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Research of Cable-sliding Friction Aseismic Bearing Application in Bridges

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ABSTRACT: Past bridge performance in strong earthquake showed there would be large force in the pier or large displacement of the deck. To overcome this problem, many seismic isolation bearing were used. The seismic isolation system was classified as "Cooperative isolation system" and "pseudo-fixed isolation system". The cable-sliding friction aseismic bearing (CSFAB), which integrates seismic isolation device and supplementary displacement restrainers, and lead rubber bearing (LRB) are selected as representative examples of isolation bearing of the two systems. FEM of a continuous beam bridge was developed and utilized in this study to assess the aseismic effectiveness of CSFAB. The performance object is preset to prevent extensive damage under earthquake, including the bearing displacement and pier curvature ductility. The results indicated that CSFAB would reduce the curvature ductility and optimize the strength demand on piers as well as the displacements of the sliding bearing. Furthermore, a study was conducted to determine the sensitivity of the bridge response to the stiffness of the elastic cables of the CSFAB. The results showed that the cable sliding friction aseismic bearing can successfully improve overall seismic behavior of the bridges, but was influenced by the stiffness of the elastic cable. For the project in this paper, the optimum stiffness of the elastic cables was set to be 3.0×10^5kN/m.
KEYWORDS:Cable-sliding Friction Aseismic Bearing, performance object, sensitivity analysis, Cooperative isolation system, pseudo-fixed isolation system

1 INTRODUCTION

In the recent magnitude 8.0 Wenchuan earthquake in 2008, many bridges suffered severe damage and collapse (Han et al., 2009). From the lessons learned, two major types of structural failures are noteworthy, namely the unseating of the girders and failures in the columns (piers) due to inadequate strength or confinement. Thus, it may be necessary to address them in the design of new bridges or retrofit of existing bridges located in seismic areas.

To prevent column (pier) failure, Various seismic isolation devices such as rubber bearings, frictional (sliding) bearings and other bearings have been developed for bridges(Buckle and Mayes, 1990; Priestly et al., 1996; Fan, 1997; Yashinsky and Karshenas, 2003; Kunde and Jangid, 2003). These bearings are usually effective only for a narrow range of frequency input, so they are not always effective in mitigating seismic motions with multiple frequency ranges (Ghobarah and Ali, 1988).

To restrain relative displacement, The friction pendulum system (FPS) (Tsopelas and Constantinou, 1996; Almazan and De la Llera, 2002; Jangid, 2008) and the triple friction pendulum bearings (Fenz and Constantinou 2008a,b, Morgan and Mahin, 2010) has become an accepted seismic isolation device for bridges, but it is very expensive for small bridge projects.

Since various seismic isolation devices have different advantages and characteristics, they are applicable in different situations. However, it may be difficult to fulfill almost the following

requirements such as large load capacity, displacement constraining capacity, ability for large deformation, insensitivity to the frequency content, stability and economical efficiency.
For the above reasons, an alternative seismic isolation bearing, known as the "cable-sliding friction seismic bearing," is proposed to improve the seismic performance of isolated bridges in this paper. The new bearing is a combination of the plane sliding-type pot bearing and restrainer cables, which takes advantage of both the friction sliding resistance and the restraint capability of the cables. Experimental tests were conducted to validate the expected seismic performance. Moreover, numerical simulation analysis for the new bearing and its application to a continuous girder-arch composite bridge are discussed in detail.

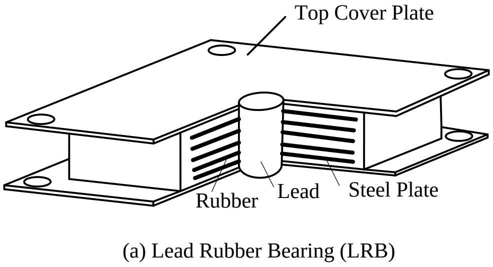
2 TYPES OF ISOLATION SYSTEM

2.1 Cooperative isolation system

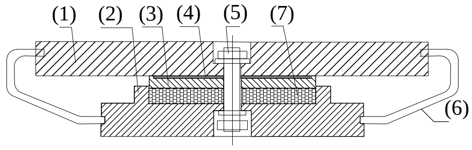
Cooperative isolation system refers to such kind of isolation bearing that no fixed bearings exist in a bridge, instead, all bearings cooperate to work in normal service condition and during earthquake. In normal service, the force caused by temperature, creep and automobile braking is resisted by the initial stiffness of the bearing. During earthquake, all the bearing yield to increase the period of the structure. In addition, the seismic force is resisted by all piers. Accounting for the two reasons together, the seismic force distributed to each pier is smaller. The earliest cooperative isolation system was applied in the bridge of Japan, which is also the first isolation bridge of Japan. Lead rubber bearing (LRB) is the most common bearing adopted in cooperative isolation system. Its schematic diagram and restoring force curves are shown in Figure. 1(a) and Figure. 2(a), respectively.

