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Seismic Performance of Continuous Girder Bridges Using Cable-sliding Friction Aseismic Bearing

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Abstract

This paper reports on the study of the performance of a new seismic control device named as cable-sliding friction aseismic bearing (CSFAB), which combines a conventional aseismic bearing with restrainer cables to dissipate earthquake energy and at the same time to control the displacement of girder to an acceptable value. A two-dimensional long-span continuous girder bridge model was developed and analyzed in the study. Considering the influence of different site conditions, the model was subjected to three historic ground motion records applied to different (A,B,C,D) site conditions specified in the USGS site classification. Compared with conventional aseismic bearing, the effectiveness of the CSFAB in controlling the girder displacement and limiting the shear force and bending moment demands on the bridge piers was assessed. Furthermore, study considering different fixed pier heights was conducted and the results showed that with the decrease of height or increase in stiffness of piers, CSFAB was to be more effective.

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Keywords: cable-sliding friction aseismic bearing; continuous girder bridge; seismic isolation; hysteresis curve; restoring force model.

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1. INTRODUCTION

Continuous girder bridges which are well-known for their versatility in meeting different requirements such as long span but practically shallow depth, and varying forms, constitute a major part of country's highway and railway systems. A large number of studies aimed at studying the dynamic behavior of continuous girder bridges under extreme dynamic loads such as earthquakes have revealed their vulnerability to collapse due to a chain of element failures. These studies have shown that although restraining the bridge girder completely at the pier locations could limit the girder displacement, it would cause a significant increase in the demands on the piers in terms of bending moments and shear forces. Therefore, many researchers have suggested that the main girder should not be fixed to the piers, but instead be allowed to experience some relative movement at these locations, which would lead to a reduction in the overall forces transmitted from the girder to the piers (Sharabash and Andrawes 2009).
In order for this design approach to be implemented successfully, the use of restrainer cables and restrainer bars located between the girder and piers of bridges become popular following the collapse of several bridges in recent earthquakes (DesRoches and Delemont 2002), but these devices inevitably need additional design of girder and piers, increasing construction cost. Meanwhile, in the last two decades a large number of studies have focused on developing effective and reliable dynamic control devices for continuous girder bridges. The most basic device that has been studied extensively is laminated rubber bearing, which would respond linearly under seismic horizontal forces (Priestley et al 1996; Yang et al. 2008). Although this class of devices is simple and cost-effective, it has a poor stability and is only used in small bridges. Another type of device that has been studied and used in the past is metallic damper (Sharabash and Andrawes 2009) which provides energy dissipation through plastic deformation, but needs to be replaced after a severe earthquake, resulting in high cost repair. Among those aseismic devices that have been either studied or applied in more recent years are lead rubber bearings whose hysteresis curves show bilinear characteristics and extensive energy dissipation, but with the increase of the lead material, the self-recovery capability of rubber bearing deteriorates gradually (Priestley et al 1996; Ye 2002). The previous studies illustrate that there is still a need for further improvement in the field of dynamic control of bridges. This study presents a new class of bearing named as cable-sliding friction aseismic bearing (CSFAB) that could overcome many of the shortcomings previously discussed, and its unique characteristics are presented in the following sections.

2. OVERVIEW OF CSFAB

CSFAB is the combination of ordinary aseismic bearing and restrainer cables, and thus can be categorized according to the types of aseismic bearing and cable materials it adopts, such as the combination of spherial steel bearing and high strength steel tendon or carbon fiber. CSFAB studied in this article is the combination of pot rubber bearing and strands. The configuration of a fixed bearing is shown in Fig.1.
While setting on the fixed pier of a continuous bridge, CSFAB ensures the bearing keep fixed in normal conditions by the effect of shear bolt and the horizontal loads are mainly transmitted to the fixed pier. In extreme loading conditions such as a severe earthquake, ship-impact, or explosion, etc. the shear bolt is sheared off as the horizontal loads exceed a certain value. As a result, the bearing is changed into a sliding one, which alters the characteristics of load transfer mechanism of the system and distributes the horizontal loads to all piers. Compared with normal conditions, girder displacement in this case inevitably becomes larger, but the cables of the bearing begin to work as a buffer and displacement-restrainer which can limit the excessive displacement.

