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CABLE-STAYED BRIDGE RETROFIT USING ISOLATION SYSTEM

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SUMMARY

Considering the dynamic behavior of cable-stayed bridges, bridge designers always focus on wind effect and almost ignore earthquake effect. However, the unexpected destruction of the Chi-Lu Bridge in the 1999 Chi-Chi earthquake shows that earthquake effect could be the decisive factor in cable-stayed bridge design, especially for those bridges with short period in the longitudinal or transverse direction.

After adjusting the seismic districts owing to the Chi-Chi earthquake, many bridges need to be retrofitted in order to comply with the new regulations in Taiwan. For cable-stayed bridges, it seems impractical to reinforce structural members. It will be more simple and efficient to conduct the bridge retrofit by using isolation systems if the system is proved to be feasible. In order to study the feasibility and efficiency for the cable-stayed bridges retrofitted by using an isolation system, this study has conducted a series of numerical experiments with great emphasis on the Chi-Lu Bridge. The results with some suggestions are given in this paper.

INTRODUCTION

A great earthquake of scale 7.3, known as the 921 or Chi-Chi earthquake, struck the central Taiwan before dawn on September 21, 1999. The strong shock caused several thousands of people's injuries and deaths. Countless houses, roads, and bridges were damaged [1]. Among them, the Chi-Lu Bridge, a cable-stayed bridge, nearby the epicenter was also badly destructed due to strong shock. The Chi-Lu Bridge might be the first case of cable-stayed bridge that was damaged by a strong earthquake. Therefore, it deserves an extensive study in depth how the bridge was destructed and how to retrofit the bridge in order to protect it from another strong quake in the future. In addition, examinations should be done and workable retrofitting strategies need to be proposed as soon as possible for other cable-stayed bridges that might have the same problem of insufficient seismic resistance in Taiwan.

The unexpected destruction of the Chi-Lu Bridge proves that the design of cable-stayed bridge may still be controlled by earthquake effect in addition to the primary wind-force effect. In view of structural system, cable-stayed bridges usually have a high flexibility in the gravitational direction due to the large ratio of span to girder depth. Comparatively, the stiffness properties in the bridge longitudinal and transverse

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direction are not exactly so, which depend on the boundary conditions of supports and the ratio of girder width to span. Generally speaking, long-span cable-stayed bridges have high flexibility and the dynamic design is mainly controlled by the aerodynamic effect [2]. But to those cable-stayed bridges with middle span or special support conditions, the earthquake effect could become the decisive factor of design in severe seismic area.

With regard to the bridge destruction by earthquake, it is more important to carry out follow-up repairing work and seismic retrofit in addition to probing into the causes of damage. In fact, lots of studies about the seismic design and retrofit of bridges have been done and can be readily found in research papers and technical books [3, 4]. Many nations such as the United States, Japan and Taiwan already established and published manuals for seismic retrofit of highway bridges [5, 6]. Basically, the strategies of seismic retrofit can be divided into two categories: strengthening of structural members and adjustment of structural system. The former reinforces structural members and raises their strength to resist earthquake forces, and the latter utilizes isolation and/or dissipation devices to change the structural characteristics of the bridge in order to isolate or dissipate the transmitted earthquake energy and reduce the earthquake forces subjected by structural members. At present, the seismic retrofitting strategies of most counties recommend to consider the installation of isolation or dissipation devices as the primary reinforcing approach first, and then employ member strengthening method to supplement insufficient part. A common retrofitting approach is to replace traditional bridge supports by base isolation bearings [7, 8]. In fact, it is possible to repair a damaged cable-stayed bridge to retain its original design strength by strengthening methods; however, it becomes very difficult in practice using a strengthening approach if an upgrade of seismic resistance of bridge is required. On the contrary, it will be more simple and efficient to conduct the bridge retrofit than conventional strengthening techniques if an isolation and/or dissipation systems can be proved feasible through analysis to improve the seismic resistance of cable-stayed bridge. And this approach can not only be applied to the seismic retrofit of a damaged cable-stayed bridge, but also deal with the problem of cable-stayed bridges having insufficient seismic resistance due to the adjustment of the seismic zone after great quakes. Therefore, the purpose of this study is to investigate the feasibility and efficiency of the cable-stayed bridges retrofitted by using an isolation system through the case study of the Chi-Lu Bridge. The results with some suggestions are presented in this paper.

