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# Development and experimental study on cable-sliding modular expansion joints

Kang Gao[1,2a], Wan C. Yuan[*1] and Xin Z. Dang[1b]

[1]*State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University,1239 Siping Road, Shanghai 200092, China*
[2]*School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia*

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**Abstract.** According to the characteristics of continuous beam bridges, the relative displacement is too large to collision or even girder falling under earthquakes. A device named Cable-sliding Modular Expansion Joints(CMEJs) that can control the relative displacement and avoid collision under different ground motions is proposed. Working principle and mechanical model is described. This paper design the CMEJs, establish the restoring force model, verify the force model of this device by the pseudo-static tests, and describe and analyze results of the tests, and then based on a triple continuous beam bridge that has different heights of piers, a 3D model with or without CMEJs were established under Conventional System (CS) and Seismic Isolation System (SIS). The results show that this device can control the relative displacement and avoid collisions. The combination of isolation technology and CMEJs can be more effective to achieve both functions, but it need to take measures to prevent girder falling due to the displacement between pier and beam under large earthquakes.

**Keywords:** continuous girder bridge; the effect in limiting relative displacement; cable-sliding modular expansion joints (CMEJs); conventional system; seismic isolation system; pseudo-static tests

## 1. Introduction

Modular bridge joint systems (MBJS) with its good three-dimensional deformation capacity, large displacement, and easy replacement have been widely used in curved bridge, skew bridge, especially in large span bridge. However, as one of the important components of bridges, the aseismic behavior of expansion joints has long been neglected by researchers (Saiidi *et al*. 1996, Kawashima and Shoji 2000, Ruangrassamee and Kawashima 2001, Zanardo *et al*. 2001, DesRoches and Muthukumar 2002) and the past papers have given importance to the enhancement of durability, cold resistance and noise-resistance of expansion joints. For example, Ancich *et al*. (2006) studied the dynamic anomalies of the modular bridge expansion joints. Crocetti *et al*. (2003) investigated the fatigue performance of the modular bridge expansion joints. Dexter *et al*. (1997, 2001, 2002) presented a systematic study of the modular bridge expansion joints. Roeder *et al*. (1993) studied fatigue cracking in modular expansion joints.

The damage of expansion joints not only poses a threat to the state of serviceability after the earthquake, but also affects the overall aseismic behavior of bridge. In recent years, some researchers have paid a closer attention to the contributions of the expansion joints under seismic events. For example, Quan and Kawashima (2010) studied the effect of steel finger-type expansion joints on the overall seismic response of a bridge. McCarthy *et al*. (2012) assessed the effectiveness of a burgeoning subgroup of modular bridge expansion joints composing of shape memory alloy improved single support bar variations. Further, McCarthy *et al*. (2013) also developed an analytical model representative of a common expansion joint and then supported it through full-scale experimental testing of the joints. Ramanathan (2012) suggested that bridge expansion joints should be incorporated in reliability models of bridge performance under seismic events, particularly when considering functionality and repair based damage levels. Gao *et al*. (2015) introduced a new device named Cable-sliding Modular Expansion Joints (CMEJs) and analyzed it under near-fault ground motions.

According to the research fruits of the diverse damages of bridge in the past, bearings' invalidation is the main reason of the damage of isolated bridges and causes oversized relative displacements between pier and girder. Eventually, it may lead to severe collision of superstructure. Aiming at this problem, this paper puts forward a device named cable-sliding modular expansion joints (CMEJs) that can control the relative displacement and avoid collision.

## 2. The principles and targets of the design

### *2.1 Design principles*

The Cable-sliding Modular Expansion Joints (CMEJs) is a new device that adds cables at the both ends of the ordinary bridge modulus expansion joints. Therefore, it has two special characters: Firstly, as an expansion joints, it can

∗Corresponding author, Professor
E-mail: yuan@tongji.edu.cn
[a]Ph.D. Student
[b]Ph.D.