2.2 Pseudo-fixed isolation system

For the friction sliding bearing, if all bearings are designed to slide, slight initial stiffness exits to resist the vibration caused by the automobile and wind, which is adverse for normal service. So shear bolt is designed in one bearing to act as fixed bearing in normal service and slight earthquake. To prevent large seismic force transferred to the pier by the fixed bearing, the strength of the shear bolt is the key parameter during the design. Mostly, the strength is designed to 10% of the bearing vertical load capacity. When the seismic force is larger than the shear strength, bolt break occurs, turning the structure to friction sliding isolation system. So such kind of isolation system is called "Pseudo-fixed isolation system".
Neither the cooperative isolation system nor the pseudo-fixed isolation system has the ability to restrain the girder displacement when rare earthquake occurs, results in pounding and unseating of the girder, which are common disasters during past earthquakes.
Cable-sliding friction aseismic bearing (CSFAB) is a new kind of isolation bearing which consists of a conventional pot bearing, high strength restrainer cables on both sides and a shear bolt in the middle (psudo-fixed bearing) (Figure. 1(b)), when the shear bolt breaks during earthquake, the high strength restainer cables work to restrain the girder displacement to a preset value.



(a) Lead Rubber Bearing (LRB)



(1)Upper plate (2)Lower plate (3)Stainless steel plate
(4)Teflon plate (5)Shear bolt (6)Cable (7)Elastomeric Pad

(b) Fixed Cable-sliding Friction Aseismic Bearing(CSFAB)

Figure. 1 Schematic diagram of LRB and CSFAB

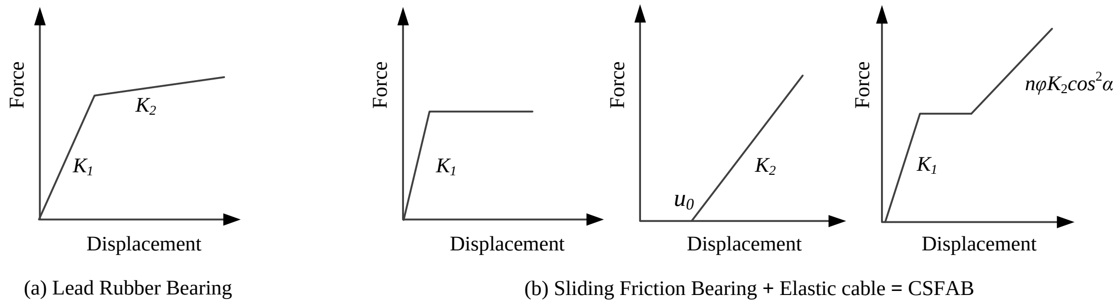


Figure. 2. Restoring force curves of LRB and CSFAB

2.3 Introduction of CSFAB

2.3.1 The cables

The free length of each restrainer cable (L), is defined by

$$L = \sqrt{H^2 + L_{xy}{}^2} \tag{1}$$

$$L_{xy} = \sqrt{[\delta_x + (A - C)/2]^2 + [\delta_y + (B - D)/2]^2} \tag{2}$$

where L_{xy} is the projected length of the cable in the horizontal plane; H is the height between cable anchorges; A and B are the length and width of the upper plate; C and D are the length and width of the lower plate; δ_x and δ_y are the design displacements in the longitudinal and transverse directions respectively.

The tensile stiffness of each cable member (K_2), is defined as

$$K_2 = EA_c / L \tag{3}$$

where E is the elastic modulus of the cable material; A_c is the cable sectional area; L is the cable length defined in equation. 1.

2.3.2 Shear Strength of the bolt

Based on the requirements of service loads, the horizontal shear resisting capacity expected of a fixed pot bearing in design is generally not less than 10% of the vertical load bearing capacity. As the shear bolt is not designed to remain intact under severe earthquakes, it is required that the shear strength of the bolt be between 10% and 15% of the vertical load capacity for this aseismic bearing system.