CHI-LU BRIDGE

The Chi-Lu Bridge is located in Nantou County of the central Taiwan. The bridge is a single pylon and one-plane cable-stayed bridge with span length of 120m on both sides of the central tower, as shown in Figure 1. The pylon was built in reinforced concrete and is 58m high above the deck with a tapered cross section from 6m by 3m to 4m by 3m at the top. The superstructure of the bridge is a two-cell prestressed cast-in-place concrete box girder, which is approximately 10.4m wide by 2.75m deep, with precast wing elements on both sides to make a total 24m wide bridge deck. Two rows of 17 stay cables extend from the pylon to the center of the bridge deck on each side of the central tower.

As the Chi-Chi earthquake hit the central Taiwan, the construction of the Chi-Lu Bridge was close to completion in spite of a small portion of deck slab near the pylon and final adjustment of the cable forces. The damages were concentrated in the connection region of the superstructure to the pylon. At the bottom of the pylon, there were large cracks and spalling of concrete. A vertical crack started from the spalling area and extended upwards. The superstructure was also severely damaged in which apparent concrete splitting and crashing could be observed at the rigid connection to the pylon. As for the cable system, one stay cable anchorage failed at the end to the deck. In addition, there were concrete cracking, crashing and spalling in the pier beam and bearing dislocation at the end span supports due to pounding.

