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Application of LRB isolation technology in continuous girder bridges

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Abstract: This paper summarizes the superiority of lead-rubber bearing (LRB) continuous girder bridges. The research method for isolation performance is discussed when pile-soil interaction is considered. By the finite element method and self-compiling program, a systematic study of the reliability of LRB continuous girder bridges is given by the use of different indicators, including the riding comfort of the LRB system, the pounding and dynamic stability when the LRB system is subjected to seismic excitations, and the reliability of the LRB system when subjected to other common horizontal loads. The results show that the LRB system has obvious advantages over the traditional continuous girder structure. The LRB isolation effect remains good even when pile-soil interaction is considered; the vertical rigidity of the LRB guarantees desirable riding comfort. The LRB demonstrates good reliability when subjected to the effects of braking, wind loads and temperature. However, it is also pointed out that the pounding of the LRB system subjected to earthquakes must be avoided, and the dynamic stability may be reduced when the LRB system has higher piers and generates a larger displacement in a strong earthquake. Useful advice and guidance are proposed for engineering application.

Key words: lead-rubber bearing (LRB); isolation technology; continuous girder bridge
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An earthquake is one of the most serious natural disasters faced by human beings. How to mitigate the effect of earthquake disasters has become an issue of global concern. Wenchuan earthquake on May 12, 2008 resulted in the death or disappearance of over 90 000 people and great economic losses incurred by heavy damage to buildings and the infrastructure. The traditional continuous girder bridges, which rely on fixed piers to receive more than 80% of a seismic response, cannot resist high intensity earthquakes. To make up for this deficiency, a new isolation technology has been proposed in recent decades, which helps to mitigate the effects of earthquakes by removing fixed piers and installing lead-rubber bearings (LRB) between piers and beams.

LRB isolation technology, a seismic protection technology developing rapidly in recent years[1-2], has been widely used in the construction of buildings and bridges abroad and at home[3]. Buildings and bridges using this technology have exhibited good seismic performances, surviving the real test of strong earthquakes such as the US Northridge earthquake in 1994 and the Japan Kobe earthquake in 1995[4].

Taking the first double-traffic double-deck isolated continuous girder bridge in the world, the Dongjiang Bridge in Dongguan, Guangdong province, as a case study, this paper gives the first systematic study on the superiority, effectiveness and reliability of the LRB continuous girder bridges using different indicators. The finite element model of one of the continuous units is shown in Fig. 1, and the parameters of LRBs used for Dongjiang Bridge are shown in Tab. 1.

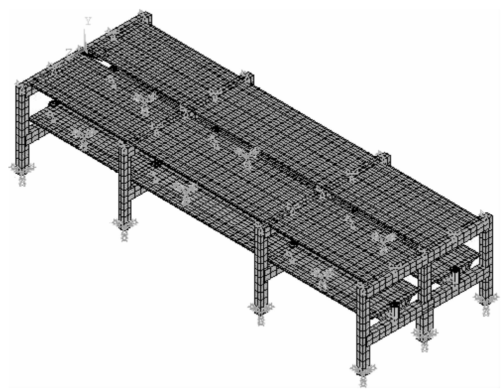

Fig. 1 Finite element model of one of the continuous units

Tab. 1 Parameters of LRBs used for Dongjiang Bridge

Design factor	Bearing type	
	GZY600 × 600	GZY800 × 800
Rigidity before yield/(kN · mm^{-1})	1.929 8	2.139 0
Rigidity after yield/(kN · mm^{-1})	0.917 6	1.333 7
Yield shear/kN	93.80	166.80

1 Superiority of LRB Continuous Girder Bridges

Compared with traditional non-isolated continuous girder bridges, the LRB system has advantages such as high safety, good economics, good durability, automatic restoration after earthquakes, etc., and it can meet all the characteristics that the isolation device must possess, including great vertical bearing capacity (In the LRB system, it is ensured by the steel plates in the bearing.), allowing the structure to move flexibly on the base surface (In the LRB system, it is ensured by the laminated rubber in the bearing.), sufficient initial stiffness and larger damping (In LRB system, it is ensured by the lead core in the bearing.). The LRB system can also be free from the influence of the deformation produced by expansion and contraction and it can rapidly recover stiffness.