2.3.3 Integral stiffness of the bearing

The restoring curves of the CSFAB is shown in Figure. 2(b), where K_1 denotes the stiffness of the sliding friction bearing, K_2 is defined in Eq.3 and u_0 denotes the design free displacement when the bearing is in normal service load. α is the angle between the longitudinal direction of the cable when engages at a lateral displacement of u_0 and the direction of the horizontal relative displacement of the friction bearing.

Figure. 2(b) shows the aseismic bearing's overall response in which n is the number of cables and φ is a coefficient that represents the equivalent linearization of cable stiffness under severe earthquakes. The maximum displacement which is the possible relative displacement between the lower plate and upper plate of the bearing under severe earthquakes is related to the design free displacement and the elongation of the restrainer cables.

2.3.4 Test and numerical simulation

To verify the design concepts and to obtain data for subsequent numerical simulation, a prototype model of the cable sliding friction aseismic bearing system was tested to a series of quasi-static cyclic loading under a 2000-ton electro-hydraulic servo loading machine in the laboratory at Tongji University in Shanghai in 2009 (Cao 2009), as shown in Figure 3.

The Comparison between a numerical hysteretic response curve calculated by finite element analysis and the experimental curve is shown in Figure 4. The agreement supported the use of this modeling method in real bridge projects.

Figure. 3 The CSFAB test equipment

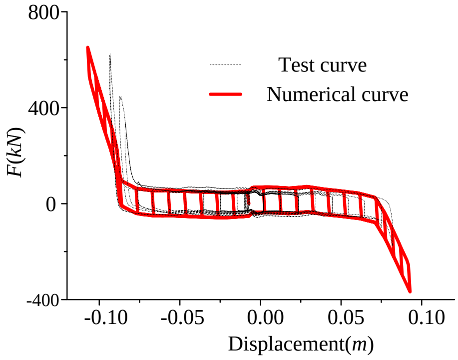


Figure. 4 Hysteristic curves comparison

3 PERFORMANCE-BASED DESIGN

Excessive relative displacement of multi-span continuous girder bridges between upper girder and lower piers can result in collapse of the bridge. 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 pier is assumed to fixed at the bottom to ignore the soil-structure interaction.

The upper composite box girder is supported on the top of single box piers, and section properties are listed Table. 1.

The Damage index and limit state of components (piers and bearings) of the bridge are listed in Table. 2 (Choi, 2002; Choi, 2004; Zhang, 2009). The performance object is to prevent extensive damage under earthquake.

Table. 1 Section properties of girder and pier

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

Table. 2 Damage index of components

components	Slight damage	Moderate damage	expensive damage	Complete damage
pier(μ_φ)	1.0	1.58	**3.22**	6.84
Sliding bearing(mm)	100	150	**200**	500
LRB(mm)	0	50	**100**	150

A 2-D finite element model of the reference bridge is developed and analyzed using *Opensees* software program (Figure. 5). In order to define the retrofit effectiveness of CSFAB, the following two cases are considered:
Case 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).
Case 2: Lead rubber bearings are adopted at all pier-girder connections. The yield strength is set to be 1177*kN*, and K_2 is assumed to be 0.1 K_1.
Case 3: 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. Critical displacement u_0 is set to be 8cm, friction coefficient adopted is 5%, and cable stiffness is 3.0×10^5kN/m.

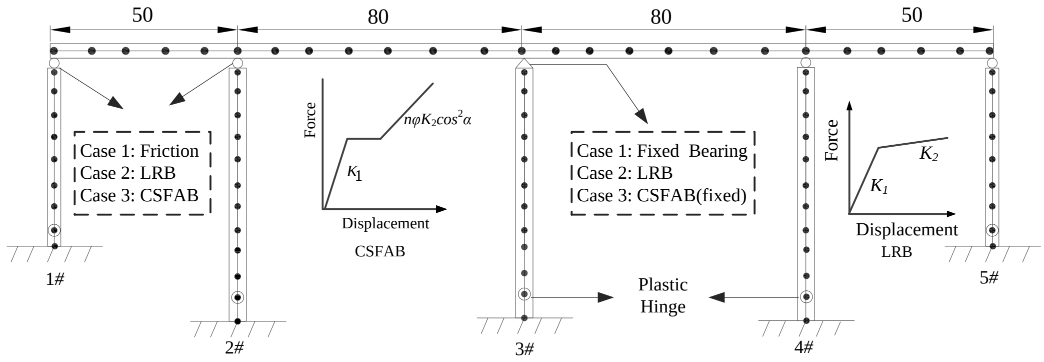


Figure. 5 Schematic diagram of analytical model for bridge structure (unit: m)

The bridge is subjected to three earthquake ground motion records, as shown in Table. 3. In this paper, acceleration peaks are adjusted to 0.6g uniformly, The input earthquake waves is in horizontal direction.

