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SHAKE TABLE TEST OF A CABLE RESTRAINER FOR CONTINUOUS GIRDER BRIDGES

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Abstract
Damage investigations revealed that girder bridges could experience girder unseating and span collapse during the past earthquakes. Cable restrainer is one of the most widely used devices to restrain the excessive displacement responses of bridges. In order to investigate the seismic performance of a new cable restrainer named Coiled Cable Restrainer (CCR), a shake table test of a 1/15 scaled two span continous girder bridge model was conducted. The bridge model was supported by unbonded laminated rubber bearings and tested under incrementally increasing input excitation. The efficacy of the new restrainer in reducing the girder displacement as well as the relative displacement between girder and pier was evaluated. The influence of the restrainer on the seismic behavior of the unbonded laminated rubber bearings was also examined. The experimental results indicated that the CCR was capable of reducing the girder-pier relative displacement and eliminating the residual displacement. Besides, sliding of the unbonded laminated rubber bearings could be effectively restrained by CCR as well. Meanwhile strain at the pier bottom could increse during restraining, which would lead to enlarged seismic force and moment of the pier. If the restrainer is designed properly, the restrained bridge can make full use of the pier strength.

Keywords: Earthquake, Continuous Girder Bridges, Coiled Cable Restrainer, Shake Table Test, Seismic Performance

1. Introduction

Unbonded laminated rubber bearings are widely used on small-medium span girder bridges in China [1,2]. One of the main expectations from the bearing is to allow horizontal movements with a minimal resistance [3]. However, the past earthquakes have caused sliding between the bearing and the girder, and even span collapse. Therefore, it is necessary to restrain the excessive displacement response of the bridge during earthquakes.

Cable restrainers are the least expensive and the most widely adopted retrofit strategy to prevent unseating failure of bridge decks [4]. Many researches have been carried out to provide appropriate design procedure for restrainers and to understand the influencing factors on the behavior of restrainers through parametric studies [5]. Saiidi et al. [6] summarized the performance of restrainers in 1989 Loma Prieta earthquake and the important aspects of restrainer design for bridges. Saber M. Abdel-Ghaffar et al. [7] studied the effects of the cable restrainers on the Aptos Creek Bridge and found that they contributed significantly to the reduction of displacement and force responses at higher acceleration levels. Saiidi et al. [8] developed three new restrainer design methods and their adequacies were assessed using numerical analysis. Furthermore, test studies of cable restrainers were also conducted to examine the effects of restrainers on the relative hinge opening [9,10] and evaluate the failure mode of restrainers [11].

Recently, Gu et al. [12] proposed a new cable restrainer named Coiled Cable Restrainer (CCR), which can restrain the longitudinal displacement in both forward-direction and backward-direction, and implemented a pseudo static test to investigate its performance. The CCR showed an obvious bidirectional restraining capacity through pseudo static test. However, the influence of this device on the seismic performance of bridges was not investigated yet.

The main objective of this paper is to investigate the influence of CCR on the seismic performance of a girder bridge supported by unbonded laminated rubber bearings. In this study, a shake table test of a scaled continuous girder bridge model is described. Test results including the displacement, pier strain and acceleration responses of the bridge model are presented and discussed. Finally, several conclusions are drawn.

2. Coiled Cable Restrainer

The Coiled Cable Restrainer (CCR) is a new superstructure restraining device. As shown in Figure 1, the CCR is comprised of an upper plate, a base plate, a long cable and cable clamps. The upper and base plate are connected to the superstructure and substructure, respectively. The cable is coiled several loops between the plates and then fixed with the cable clamps.

Figure 2 presents the constitutive relation of the CCR. K is the lateral stiffness and u_0 is the lateral restraining displacement, which is designed to allow the girder movement under operational conditions. Hence, the restrainer mainly consists of two operation stages. In the first stage, the relative displacement between the two plates is within u_0 and the cable remains loose. In the second stage, the relative displacement surpasses u0, and the restrainer triggered to restrain the further movement of the superstructure. Detailed design method of CCR could be found in Gu et al. [12].