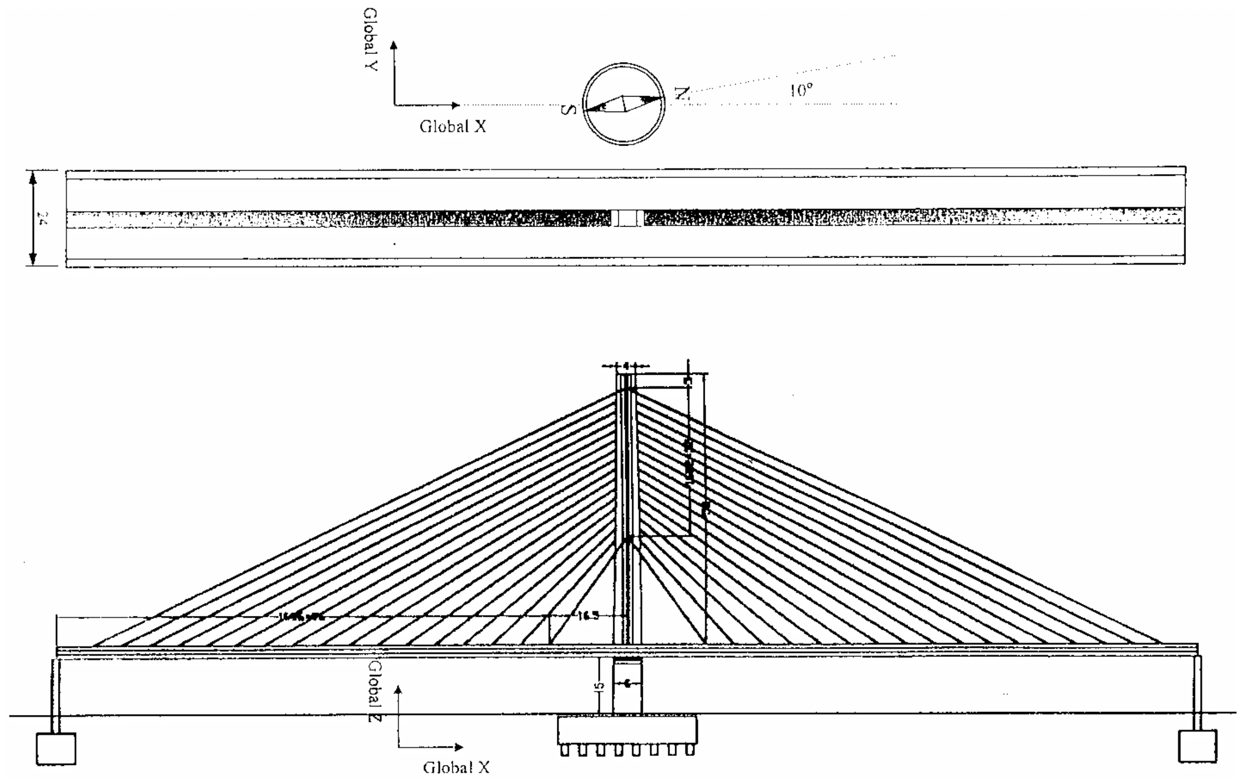

Figure 1 Chi-Lu Bridge

The Chi-Lu Bridge might be the first case of cable-stayed bridge experienced a large magnitude, near-fault earthquake. It provides an excellent chance to study the dynamic behavior of a cable-stayed bridge subjected to a great earthquake. Therefore, it would be very helpful to conduct an extensive study in depth how the bridge was destructed and how to retrofit the bridge in order to protect it from another strong quake in the future.

RETROFIT USING LEAD-RUBBER BEARINGS

The lead-rubber bearing (LRB) has been extensively used as a base isolation device, especially in bridge design or retrofit, in many countries around the world. It has the advantages of stable properties, little rate-dependence, and simple force-displacement hysteresis loop curves, which provides an economic solution to the problem of seismic isolated structures [9]. In practice, a bilinear model is often used for simulating the hysteresis behavior of the bearing and gives satisfactory results.

In this study, the lead-rubber bearing has been adopted as the isolation system for retrofitting simulation of the Chi-Lu Bridge. In order to investigate the influence of different allocation of isolation devices on the reduction of earthquake forces, case studies of two-point isolation at both end supports and three-point isolation at the connection of the superstructure to the pylon and end supports, as shown in Figure 2, have been conducted. The design of lead-rubber bearings are carried out following the procedure in Figure 3 and a pair of bearings are assumed to be installed at each isolation point. The static and dynamic characteristics of the lead-rubber bearing are also examined during the design process. After completing the design, the property of the lead-rubber bearing is incorporated into the structural analysis model of the Chi-Lu Bridge using a bilinear hysteresis model. A nonlinear dynamic analysis is then performed to evaluate the effect of the proposed isolation system on the structural response of the bridge subjected to strong ground motions.