Table. 3 Selected earthquake motion records

NO.	Wave records	Site	Magnitude	PGA/g
1	1999 CHI-CHI	CHY006	7.3	0.364
2	1979 IMPERIAL VALLEY	EI Centro allay 5#	6.5	0.537
3	1992 LANDERS	YermoFire Station	7.3	0.152

The results which are adopted as the average of the ones under three earthquakes, are listed in Table. 4.

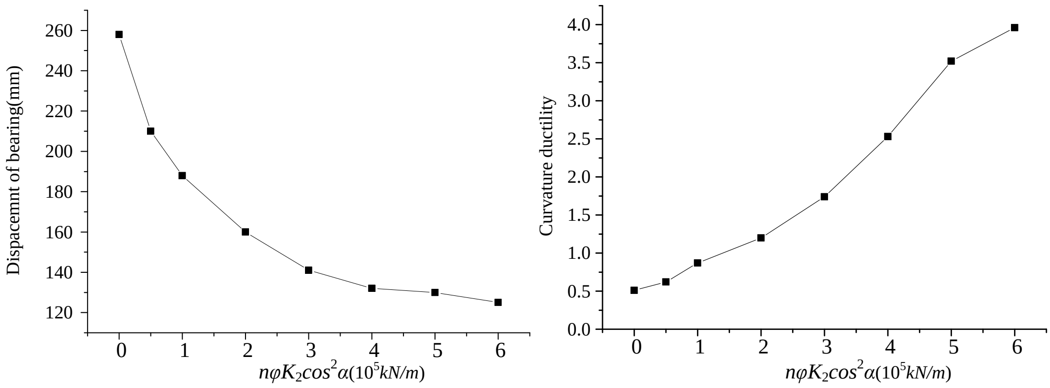
Table. 4 comparison of three cases

CASE	Bearing displacement(mm) 1#	curvature ductility (μ_φ) 3#
1	108	4.86
2	213	0.82
3	120	1.74

It can be concluded that the curvature ductility is too large for case 1 and the bearing displacement is too large for case 2 to fulfill the performance object. For case 3, although the bearing diaplacemen is a litter larger, it is still much small than the performance object (200mm). At the same time, curvature ductility (μ_φ) of fixed pier are mcuh smaller than the one in case 1, also smaller than the performance object (3.22). That is because the shear bolt of the fixed bearing will be cut off in case in 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.

4 SENSITIVITY ANALYSIS

In considering the alternative scheme with a cable-sliding friction seismic bearing, the elastic stiffness of the restrainer cables was a critical parameter that must be determined. The sensitivity analysis is performed, the results (bearing displacement at 1# and curvature ductility at 3# pier) are shown in Figure. 6. When the stiffness is less than 3.0×10^5kN/m, the bearing displacement reduces quickly, and the curvature ductility increases slowly. When the stiffness is large than 3.0×10^5kN/m, the bearing displacement reduces slowly, and the curvature ductility increases quickly. To fulfill different performce object, different stiffness is selected. In the bridge project of this paper, 3.0×10^5kN/m is set as the optimum stiffness.



(a) displacemnt (a) curvature ductility of the pier

Figure. 6 Bridge responses versus the stiffness of the elastic cable of the CSFAB

5 CONCLUSIONS

The seismic isolation system is classified as “Cooperative isolation system” and “pseudo-fixed isolation system”. The lead rubber bearing (LRB) and the cable-sliding friction aseismic bearing (CSFAB) are selected as representative examples of isolation bearing of the two systems.

FEM of a continuous beam bridge was developed and utilized in this study to assess the aseismic effectiveness of CSFAB. The perfomance object is preset to prevent extensive damage under earthquake. The results indicated that CSFAB wsould reduce the curvature ductility and optimize the strength demand on piers as well as the displacements of the sliding bearing.

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