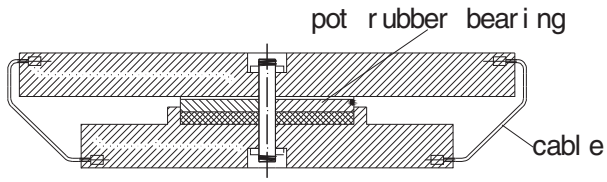

Fig.1 Configuration of fixed CSFAB

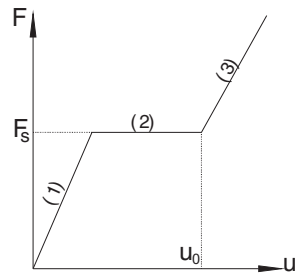

Fig.2 Restoring force model

An important task of this study is to design the CSFAB to limit the excessive displacement. An ideal restoring model developed in this article can be divided into three phases, as shown in Fig.2: (1) energy dissipation phase; (2) transformation phase which is characterized by a very low modulus and thus resembles yielding in materials with typical plastic behavior;(3) displacement-limiting phase, in which cables provide a large longitudinal stiffness to limit the excessive relative displacement between the superstructure and the substructure. F_s and u_0 are defined as the critical friction force and displacement respectively, and cables work only when the relative displacement between the girder and piers exceeds u_0. Using the restoring force model, a former study has shown that it is feasible to simulate CSFAB behavior using finite element modeling (Cao 2009).

3. CASE STUDY

Excessive relative displacement of multi-span continuous girder bridges between upper girder and lower piers can result in collapse of the bridge in a chain. However, CSFAB can be designed to provide sufficient stiffness to limit the relative displacement below a pre-determined value, and thus serve as a more effective alternative to conventional aseismic bearings. A multi-span continuous bridge considered in this paper consists of four spans (55m+2×85m+78m) and is based on the north approach bridge of Jiubao Bridge in Hangzhou city. The upper composite box girder is supported on the top of single box piers, and section properties are listed in Table 1. The piers are fixed at the bottom as the effect of soil-structure interaction is ignored. The calculation model of whole bridge is shown in Fig.3.

Table 1 Section properties

	Area(m^2)	Moment of inertial(m^4)
Girder	2.054	120.70
Pier	15.91	179.43

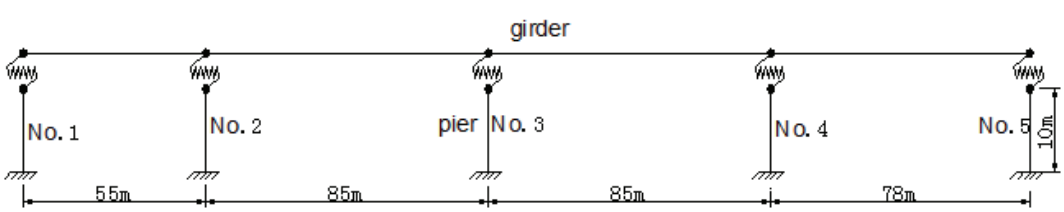

Fig.3 Calculation model of case study

A 2-D finite element model of the reference bridge is developed and analyzed using SAP2000 finite element software program. In order to define the retrofit effectiveness of CSFAB, the following two cases are considered:

① A fixed pot rubber bearing is set at the top of No.3 pier (fixed pier), and sliding ones are set at the top of other piers (sliding piers).

② A fixed CSFAB is set at the top of No.3 pier, and sliding ones are set at the top of other piers. However, as designed, the shear bolt of fixed CSFAB will be sheared off in a severe earthquake, thus changing the fixed bearing into a sliding one.

In finite element models, pot rubber bearings and elastic cables are simulated using wen-plastic link element and multilinear elastic link element respectively (Yan et al. 2009). Critical displacement u_0 is 6cm, friction coefficient adopted is 2%, and cable stiffness is 1.0×10^6kN/m.

3.1 Influence of site condition

To evaluate the effectiveness of CSFAB on different site conditions, the bridge is subjected to three earthquake ground motion records applied to different A,B,C,D site condition specified in USGS site classification, as shown in Table 2. In this paper, acceleration peaks are adjusted to 0.4g uniformly. The input earthquake waves in horizontal and vertical directions which can be achieved by multiplying an adjustment coefficient to the corresponding horizontal seismic waves, and a damping ratio of 5% are adopted. The time history analysis results in the two cases are listed in Table 3 to Table 4 and Fig.4.

Table 2 Selected earthquake motion records

Site condition	No.	earthquake wave records	site	magnitude	PGA/g
A	1	1989 LOMA PRIETA	Gilroy Array 1#	7.1	0.209
	2	1999 CHI-CHI	HWA	7.3	0.107
	3	1992 LANDERS	Amboy	7.3	0.146
B	4	1979 IMPERIAL VALLEY	El Centro allay 4#	6.5	0.157
	5	1992 LANDERS	Coolwater	7.3	0.417
	6	1989 LOMA PRIETA	Anderson Dam	6.9	0.240
C	7	1999 CHI-CHI	CHY006	7.3	0.364
	8	1979 IMPERIAL VALLEY	El Centro allay 5#	6.5	0.537
	9	1992 LANDERS	YermoFire Station	7.3	0.152
D	10	1979 IMPERIAL VALLEY	Agrarias	6.5	0.221
	11	1999 CHI-CHI	CHY039	7.3	0.114
	12	1989 LOMA PRIETA	Redwood City	6.9	0.083

From Table 3, it can be concluded that the maximum displacements at the end of girder along the bridge in case② are larger than the ones in case①, because the shear bolt of fixed bearing in case② will be broken in a severe earthquake, making the longitudinal constraint of girder weaker than that of case①. However, the maximum displacements at the top of piers in case② are smaller than the ones in case①, as seismic forces transmitted from girder to piers are smaller than that of case①.