2 Efficiency of LRB Continuous Girder Bridges

2.1 General situation

The seismic responses of continuous girder bridges can be

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greatly reduced by the LRB system, which has been proved by many researchers [5-7]. The comparison of the first three orders of the natural period of the Dongjiang Bridge before and after isolating is shown in Tab. 2.

Tab. 2 Comparison of the first three orders of natural period of Dongjiang Bridge before and after isolation

Vibration mode	Natural period/s	
	Before isolation	After isolation
1	1.929 8	2.139 0
2	0.917 6	1.333 7
3	0.906 8	1.206 6

It can be seen from Tab. 2 that each order of the natural period is obviously stretched after the LRB is installed. The isolation effect of the fixed pier bottom is shown in Tab. 3, in which the isolation rate is defined as

$$\text{Isolation rate} = \frac{\text{Non-isolated response} - \text{Isolated response}}{\text{Non-isolated response}} \times 100\% \tag{1}$$

and E1 and E2 are in accord with the provision of "Guidelines for aseismic design of highway bridges" (JTG/T B02-01—2008) [8].

Tab. 3 Isolating effect of the fixed piers of Dongjiang Bridge

Item	Seismic excitation of bridge in axial direction						Seismic excitation of bridge in cross direction					
	E1			E2			E1			E2		
	Before isolation	After isolation	Isolation rate/%	Before isolation	After isolation	Isolation rate/%	Before isolation	After isolation	Isolation rate/%	Before isolation	After isolation	Isolation rate/%
Shear/kN	422.24	179.67	57.45	856.49	265.29	69.03	907.78	189.31	79.15	1 741.18	216.91	87.54
Moment/(kN · m)	5 030.26	2 006.36	60.11	10 462.36	2 829.47	72.96	10 856.58	2 086.64	80.78	1 786.98	257.65	85.58

After isolation, the horizontal force of this bridge subjected to seismic excitations is shared evenly by piers according to their stiffness. It can be seen from Tab. 3 that after the LRB is adopted, the response of the continuous girder bridge has been greatly reduced, a clear evidence for the effectiveness of the LRB system.

2.2 Isolation properties of LRB system when considering pile-soil interaction

If the ground conditions where the structure is located are good, then there is no need to consider the pile-soil interaction and the model can include only girders, piers and bearings without regard for pile caps and piles; however, if the ground conditions are poor, then all of the above elements must be considered in the model.

When the effect of pile-soil interaction on the seismic response of bridges is taken into consideration, the following method can be adopted: treating the pile group base as a sub-structure, determining its equivalent rigidity, and then analyzing the dynamic response by applying the restraining stiffness to the pile cap. With the clear concept and the simple computing principle, this method can meet the precision requirements of engineering applications; it, therefore, has become the recommended approach of the existing code[8].

In the calculation of the equivalent dynamic rigidity of the pile group base, the pile foundation embedded in the soil layer can be regarded as a foundation beam supported elastically by the soil around the pile. In this way, the restraining effects of the soil around the pile can be replaced by equivalent soil springs distributed discretely along the piles[9]. The stiffness of the soil springs can be calculated in accordance with the m method provided in the "Code for design of ground base and foundation of highway bridges and culverts" (JTG D63—2007) [10]. The m method is a common design method for static forces of piles in Chinese highway bridge design, and when calculating the equivalent dynamic rigidity of pile groups base, the m value can be set 2 to 3 times the static value specified in the code[9].

According to the above mentioned principle, the equivalent rigidity of spring for each layer of soil k_s can be calculated by

$$k_s = ab_p mz \tag{2}$$

where a is the soil thickness; b_p is the calculation width of the pile; m is the value of the corresponding soil layer; and z is the soil depth.

Refs. [11-12] show that the LRB system of the continuous girder bridge still demonstrates a good isolation performance when the pile-soil interaction is taken into consideration.

3 Reliability of LRB Continuous Girder Bridges

There is a widespread concern about the reliability of the LRB continuous girder bridge system considering that the fixed piers are removed and all the bearings are LRB. This paper systematically studies the reliability of LRB continuous girder bridges by use of different indicators.