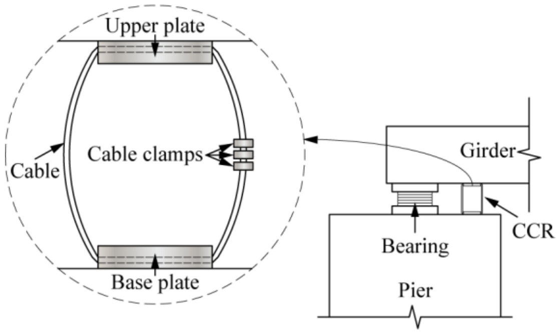


Figure 1 – Configuration of CCR

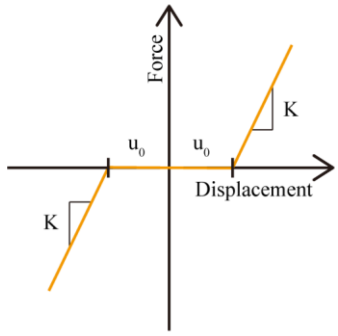


Figure 2 – The constitutive relation of CCR

3. Test setups

The design of the test model was based on data obtained from a two-span continuous girder bridge as shown in Figure 3. The method for scaling the model was based on dimensional analysis. The acceleration scale factor Sa was designed to be 1.0. The dimension of the shake table is 4 m × 4 m so the length scale factor S_L of the test model was selected to be 1/15. Yet, to build the small-size bridge with concrete materials was challenged. Therefore, steel was selected to construct the test model and the elastic modulus scale factor S_E was claculated t be 6.78. However, based on the classic similitude law for dynamic equations $S_m=S_ES_L^2/S_a$, the mass of the model could exceed the capacity of the shake table. To deal with this problem, the similitude law was transformed to be $S_m=S_kS_L/S_a$. The three key scale factors are determined to be 1/125 (mass scale factor, S_m), 1/15 (stiffness scale factor, S_k) and 1.0 (acceleration scale factor, S_a). Table 1 summarizes the dimensional similitude requirments for the representative physical quantities for the test. More details about the design of the test model refer to Li et al. [13].

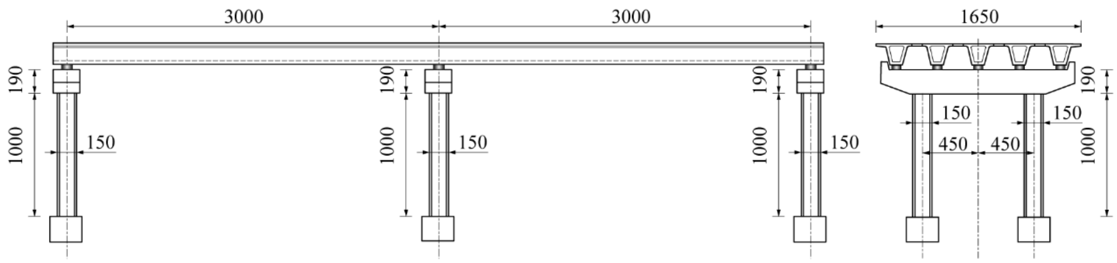


Figure 3 – Prototype bridge of the shake table test (unit: cm)

Table 1 – Some main scale factors

Parameter	Dimension	Equation	Scale factor
Stiffness, k	N/m	S_k	0.0667
Acceleration, a	m/s^2	S_a	1
Mass, m	kg	S_m	0.0044
Length, l	m	$S_l=S_mS_a/S_k$	0.067
Elastic modulus, E	N/m^2	$S_E=S_k^2/(S_mS_a)$	1
Area, S	m^2	$S_S=(S_mS_a/S_k)^2$	0.0044
Force, F	N	$S_F=S_mS_a$	0.0044
Time, t	s	$S_t=(S_m/S_k)^{0.5}$	0.258
Stress, σ	N/m^2	$S_\sigma= S_k^2/(S_mS_a)$	1

Figure 4 depicts the layout of the bridge model for the shake table test. The piers were mounted on the shake table and the girder was supported by scaled unbonded laminated rubber bearings. The scaled bearings were designed with a plan dimension of 60 mm × 60 mm and a total height of 25 mm (shown in Figure 5). The lateral stiffness of one bearing is equal to be about 211.8 kN/m.