Table 3 Maximum displacements along the bridge

		1	2	3	4	5	6	7	8	9	10	11	12
Girder	case①/cm	2.9	3.8	5.0	7.6	8	6.5	8.8	1.8	2.4	5.1	9.2	4.5
	case②/cm	7.7	8.1	11	10.8	9.7	7.6	9.9	7.7	10.2	9	13.2	10.2
	(②-①)/①/%	166	113	120	42	21	17	13	328	325	77	44	127
Pier	case①/cm	2.4	3.2	4.1	6.2	6.8	5.5	7.6	1.5	1.9	4.2	7.9	3.6
	case②/cm	0.5	0.6	1.8	1.7	1	0.5	1.2	0.3	1.4	1	2.8	1.6
	(②-①)/①/%	-79	-81	-56	-73	-85	-91	-84	-80	-26	-76	-65	-56

Table 4 Moment/shear force at the bottom of piers

	Sliding pier			Fixed pier		
	case (kN.m/kN)	case(kN.m/kN)	(-)/ (%)	case (kN.m/kN)	case(kN.m/kN)	(-)/(%)
1	9408/1556	48068/5055	411/225	678436/37087	67875/7073	-90/81
2	9453/1570	84402/8572	793/446	516700/51066	96137/9771	-81/81
3	8519/1440	253308/26204	2873/1720	652366/64629	282985/29376	-57/55
4	9209/1520	233980/24048	2441/1482	998889/98903	259623/26584	-74/73
5	8647/1465	160661/16192	1758/1005	1.09E+06/108342	151911/15251	-86/86
6	9257/1547	31141/3165	236/105	885637/87762	82232/8390	-91/90
7	8663/1468	168482/17371	1845/1083	1.23E+06/121577	180588/18611	-85/85
8	9138/1415	51789/5583	467/295	240016/23561	56398/6064	-77/74
9	9701/1589	203588/21028	1999/1223	313630/31160	226102/23379	-28/25
10	7254/4339	140866/14287	1842/229	682900/67420	167688/17144	-75/75
11	8593/1455	407911/42095	4647/2793	1.27E+06/126294	434909/44837	-66/65
12	8737/1476	216432/22382	2377/1416	582227/57464	247032/25311	-58/56

The seismic responses of fixed pier (No.3 pier) and sliding pier (taking No.1 pier for example) are listed in Table 4. It can be concluded that bending moments and shear forces at the bottom of fixed pier in case ② are smaller than the ones in case①, because the shear bolt of the fixed bearing will be cut off in case② in a severe earthquake, and the horizontal seismic forces transmitted from girder to the fixed pier initially are taken on by all piers, minimizing the forces taken by the fixed pier accordingly. In Table 4, the maximum reduction of bending moment at the bottom of the fixed pier is -91%, and the maximum reduction of shear force at the bottom of fixed pier is -90%. Compared with the fixed pier, bending

moments and shear forces at the bottom of sliding pier in case② are larger than the ones in case①, because the forces transmitted from the girder to other sliding piers in case② are larger than those in case ①, but still smaller than the forces transmitted to the fixed pier in case①.

It is also shown in Table 4 that the forces transmitted from girder to piers in case② are more balanced than those in case①, but as design, all piers have uniform section properties, which means that retrofit ability of each pier is exploited more fully in case② than that in case①, and all piers unit to resist the earthquake force.

Furthermore, it both reveals the well adaptation to the different site condition of CSFAB in Table 4, as there is a similar trend as above for each site condition.