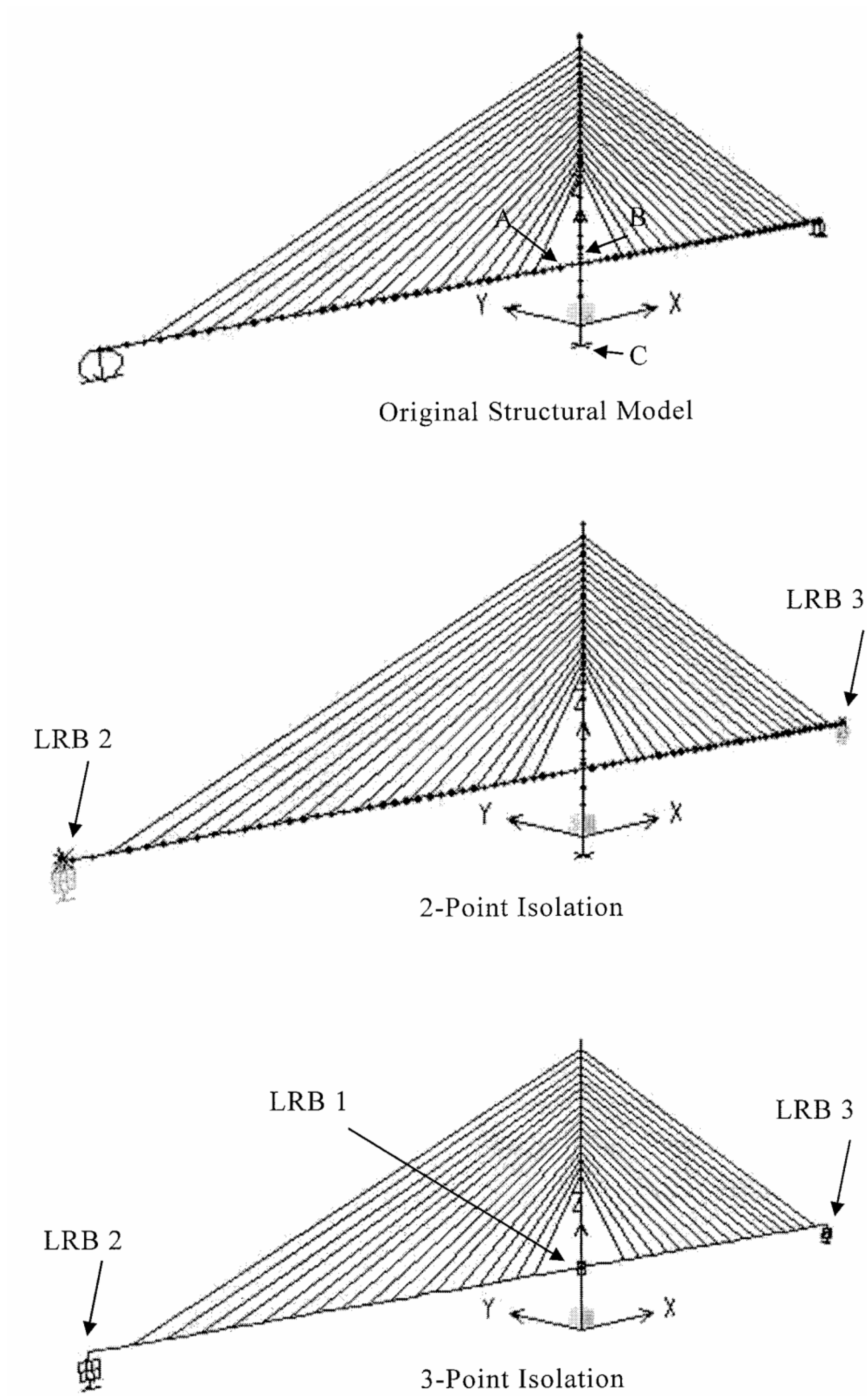

Figure 2 Case Studies of Isolation for the Chi-Lu Bridge

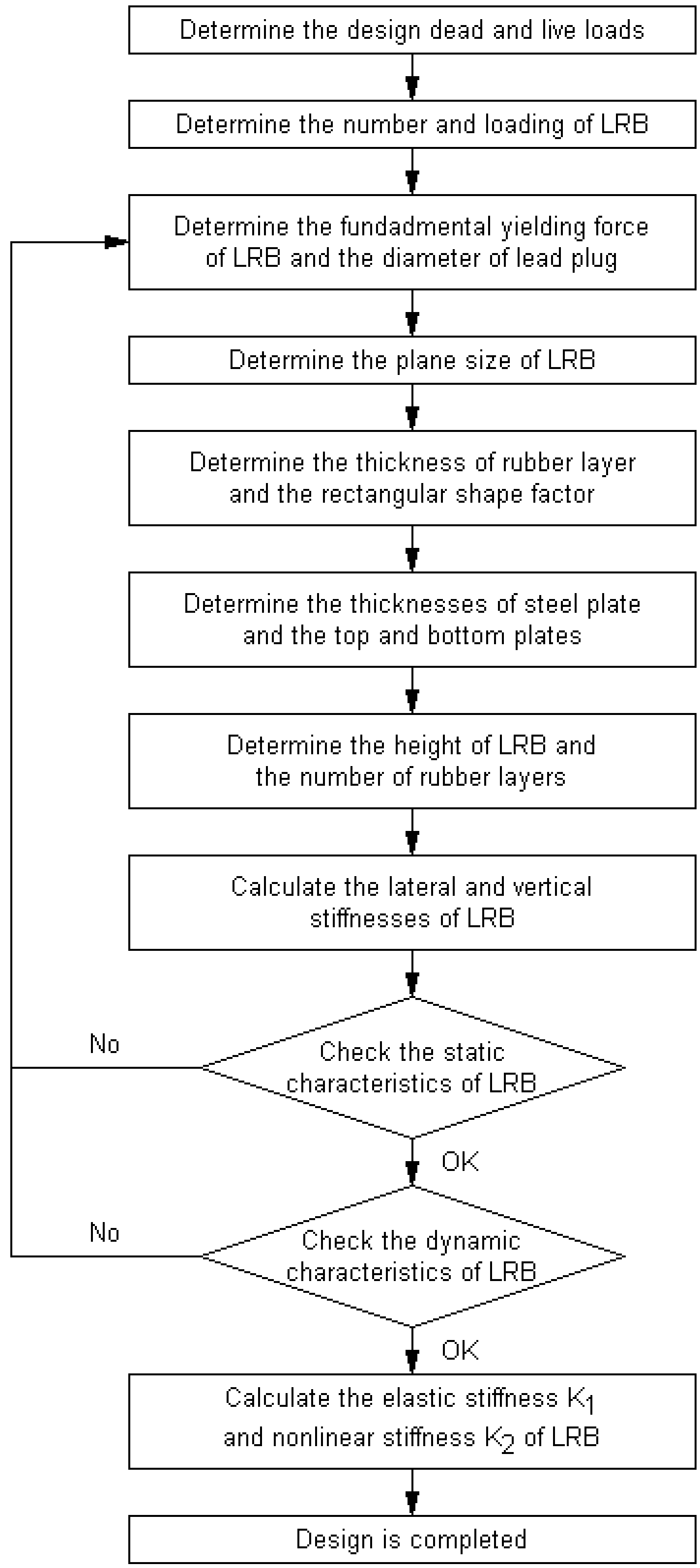

Figure 3 Flow Chart of the Lead-Rubber Bearing Design

STRUCTURAL MODELING AND DYNAMIC ANALYSIS

In order to study the feasibility and efficiency for the cable-stayed bridges retrofitted by using isolation system, this study has conducted a series of numerical experiments employing the nonlinear version of the SAP2000 structural analysis program [10]. At first, structural analysis is performed to evaluate the dynamic behavior of the Chi-Lu Bridge subjected to strong ground motions. The isolated structure with the lead-rubber bearings is then analyzed to assess the variation of the structural response resulting from the base isolation. In the SAP2000 model of the Chi-Lu Bridge, the pylon, superstructure and stay cables are all modeled using the Frame element. The pin condition at the ends of cables is modeled using the end releases in SAP2000. The influence of geometric nonlinearity on the axial stiffness of the cable is taken into account with the use of the equivalent stiffness. In addition, roller in the longitudinal direction and hinge in the transverse direction are used to model the boundary conditions of the superstructure at the end supports. The connection of the superstructure to the pylon is modeled as a rigid joint and the foundation of the tower is assumed to be clamped. When adding the isolation bearing to the model, the installation point is cut apart and an Nllink element of SAP2000 is inserted to simulate the lead-rubber bearings and take the nonlinear behavior of the bearing into account.

For the purpose of evaluating the effect of the base isolation, structural modal analysis is first performed to realize how the vibration periods vary for the Chi-Lu Bridge with no isolation, two-point isolation, and three-point isolation. The nonlinear time-history analysis is then carried out to evaluate the structural response of the Chi-Lu Bridge subjected to strong ground motions. The algorithm built in the SAP2000 program for nonlinear time-history analysis is the Fast Nonlinear Analysis method developed by Wilson [11], in which only a limited number of elements, e.g. the Nllink element in this study, are treated nonlinearly. The strong ground motions used in this study was recorded during the Chi-Chi earthquake at the TCU084 station at Sun Moon Lake in Nantou County, which is about 15km far from the Chi-Lu Bridge and 13.8km from the epicenter. The peak ground accelerations in the global X, Y, and Z direction of the bridge are 497gal, 978gal and 312gal, respectively, as shown in Figure 4. It is noted that only the horizontal ground motions (records in the X and Y direction) are imposed for the time-history analysis in this study. Moreover, each case including the P-Delta effect has also been analyzed to account for the effect of a large axial load upon the transverse bending behavior of the Frame elements [10]. The results with and without considering the P-Delta effect are then compared to evaluate this effect on the structural analysis of cable-stayed bridges.