The dimension of CCR is illustrated in Figure 6. The steel upper and base plates of the CCR were made dumbbell-shaped so that the cable was much easier to be coiled between them. The cable was made of steel wire rope and the diameter was 4 mm. The lateral restraining displacement was designed to be 30 mm, and the lateral stiffness of the restrainer was about 6621 kN/m, which was determined through the previous pseudo static test. [12]

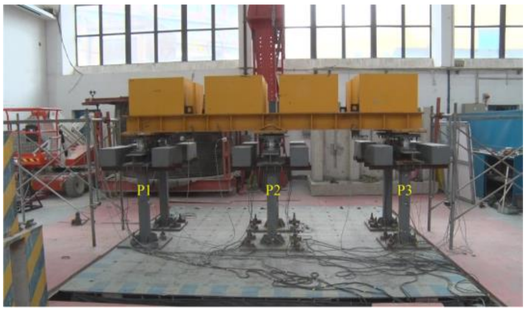


Figure 4 – Layout of the bridge model

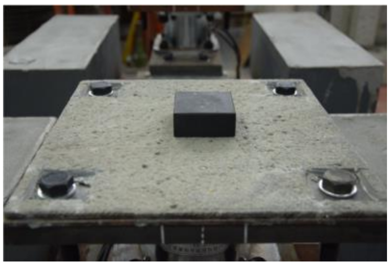


Figure 5 – Unbonded laminated rubber bearing

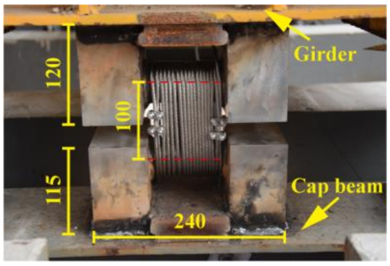
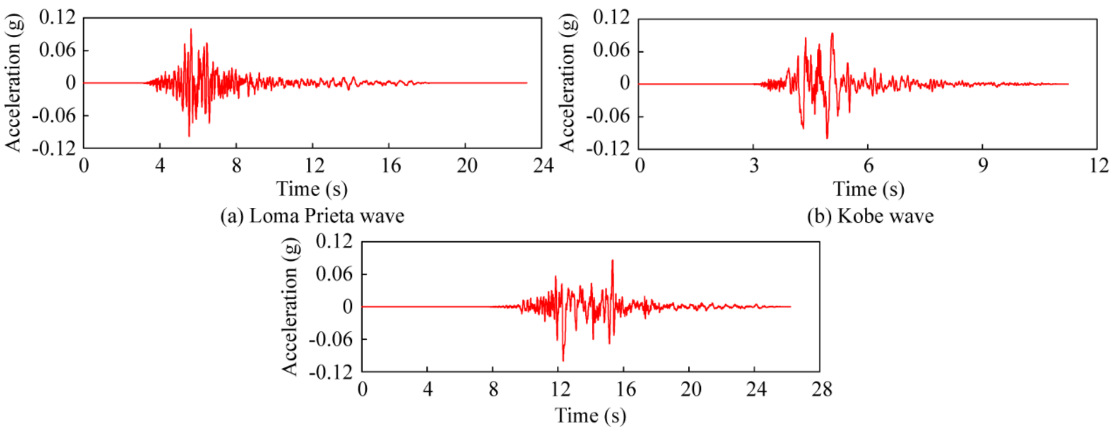


Figure 6 – Dimension of CCR (unit: mm)

The test focused on the seismic behavior of the girder, bearings and piers. Eight pull rope displacement sensors were used to measure the absolute girder and pier top displacement and the girder-pier relative displacement. Nine accelerometers were used to capture the accelerations of the girder and piers. Twelve strain gauges were used on the piers to measure the local strains. Six three-dimensional force sensors were installed on the piers to determine the bearing forces.