3.1 Riding comfort evaluation of LRB system

When the horizontal stiffness of the LRB is comparatively small, it is often estimated that the riding comfort of the LRB system of a continuous bridge may be poor.

Traffic load is always regarded as a static load with changing locations in calculating the maximum static response of bridges. However, in fact, it should be regarded as a dynamic load, and the dynamic response should be analyzed by the dynamic method[13]

By the method in Ref. [14], this paper evaluates the riding comfort of the Dongjiang Bridge and the calculation conditions of the riding load are shown in Tab. 4

Tab. 4 Calculaton conditions of riding load

Item	Condition 1	Condition 2
Load level	Car-level super 20	Trailer-level 120
Vehicle speed/(km · h^{-1})	108	72
Vehicle spacing/m	15	200
Loading arrangement column	2	2
Concentrated load number when suffused	13 × 2	4 × 2
Total length of fleet/m	172.6	212.8
Time of fleet across the bridge/s	14.84	26.82
Total time adopted by calculation/s	20	30
Time step adopted by calculation/s	0.01	0.015

Take condition 1 as an example, the equivalent nodal moment time history of a certain node on the main beam is shown in Fig. 2.

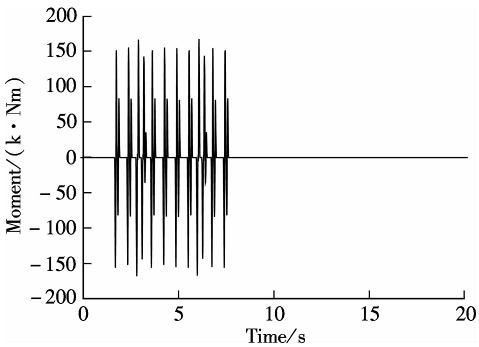

Fig. 2 Moment-time history of a point under condition 1

The Sperling indicator W_s is adopted to evaluate the riding comfort of the Dongjiang Bridge and it can be written as

$$W_s = 2.7 \times \sqrt[10]{Z^3 f^2 F(f)} \tag{3}$$

where Z is the vibration amplitude, cm; f is the strong vibration frequency, Hz; $F(f)$ is a function related to the vibration frequency, called as the frequency correction factor, which represents the modification of people's sensitivity degree to different vibration frequencies.

For the Dongjiang Bridge, the evaluation result of the Sperling indicators and the corresponding calculated frequencies under condition 1 are shown in Tab. 5.

Tab. 5 Sperling index evaluation under condition 1

Predominant frequency/Hz	Displacement amplitude/mm	Indicator value	Evaluation conclusion
0.081	14.761	0.992	No feeling
0.293	7.761	1.368	Feeling a slight vibration
0.654	2.210	1.294	Feeling a slight vibration

It can be seen from Tab. 5 that the adoption of the LRB system does not affect the superior riding comfort of the Dongjiang Bridge. It is because in spite of small horizontal stiffness, the vertical stiffness of the LRB is basically the same as that of other bearings and the vertical traffic loads will not lead to the horizontal vibration of bridge. So the inherent characteristics of the LRB ensure good riding comfort on the bridge, which makes checking unnecessary.

3.2 Pounding analysis of LRB system subjected to seismic excitations

Isolation technology can increase the displacement of girders and create poundings between adjacent beams or between beams and abutments, and, thus, cause damage to beams or even lead to girder falling[15]. So the poundings between beam bodies in the LRB system when subjected to seismic excitations should be avoided.

Current researches on bridge pounding problems in earthquakes are mainly based on the rigid pounding theory[16-17]. The pounding time history of the Dongjiang Bridge subjected to seismic excitation is analyzed by the method in Ref. [18]. Two natural and one artificial waves are adopted. If the axial force occurs in the pounding elements, it means that pounding does occur in the earthquake; while if the axial force of the pounding elements remains zero, it means that there exists no pounding.

In addition, the effect of expansion and contraction should be considered in measuring the width of the expansion joints. There are two conditions:

Condition 1 The total width of the expansion joints is 10 cm;

Condition 2 The total width of the expansion joints is the remainder after the expanded length is deducted from 10 cm.