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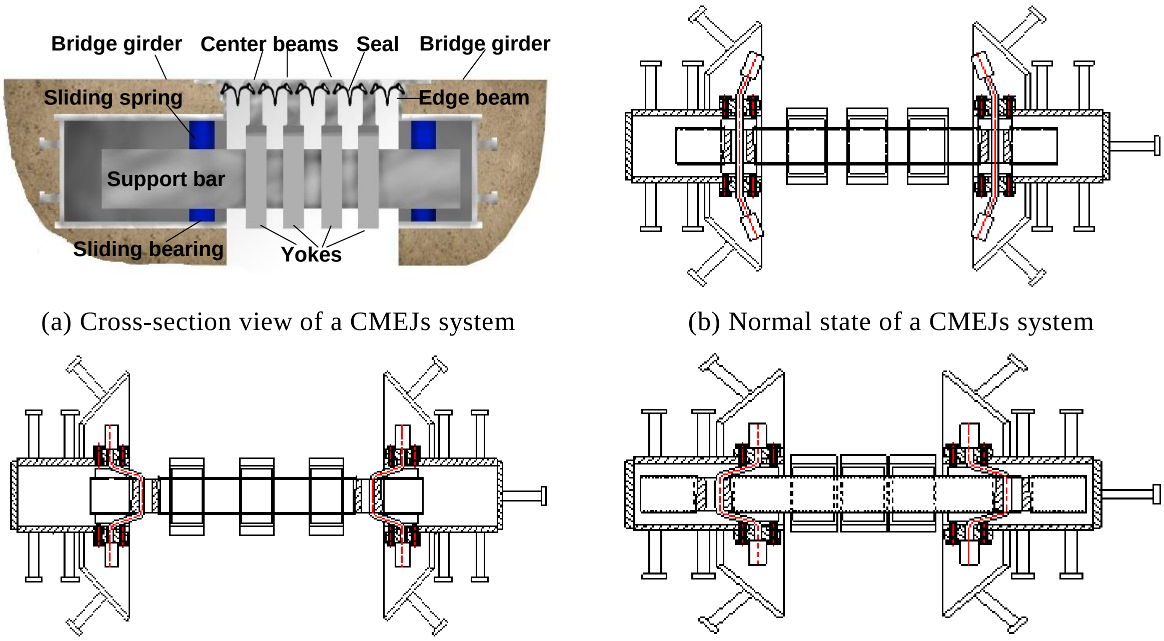


(a) Cross-section view of a CMEJs system (b) Normal state of a CMEJs system

(c) When the adjacent girders apart from each other (d) When the adjacent girders get close

Fig. 1 Working mechanism of CMEJs

satisfy the relative displacement between adjacent girders or between girders and abutments because of temperature change and overcome displacement caused by the impact force of automobile; Secondly, as a restrainer, CMEJs can effectively control the relative displacement between adjacent girders and avoid collision under earthquake. In a modular expansion joints, there is a support box every few meters along the transverse direction of the bridge, as shown in Fig. 1.

Based on the conventional design, CMEJs uses cables through the both ends of the support boxes and support bars and connect them. When earthquake occurs, the relative displacement between beams is limited through controlling movement of bars in the boxes by cables. Because both ends of the support boxes are fixed in the two ends of the beams, the cable can limit the relative displacement of beams. Fig. 1 is the working mechanism of CMEJs.

### *2.2 Targets*

Under earthquakes, this device can effectively constrain the relative displacement between support boxes and support bars, so as to control the relative displacement between adjacent girders and avoid girder falling.

In order to achieve the above purposes, based on the traditional modulus expansion joints, the author introduced CMEJs which uses cables through the both ends of the support boxes and support bars and connect them. According to the design requirement, cables are given a free movement and then fixed in the bridges.

Based on the above design principles, CMEJs has the following three targets:

1) Under normal load, CMEJs and traditional modulus expansion joints have the same function that is not only control longitudinal, transverse and vertical displacement or rotation angle, but also can control relative displacement between adjacent girders or between girders and abutments because of temperature change and overcome displacement caused by the impact force of automobile.

2) Under minor and moderate earthquakes, it has relative displacement between adjacent girders. Cables can control the longitudinal displacement of bridge through controlling the movement of the support bars in the support boxes, which can adjust and transfer forces from earthquakes.

3) During rare earthquakes, when the adjacent girders get close and an impending collision, the cable can control the girders to prevent collision and play a role in limiting the relative displacement, as shown in Fig. 1(d); And vice versa, as is shown in Fig. 1(c). In addition, as the cable is running through support boxes and bars, CMEJs will not be easily damaged. According to the requirements of different bridges, adjusting cable's free movement can realize the limiting effect. When an earthquake occurs, if the relative displacement between the girders is within the free movement, the cables do not work; if larger than the free movement, they can work effectively.

## 3. Determination of CMEJs design parameters

This section introduces the design method of CMEJs' control parameters which makes the device to reach the expected performance objectives. Fig. 2 is the design flow chart of CMEJs.