Three recorded earthquake motions were considered as input records, including the 1989 Loma Prieta earthquake (Foster City/90), the 1995 Kobe earthquake (Kobe University), and the 1999 ChiChi earthquake (TCU102). The input motions were all scaled to 0.1 g at first and then applied to the model with various PGA. The time-history curves of the three scaled ground motions with the PGA of 0.1 g are shown in Figure 7. Detailed loading protocols are listed in Table 2.



(c) ChiChi wave

Figure 7 – Input ground motion records

Two configurations of the model were investigated. In model A, the girder was only isolated by the bearings. In model B, the CCR was installed on the cap beams of side piers. Model A was constructed and tested first. After that, restrainers were assembled and thus Model A converted to Model B. Then, Model B was tested.

Table 2 – Loading protocols

Input motion	**Loma Prieta**					**Kobe**			**ChiChi**			
PGA/g	0.2	0.4	0.6	0.8	1.0	0.2	0.4	0.6	0.1	0.2	0.3	0.4

4. Test results

The maximum and residual recorded girder displacement as well as girder-pier relative displacement are presented in this section. Note that only the responses of the pier P2 and P3 (Figure 4) are listed since the bridge model is symmetrical.

Table 3 indicates that, in general, the girder and girder-pier relative displacement of the two models are similar under mild excitations as the maximum girder-pier relative displacement in these tests are all within the lateral restraining displacement of the restrainer. Under stronger excitations, however, both of the maximum and the residual displacement responses in Model B shows an obvious reduction comparing with those of Model A. In PGA = 1.0 g test, the maximum girder displacement decreases by 13% and the maximum girder-pier relative displacement decreases by more than 40%.

Table 3 – Displacement responses of the test model under Loma Prieta wave

PGA	**Model**	**Position**					
		Girder displacement/mm		**Girder-pier relative displacement (P2)/mm**		**Girder-pier relative displacement (P3)/mm**	
		maximum	residual	maximum	residual	maximum	residual
0.2 g	**A**	16.6	0.3	9.0	0.2	9.2	0.1
	B	16.6	0.2	9.6	0.2	0.7	0.2
0.4 g	**A**	31.0	0.4	16.0	0.2	16.2	0.3
	B	33.8	0.2	18.6	0.2	18.3	0.3
0.6 g	**A**	43.6	0.4	24.6	0.5	24.2	0.6
	B	47.7	0.4	25.7	0.4	24.2	0.2
0.8 g	**A**	51.7	4.4	33.8	5.2	34.6	5.6
	B	58.2	0.3	30.7	0.3	27.7	0.2
1.0 g	**A**	80.5	36.0	64.4	36.5	65.1	36.9
	B	69.8	0.5	35.8	0.3	31.4	0.2

Figure 8 presents the time-history curves of the displacement responses of the two models in PGA = 1.0 g Loma Prieta test. The pier top displacement of the restrained model was almost identical to that of the unrestrained model. Conversely, the girder displacement was significantly restrained by the CCR. In Model A, the girder began to slide at about 7.5 s, but it did not occur in Model B. Therefore, it can be concluded that the CCR performed well in restraining the girder from further movement so that girder unseating could be prevented.

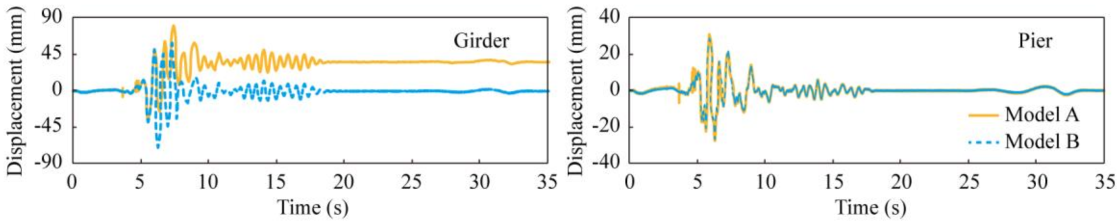


Figure 8 – Time-history curves of the displacement responses under Loma Prieta wave, PGA=1.0g