Time history calculation results of the Dongjiang Bridge show that pounding only occurs under condition 2, E2 level and artificial wave. The axial force of the pounding element is shown in Fig. 3.

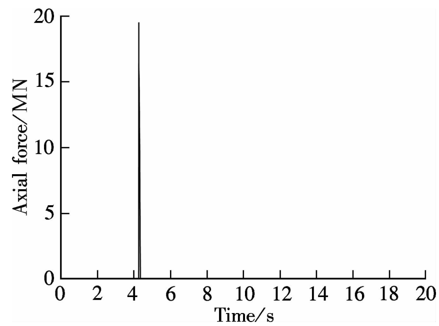

Fig. 3 Axial force of pounding element excited by artificial wave under condition 2 and E2 level

Since the pounding will occur when two conditions are simultaneously satisfied (One is the global temperature rising by 30 ℃; the other is the E2 level of seismic excitation.) and only one in three seismic waves will cause pounding between a main bridge and an approach bridge, the possibility of pounding in this bridge is in fact extremely little.

For LRB system continuous girder bridges, it is obligatory to carry out a pounding analysis when the bridge is subjected to seismic excitation. And the width of expansion joints and the stiffness of LRBs should be adjusted to make sure that pounding will not occur when the seismic response is reduced moderately at the same time.

3.3 Dynamic stability of LRB system subjected to seismic excitations

After the LRB is installed, relative motion will occur between girders and piers if an earthquake happens, giving rise to an eccentricity of the vertical force transmitted by girders to piers. Therefore, it is necessary to analyze the dynamic stability of the LRB system continuous girder bridge subjected to seismic excitation.

The dynamic stability of the Dongjiang Bridge is analyzed by the method proposed in Ref. [19]. The characteristic equation of the stability safety factor is

$$([K_D] + \lambda [K_G])\{\Delta\delta\} = 0 \tag{4}$$

If the equation is n-order, then theoretically there are n eigenvalues $\lambda_1, \lambda_2, \cdots, \lambda_n$. However, in engineering only the smallest eigenvalue or the minimal stability safety factor has real meaning, when the eigenvalue is λ_{cr} and the critical load is $\lambda_{cr}\{F\}$.

For the Dongjiang Bridge, there are eight calculation conditions:

1) Seismic excitation acting only in the axial direction along the bridge;

2) Seismic excitation acting only in the vertical direction;

3) Seismic excitation acting in the axial direction along the bridge plus gravity action;

4) Seismic excitation acting in the vertical direction plus gravity action;

5) to 8) Corresponding to 1) to 4) after global warming up 30 ℃.

The dynamic stability eigenvalues of the Dongjiang Bridge when subjected to seismic excitation and critical seismic action are shown in Tab. 6. The eigenvalue curve of conditions 2) and 6) under critical seismic action is shown in Fig. 4.

Tab. 6 Elastic dynamic stability eigenvalue of Dongjiang Bridge

Conditions	Peak acceleration	λ_{max}	t_{max}/s	λ_{min}	t_{min}/s
1,5	1 341*g*	32 905. 21	0. 04	1. 000 5	5. 14
2,6	12. 7*g*	178 922. 76	0. 02	1. 0047	2. 44
3,7	1 270*g*	15. 14	0. 02	1. 001 97	5. 14
4,8	11. 9*g*	19 761. 79	2. 26	1. 006 4	2. 44

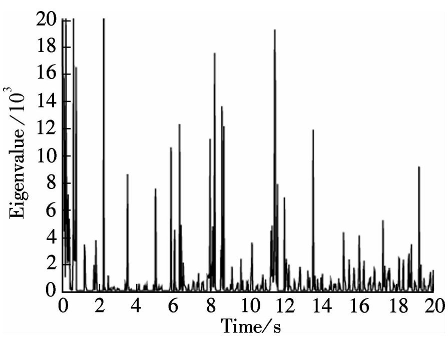

Fig. 4 Eigenvalue curve of conditions 2 and 6

It can be seen from Tab. 6 that although isolated bearings are adopted and fixed piers are removed, the Dongjiang Bridge still has very good dynamic stability.

