1.25%	184.98	-197.33	27.88	-26.36
1.5%	186.42	-206.09	33.02	-32.74
1.75%	181.74	-212.09	40.56	-38.74
2.00%	177.54	-214.25	46.88	-45.14

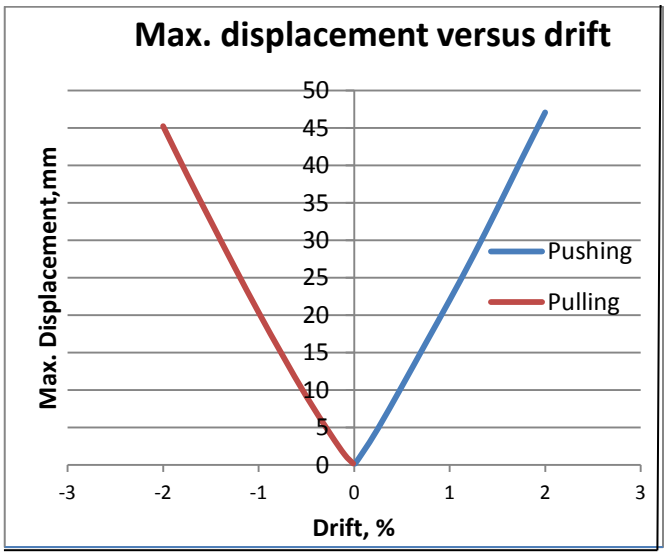

Fig.7: Displacement versus drift

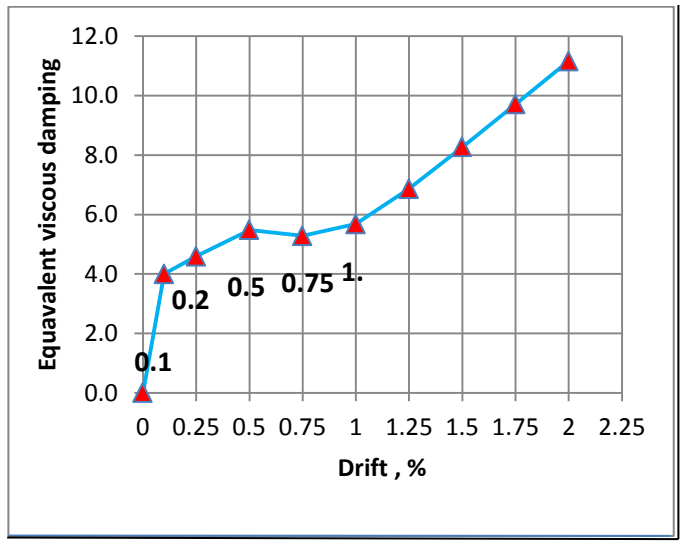

Fig. 8: Equivalent viscous damping for every drift

From Figure 6, the value of ductility displacement (μ_Δ) can be calculated using the following equation:

$$\mu_\Delta = \frac{\Delta_{ult}}{\Delta_y} \quad ; \quad \mu_\Delta = \frac{33.8mm}{15mm} = 2.25 \tag{1}$$

where μ_Δ is the ductility displacement, Δ_{ult} is the ultimate lateral displacement and Δ_y is the yield lateral displacement. The value of ductility displacement is 2.25 is considered as Ductility Class Low (DCL) which only can survive under low peak ground acceleration (PGA < 0.08g where g = 9.81 m/s^2). Based on the ductility displacement value, the bridge piers together with cap beam can only survive with low seismic load and did not survive under moderate earthquake because this type of pier is only designed to cater for gravity load which consist of dead load and imposed load only. Table 2 shows all the parameters which obtained from hysteresis loops as plotted in Figure 5. These parameters are very important for designed purposes in order to determine the frequency, period, percentage of equivalent viscous damping, dynamic analysis, time history analysis and others. Finally, these data can be used to design unskewed bridge piers which cater for moderate and strong earthquake.

TABLE II: Parameters obtain from hysteresis loops

Parameters	Pushing Direction	Pulling Direction
Maximum Lateral Strength Capacity	186.42 kN	-206.09 kN
Elastic Stiffness (Ke)	7.78 kN/mm	7.77 kN/mm
Secant Stiffness (Ksec)	2.94 kN/mm	2.81 kN/mm
Effective Stiffness (Keff)	5.52 kN/mm	4.83 kN/mm
Displacement Ductility	2.25	2.18

5. Conclusions and Recommendations

Based on visual observation, analysis and interpretation of result, the following conclusions and recommendations can be drawn as follows:

- From visual observation, there are a lot of cracks occurred at the top and bottom of the two bridge piers due to the existence of the plastic hinge zone at these areas.
- The bridge piers behave linearly until it reached the yield load of 110kN and behave non-linear behavior with ultimate maximum displacement of 186.2kN and finally experienced the strength degradation before the structure started to collapse.
- The equivalent viscous damping has linearly increase with percentage of drift and the first cycle of equivalent viscous damping has higher value than second cycle.

- The displacement ductility for bridge pier is 3.38 and can only survive under low or moderate earthquake excitations with some cracks at top and bottom column.
- It is recommended that the design of bridge piers together with capping beam using current seismic code practice such as Eurocode 8 for better seismic performance under ground motion.
- In order to reduce the crack and damage at top and bottom part of the column, fuse bars can be installed at bottom of the column and apply the Damage Avoidance Design together with rock column concepts where the foundation beam, column and capping beam are discontinuous (not fixed moment) each other.

6. Acknowledgement

Special thanks to Fundamental Research Grant Scheme (FRGS), MOHe, Putrajaya, Malaysia and RMI (Research Management Institute) for funding this research work. Gratitude and appreciation to the laboratory staff members for their invaluable assistance during the course of this experimental research work.

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