In Table 4, it can be seen that the acceleration and pier bottom strain in cases with CCR are generally higher in PGA = 0.8 g and PGA = 1.0 g Loma Prieta test. While the restrainer restraining the girder, the cable became tightened and provided a restore force to the girder, resulting in the increase of the inertia force of girder. Also, such a restore force can convert to the pier, which led to the larger pier bottom strain. Noticed that the acceleration and pier bottom strain had a slight increase in PGA = 0.6 g test, which shall not occur as the CCR was not supposed to work in that case. It is possible that such an early-restraining phenomenon comes from the assemble error while coiling the cable. In the design concept, the lateral restraining displacement of each cable loop should be the same as 30 mm. However, some loops actually may have a smaller lateral restraining displacement so that the restrainer would provide a small lateral stiffness before the relative displacement went to 30 mm.

Table 4 – Acceleration responses of the test model under Loma Prieta wave

PGA	**Model**	**Position**		
		Girder acceleration/g	**P2 bottom strain/με**	**P3 bottom strain/με**
0.2 g	**A**	0.16	195	208
	B	0.15	164	189
0.4 g	**A**	0.27	337	377
	B	0.32	317	398
0.6 g	**A**	0.40	501	520
	B	0.49	468	665
0.8 g	**A**	0.44	670	587
	B	0.69	580	896
1.0 g	**A**	0.42	608	598
	B	0.98	761	1326

As shown in Table 4, the girder acceleration of Model A under Loma Prieta wave remained as about 0.4 g from PGA = 0.6 g to 1.0 g, which means that the unbonded bearings might have already slid. The hysteresis curves of the bearing on P3 are presented in Figure 9. It can be seen that the bearing slightly slid in Model A under the excitation of PGA = 0.6 g and 0.8 g, and had an obvious slide in PGA=1.0 g. By contrast, the bearing in Model B did not slide during the test. Hence, it verifies that the CCR is capable of restricting the sliding of the unbonded laminated rubber bearings.

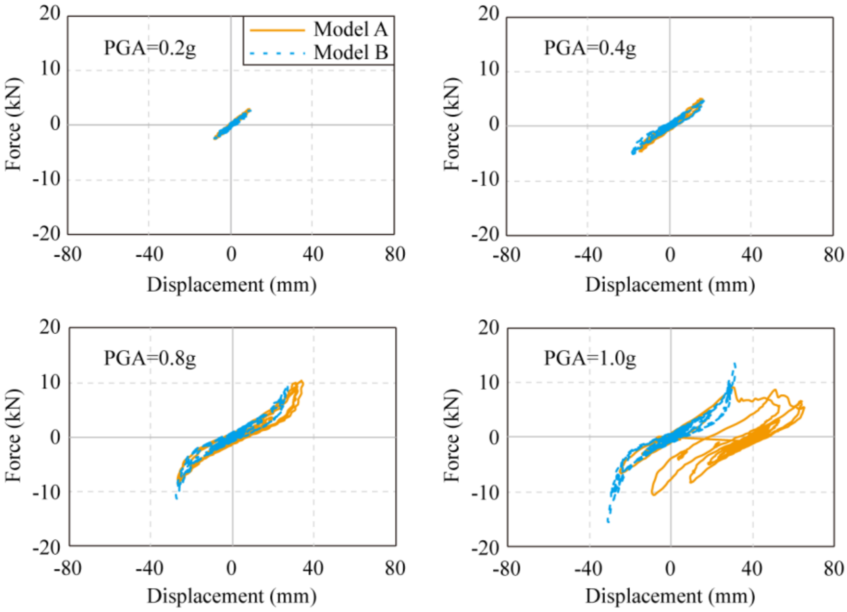


Figure 9 – Hysteresis curves of the unbonded laminated rubber bearings in Loma Prieta test

Trends are similar under each input motion. Table 5 and Table 6 list the responses under Kobe PGA = 0.6 g test and ChiChi PGA = 0.4 g tests, respectively. Unlike the results in the Loma Prieta tests, the data shows that the maximum girder displacement under these excitations was not effectively restrained in Model B though the residual displacement could be obviously reduced. Meanwhile the pier bottom strain had a more drastic increase, especially in Kobe PGA = 0.6 g test. This difference in restraining effect may attribute to the seismic characteristics of the ground motion and the dynamic characteristics of the bridge model. However, although the restraining effect of the CCR under these two pulse-like ground motions (Kobe and ChiChi) was not as obvious as that under the far-field one (Loma Prieta), it still showed satisfactory restraining and self-centering capacity.