NUMERICAL RESULTS AND DISCUSSION

Table 1 lists the results of modal analysis of the Chi-Lu Bridge and the isolated structure with and without considering the P-Delta effect. The results show that the fourth mode (period = 0.71 seconds, participating mass ratio = 26.67%) is the primary vibration mode in the global X (longitudinal) direction of the Chi-Lu Bridge. In the global Y (transverse) direction, the dominant vibration mode is the sixth mode (period = 0.59 seconds, participating mass ratio = 58.15%). From the results, it can be found that the primary period (0.62 seconds) in the X direction of the bridge with two-point isolation is shorter than the original structure. This is due to that the Chi-Lu Bridge was not restrained longitudinally at the end supports but now the lead-rubber bearings offer some stiffness in the X direction. Comparatively, in the case of the isolated bridge with three-point isolation, the dominant modes in the X and Y direction move to the second and third vibration modes and the corresponding periods are lengthened to 1.67 seconds and 1.66 seconds, respectively. This result indicates that only the base isolation in the location of the superstructure connected to the pylon will change the dynamic behavior of the isolated bridge significantly. In addition, analysis shows that the periods are lengthened about 1% to 2% when considering the P-Delta effect, which demonstrates that the influence of the P-Delta effect is very small and can be ignored for the Chi-Lu Bridge.