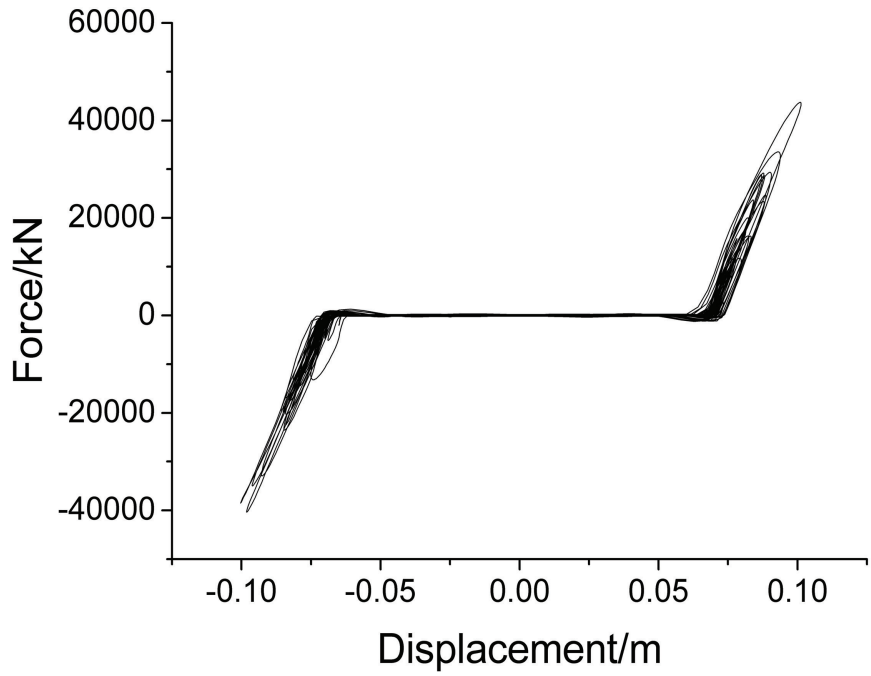

Fig.4 Force deformation relationship of CSFAB for bridge subjected to No.11 record

It is shown in Fig.4 that the typical force displacement relationship of CSFAB in the case of No.11 record loading (1999 chi-chi) matches ideal restoring force model in Fig.2 well. The maximum displacement of CSFAB in Fig.4 is limited below 0.10m, providing a practical solution for preventing girder falling caused by excessive displacement.

3.2 Influence of pier height change

To evaluate the effectiveness of CSFAB to different pier height, four finite element models with different fixed pier height of 10m,15m, 20m, and 25m respectively in case② are established, and earthquake ground motion records adopted in this section are also same to those in Table 2. The results are shown in Table 5 to Table 7.

Table 5 Maximum displacements of girder with different pier height (unit: cm)

wave Height/m	1	2	3	4	5	6	7	8	9	10	11	12
10	7.7	8.1	11	10.8	9.7	7.6	9.9	7.7	10.2	9	13.2	10.2
15	7.6	8.1	11	12.6	10.6	7.7	10	7.7	9.8	9.1	12.1	10.6
20	7.8	7.7	10.3	11.4	10.9	7.8	10.1	7.8	9.9	9.1	14	10.7
25	7.9	8.4	10.9	13.1	11.7	7.7	10.1	7.8	10	9.3	13.2	10.5

Table 6 Maximum moments at the bottom of piers with different pier height (unit: kN.m)

Wave Height/m	1	2	3	4	5	6	7	8	9	10	11	12
10	64518	97681	282985	275515	169927	78450	199004	59889	234749	167688	455945	255518
15	85664	82657	285831	414130	252763	83226	206088	61520	202834	170317	364912	270875
20	94523	65563	231584	324805	255745	84810	210244	59166	208682	172050	500865	261627
25	88659	123773	279179	427924	356646	79780	208434	62664	211159	178862	422881	261890

It can be concluded from Table 5 and Table 6 that with the increase of pier height, structure responses are increased accordingly. For example, the maximum structure response increases with the different height of 10m and 25m are listed in Table 7.

Table 7 Comparison of responses of different pier height conditions

Height	Maximum displacement/cm	Maximum moment/kN.m
10m	10.8	169927
25m	13.1	356646
Increase	21%	110%

It is shown in Table 7 that with the increase of pier height, the maximum displacements at the end of girder along the bridge increase marginally, but bending moments and shear forces both show a significant increasing trend, indicating that the shorter and stiffer the pier is, the more effective CSFAB retrofit is.

4. CONCLUSION

This paper presents an analytical study on the feasibility of using a new class of aseismic bearing—— CSFAB for the seismic control of continuous girder bridges. A 2-D continuous bridge model is developed and utilized in the study. The model is subjected to two orthogonal components of three historic earthquake motion records for each site condition respectively. The seismic behavior of a CSFAB-

controlled bridge is compared with the behavior of an identical bridge controlled by ordinary aseismic bearing, and it indicates a more retrofit effectiveness of CSFAB, key findings are summarized below:
(1) CSFAB shows a well adaptation to different site conditions, and all piers unit to resist the earthquake force.
(2) The displacements of both girder and pier can be limited below a pre-determined value, and thus CSFAB serves as a more effective alternative to conventional aseismic bearings;
(3) A further study considering the influence of pier height to the effectiveness of CSFAB reveals that CSFAB can achieve the aims of limiting displacement, and the shorter and stiffer the pier, the more effective the CSFAB retrofit is.

5. ACKNOWLEDGEMENTS

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