When the LRB is used, the displacement of girders will increase, leading to the increase in the eccentricity of vertical forces exerted on the piers, while the displacement of the piers will be greatly reduced. This is the reason why the LRB system continuous girder bridges have good dynamic stability when subjected to seismic excitation.

Generally speaking, the continuous girder bridge that has higher piers will generate larger displacement after a strong earthquake. The adoption of LRB isolation technology can affect its dynamic stability. Therefore, a check for its dynamic stability is necessary.

3.4 Reliability of LRB system subjected to other horizontal load

Seismic action is only an event with a low probability of occurrence, most of the time bridges are exposed to such factors as brakings, wind loads and temperature. These factors must be taken into consideration at the very beginning of designing the LRB to make sure that the bridge can meet the requirements of normal use under the actions of these horizontal loads.

To make sure that the isolating bearings do not yield to the effects of braking and wind loads, the maximum braking resistance or wind loads exerted upon each continuous unit must not exceed the sum of the yield shear of the LRB in this continuous unit. The value of braking must be set according to the provision of item 4. 3. 6 in the "General code for design of highway bridges and culverts" (JTG D60—2004)[20], and the direction should be along the bridge decks; the wind load can be applied according to the provision of item 4. 3. 7 in the same code.

For each continuous unit of the Dongjiang Bridge, the maximum braking resistance received by the unit is 1 382. 9 kN, and the maximum wind load is 558. 7 kN, both of which are much smaller than 2 751. 1 kN, the sum of yield shear of LRBs in this continuous unit, so under normal use, the actions of braking and wind loads will not make LRBs of this bridge yield.

As far as the effect of temperature is concerned, there is no need to ensure that the maximum displacement of girders in the LRB system exceeds the width of the expansion joints, but it needs to examine whether piers can withstand the shears and moments generated by temperature or not.

After overall heating and cooling 30 ℃ to the Dongjiang Bridge, it is found that the maximum displacement of the girders at expansion joints is 1. 66 cm, which does not exceed the width of the expansion joints; the maximum shear of pier bottoms is 437. 14 kN, and the maximum moment of pier bottoms is 5 640. 31 kN · m, which can be fully withstood by the piers.

In fact, as long as the parameters of the LRB are reasonably designed, the vast majority of the LRB system of a continuous girder bridge can fully meet the requirements of normal use when subjected to braking, wind loads and temperature.

4 Conclusions

Taking the first double-traffic double-deck isolated continuous girder bridge of the world, the Dongjiang Bridge in Dongguan, Guangdong province, as a case study, this paper gives the first systematic study on the superiority, effectiveness and reliability of the LRB continuous girder bridges using different indicators. And the following conclusions are obtained:

1) The LRB system has obvious advantages over traditional continuous girder bridges. It makes full use of an isolation mechanism, with a superior isolation effect being achieved.

2) The inherent characteristics of the LRB system guarantee desirable riding comfort. The LRB system maintains a very good isolation performance even when the pile-soil interaction is taken into consideration. So long as the design parameters of the LRB are reasonable, the LRB system can fully meet the requirements of normal use when subjected to the effects of braking, wind loads and temperature.

3) The pounding of the LRB system subjected to seismic

action must be analyzed; and the dynamic stability needs to be checked when the LRB system has higher piers and generates larger displacements in a strong earthquake.

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LRB 隔震技术在连续梁桥中的应用

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摘要:总结了 LRB 体系连续梁桥的优越性,讨论了考虑桩-土共同作用时隔震性能的研究方法.采用有限元法,自编程序,系统地从行车舒适度、地震作用下的碰撞和动力稳定及其他常见水平荷载作用等方面分析了 LRB 体系连续梁桥的可靠性.结果表明,LRB 体系较之传统的连续梁桥结构具有明显的优越性,考虑桩-土共同作用时,依然具有非常良好的隔震效果,LRB 的竖向刚度保证了其行车舒适度不会降低,在制动力、风荷载和温度作用下,LRB 体系连续梁桥均表现了良好的可靠性,但必须避免其地震作用下的碰撞,墩较高、大震位移较大时,其动力稳定性能会受到影响.研究成果为工程应用提供了有益的建议和指导.

关键词:铅芯橡胶支座;隔震技术;连续梁桥

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