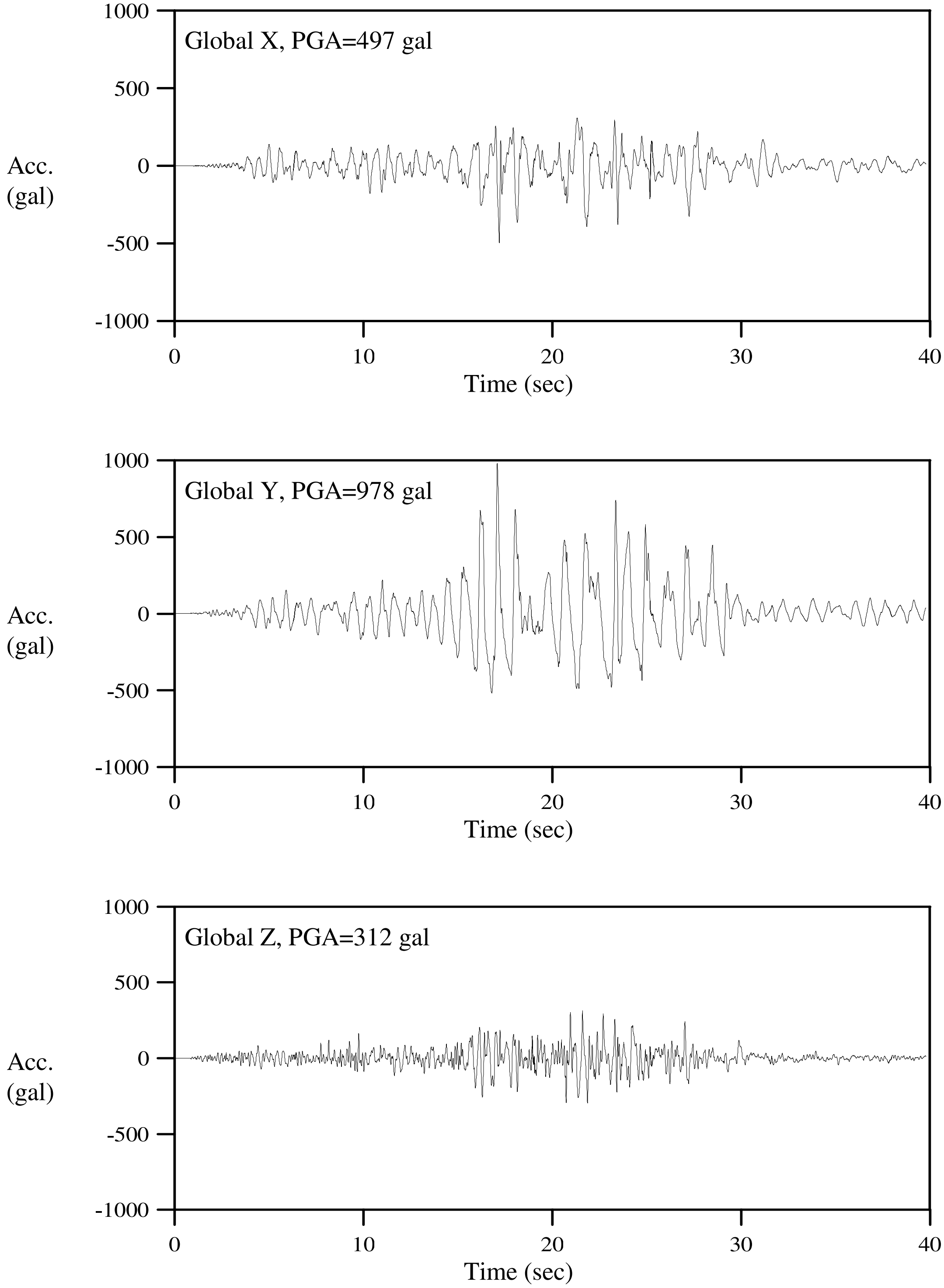

Figure 4 TCU084 Ground Accelerations of the Chi-Chi Earthquake

Table 1 Primary Vibration Modes in the Longitudinal and Transverse Direction of Bridge

	Vibration mode	Period (sec)	Participating mass ratio (%)		
			Global X	Global Y	Global Z
Original bridge	4	0.7103	26.67	0	0
	6	0.5855	0	58.15	0
Original bridge (with P-Δ effect)	4	0.7161	26.45	0	0
	6	0.5919	0	57.54	0
2-point isolation	6	0.6178	42.46	0	0.0005
	5	0.9417	0	69.81	0
2-point isolation (with P-Δ effect)	6	0.6218	42.05	0	0.0005
	5	0.9418	0	69.26	0
3-point isolation	2	1.6749	89.74	0	0.0001
	3	1.6553	0	78.82	0
3-point isolation (with P-Δ effect)	2	1.6762	89.14	0	0.0001
	3	1.6669	0	80.41	0

The results of the nonlinear time-history analysis of the Chi-Lu Bridge subjected to the horizontal components of the TCU084 ground accelerations are summarized in Table 2, 3 and 4. Only the maximum displacements and member forces at the point A, B and C shown in Figure 2 are listed. The point A is located in the superstructure near the pylon and the point B is at the bottom of the pylon. Severe damages have been observed at these two locations after the Chi-Chi earthquake. The point C is at the foundation of the tower for examining the variation of the base shear before and after the isolation. From the results, it can be readily seen that the bridge with isolation experiences larger displacements but smaller member forces than the original bridge, as expected for the isolated structure. In the case of three-point isolation, the maximum displacement in the Y direction is about two times of that in the X direction at the point A and B, which is almost the same as the ratio of the peak ground acceleration of the Y direction to the X direction.

Regarding the member forces, the lateral forces at the point A, B and C tend to rise in the case of two-point isolation. This should result from the force redistribution and the pier below the pylon is taking part of the lateral load that was originally carried by the pot bearings at the end supports. Relatively, three-point isolation gives excellent performance in reducing the maximum member forces of the bridge. At the point C, the shear force is down from 10576 tons to 504 tons in the X direction and from 10138 tons to 4403 tons with adding the three-point isolation, apparently a big reduction than the original structure.

That the three-point isolation gives rise to a much better performance than the two-point isolation comes from having all of the supports replaced by base isolation devices. In addition, the Chi-Lu Bridge is designed to let the pier under the pylon carry most weight of the superstructure. And the isolator design process adopted in this study is started from the vertical load taken by the designated support. Therefore the three-point isolation yields a much better result than the two-point isolation due to the coincidence with the characteristics of the structural system.

Table 2 Maximum Displacements and Member Forces at the Point A

	Maximum displacements (cm or rad) - Global coord.					
	UX	UY	UZ	RX	RY	RZ
Original bridge	-5.2366	15.9177	-1.0834	-0.0155	-3.60E-03	-8.05E-06
Original bridge*	-5.2678	-16.8524	-1.0974	-0.0151	-3.65E-03	-8.75E-06
2-point isolation	-4.7242	15.3999	-0.8952	-0.0142	-2.99E-03	-2.84E-05
2-point isolation*	-4.7568	15.4484	-0.8960	0.0153	-2.97E-03	-2.63E-05
3-point isolation	20.6462	-46.2607	0.1000	0.0095	3.33E-04	5.48E-06
3-point isolation*	19.9239	-50.2100	0.0977	0.0089	3.25E-04	6.26E-06
	Maximum member forces (ton or ton-cm) - Local coord.					
	P	V2	V3	T	M2	M3
Original bridge	-5158	515	-4383	-605463	7413121	-1098475
Original bridge*	-5162	518	-4346	-588137	-8018925	-1083978
2-point isolation	5133	-608	5187	-553729	24223698	-1216933
2-point isolation*	5266	-618	5357	-543411	26975526	-1438820
3-point isolation	-2541	-956	3165	340201	-5413077	-605723
3-point isolation*	-2443	-881	-5422	-349333	-5806503	-552309

*The case with the P-Delta effect.