Table 5 – Seismic responses of the test model under Kobe wave, PGA = 0.6 g

Response		**Model**	
		A	**B**
Girder displacement/mm	Maximum	33.1	50.3
	Residual	7.0	1.8
Girder-pier relative displacement at P2/mm	Maximum	35.5	38.4
	Residual	6.8	1.4
Girder-pier relative displacement at P3/mm	Maximum	39.6	31.9
	Residual	7.3	0.5
Girder acceleration/g		0.48	1.20
P2 bottom strain/με		584	1027
P3 bottom strain/με		526	1636

Table 6 – Seismic responses of the test model under ChiChi wave, PGA = 0.4 g

Response		**Model**	
		A	**B**
Girder displacement/mm	Maximum	95.2	95.0
	Residual	9.7	0.2
Girder-pier relative displacement at P2/mm	Maximum	40.7	34.6
	Residual	9.1	0.1
Girder-pier relative	Maximum	42.4	29.5

displacement at P3/mm	Residual	9.5	0.1
Girder acceleration/g		0.39	0.87
P2 bottom strain/με		534	635
P3 bottom strain/με		494	1284

Figure 10 shows the maximum P3 bottom strain under different excitations. The yield strain of the pier is about 1960 με. In Model A, while the bridge model was only isolated by unbonded laminated rubber bearings, the maximum pier bottom strain was much less than the yield strain of the pier. In Model B, even though the pier bottom strain experienced an obvious increase, the pier still remained elastic. Therefore, it can be inferred that the isolated bridge retrofitted with CCR can avoid pier damages if the restrainer is properly designed. In other words, the restrained bridge can make full use of the strength of pier while restraining.

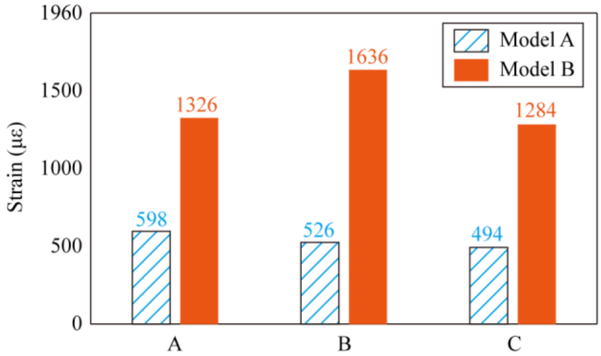


Figure 10 – Maximum P3 bottom strain (A: Loma Prieta, PGA= 1.0 g test; B: Kobe, PGA = 0.6 g test; C: ChiChi, PGA = 0.4 g test)

5. Conclusions

This study focuses on the influence of a new cable restrainer, named Coiled Cable Restrainer, on the seismic behavior of a girder bridge. A shake table test of a 1/15 scaled girder bridge supported by unbonded laminated rubber bearings is introduced. Seismic responses of the tested model are presented and analyzed.

According to the experimental study, some conclusions can be drawn as follow:

(1) The CCR performs well in restraining the girder-pier relative displacement as well as reducing the residual displacement under strong earthquakes.

(2) Sliding of the unbonded laminated bearing can be effectively restrained by the restrainer, which indicates that the CCR is capable of preventing the bridge from unseating.

(3) The isolated bridge retrofitted with CCR can make full use of the pier strength while restraining if the restrainer is designed properly.

(4) The restraining effect of CCR shows sensitivity to the seismic characteristics of the ground motion. Based on the test results, the CCR performs better under far-field ground motion.

6. Acknowledgements

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7. Copyrights

8. References

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