Table 3 Maximum Displacements and Member Forces at the Point B

	Maximum displacements (cm or rad) - Global coord.					
	UX	UY	UZ	RX	RY	RZ
Original bridge	-5.7272	18.2394	-0.0025	-0.0174	-0.0034	0
Original bridge*	-5.7646	18.4687	-0.0025	-0.0171	-0.0034	0
2-point isolation	-5.1186	17.4642	-0.0034	-0.0173	-0.0027	0
2-point isolation*	-5.1079	17.4542	-0.0034	-0.0192	-0.0028	0
3-point isolation	20.6878	-46.9567	0.0003	0.0098	0.0003	0
3-point isolation*	19.9645	-50.3628	0.0004	0.0091	0.0003	0
	Maximum member forces (ton or ton-cm) - Local coord.					
	P	V2	V3	T	M2	M3
Original bridge	-75	-699	2980	4	5874225	-2197940
Original bridge*	-76	714	3249	5	-6017044	-2207502
2-point isolation	-109	617	3242	5	9371983	1986534
2-point isolation*	-111	600	3453	5	9526836	2015648
3-point isolation	5	156	-209	1	834963	-142913
3-point isolation*	-4	130	-238	1	-828889	-128521

*The case with the P-Delta effect.

Table 4 Maximum Displacements and Member Forces at the Point C

	Maximum displacements (cm or rad) - Global coord.					
	UX	UY	UZ	RX	RY	RZ
Original bridge	0	0	0	0	0	0
Original bridge*	0	0	0	0	0	0
2-point isolation	0	0	0	0	0	0
2-point isolation*	0	0	0	0	0	0
3-point isolation	0	0	0	0	0	0
3-point isolation*	0	0	0	0	0	0
	Maximum member forces (ton or ton-cm) - Local coord.					
	P	V2	V3	T	M2	M3
Original bridge	-100	10576	-10138	5	14465836	-14186655
Original bridge*	-101	10593	-10632	-21	13530883	-14232225
2-point isolation	-133	-10522	10417	132	11635675	-9092649
2-point isolation*	-138	-10394	10071	184	15074656	-13222675
3-point isolation	9	-504	4403	-172	-1344618	973450
3-point isolation*	10	-581	4853	-198	1429316	911474

*The case with the P-Delta effect.

In addition, when taking the P-Delta effect into account, analysis shows that the maximum displacements and member forces in the X and Y direction have increased about 3% averagely. The results vary with the location of the structural members. The variation at the point A of the superstructure is very small. The point B and C located at the bottom of the pylon and the tower foundation, relatively, have a bigger change than the point A. This implies that the P-Delta effect is more significant to the pylon than superstructure for a cable-stayed bridge. However, this study demonstrates that the overall influence of the P-Delta effect on the structural analysis is little and can be ignored for the Chi-Lu Bridge.

CONCLUSIONS

A case study of the Chi-Lu Bridge retrofitted by using the lead-rubber bearing has been conducted to investigate the feasibility and efficiency of isolation systems for retrofitting cable-stayed bridges. Nonlinear time-history analysis is carried out to evaluate the performance of the isolated structure employing the SAP2000 structural analysis program. The results of numerical experiments show that the member forces are reduced significantly when all of the bridge supports are replaced by the lead-rubber bearings. This demonstrates that the base isolation is an effective strategy to the retrofit of the cable-stayed bridge in case that the earthquake effect becomes a decisive factor to the structural safety. In addition, the influence of the P-Delta effect on the structural analysis of cable-stayed bridges has also been studied. The results show that the influence is little and can be ignored for middle-span cable-stayed bridges such as the Chi-Lu Bridge. However, it might be not the case and the P-Delta effect needs to be taken into account for the structural analysis of a long-span cable-stayed bridge.

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