Firstly, according to the design method of cable and safety distance of expansion joints, an assumed cable stiffness $K$ is given; Secondly, Input the $K$ into target model, then use the Sap2000 to calculate the model. Thirdly, Result analysis: If the relative displacement between girders and

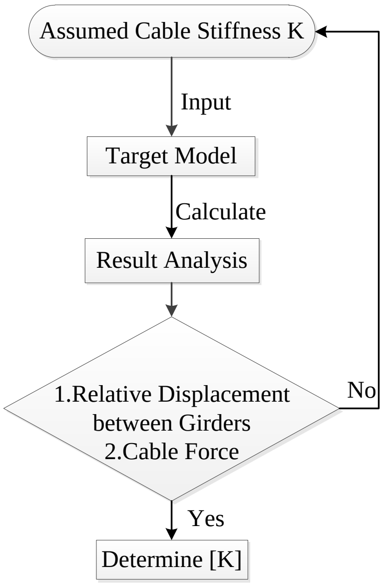


Fig. 2 Design flow chart of CMEJs

cable force within the scope of design, then to the next step; if not, repeat the first two steps until the control parameters within the safety range. Extract the *K* at this time and mark as *K′*; Finally, in order to consider the reduction of cable stiffness and ensure the structural safety, the *K′* multiply by 1.25 times of the expansion coefficient and the final [*K*]=1.25*K′*.

## 4. Restoring force model of CMEJs

CMEJs has the following features:

1) When the relative displacement of the adjacent girders is less than the free movement of cables. Cables don't play any role and the stiffness is 0;

2) When the relative displacement of the adjacent girders is larger than the free movement of cables. Cables should not be ignored and the stiffness is *K*. Fig. 3 is the force vs. displacement relation of CMEJs.

$$f=\begin{cases}\tilde{k} & \Delta_d>\Delta_g\\ 0 & \Delta_d\le\Delta_g\end{cases} \tag{1}$$

$$f=\begin{cases}k(\Delta_d-\Delta_g) & \Delta_d-\Delta_g>0\\ 0 & \Delta_d-\Delta_g\le 0\end{cases} \tag{2}$$

where $\Delta_g$ is the initial clearance between two decks, $\Delta_d$ is the relative displacement between the adjacent decks, and $\tilde{k}$ is the stiffness of the cables. The stiffness $\tilde{k}$ is determined from

$$\tilde{k}=\frac{nEA}{L} \tag{3}$$

where *E* is the modulus of elasticity of the cable, *A* is the sectional area of the cable, *n* is the number of the cable, and *L* is the length of the cable.

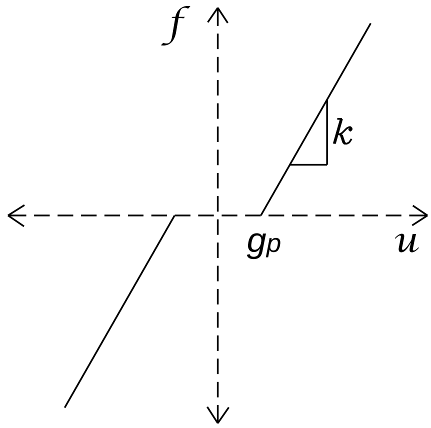


Fig. 3 Force vs. displacement relation of CMEJs

Table 1 Pseudo static test conditions

| Test Conditions | Compression capacity of the centre beam/mm | Determination of content |
|---|---|---|
| Condition 1 | 0 | The relationship between stretching resistance and cable at different displacements. And also tested the limiting function and cable force. |
| Condition 2 | 3 | |
| Condition 3 | 5 | |

## 5. Pseudo static test and analysis of CMEJs

### *5.1 Test device*

The quasi-static test is carried out in Datong Road and Bridge Components Company, Chengdu, China, which is the largest bridge components production enterprise in China and equipped with complete production facilities and testing equipment. We use a self-made test platform, including supporting platform, CMEJs specimen, pull and push transmission rod, pull and push sensor, displacement sensor etc., as shown in Fig. 4.

### *5.2 Test items*

In this experiment, three items were tested: 1. displacement of expansion joints; 2. Cable forces; 3. The relationship between cable elongation and tensile force at different displacements. Three cases are considered as following.

### *5.3 Test conditions*

In pseudo-static test, three cases are considered according to the different compression capacity of the centre beam, which are shown in Table 1.

Conditions 1, 2 and 3 are the compression values of the centre beams (as shown in Fig. 1(a)). Centre beams can move slightly in the transverse direction because of the displacement springs in the Yokes. Condition 1-the centre beam is compressed to 0 mm; Condition 2-the centre beam is compressed to 3 mm; Condition 3-the centre beam is compressed to 5 mm. In practice, the expansion joints will subject to self-weight and the wheel pressure on the road.

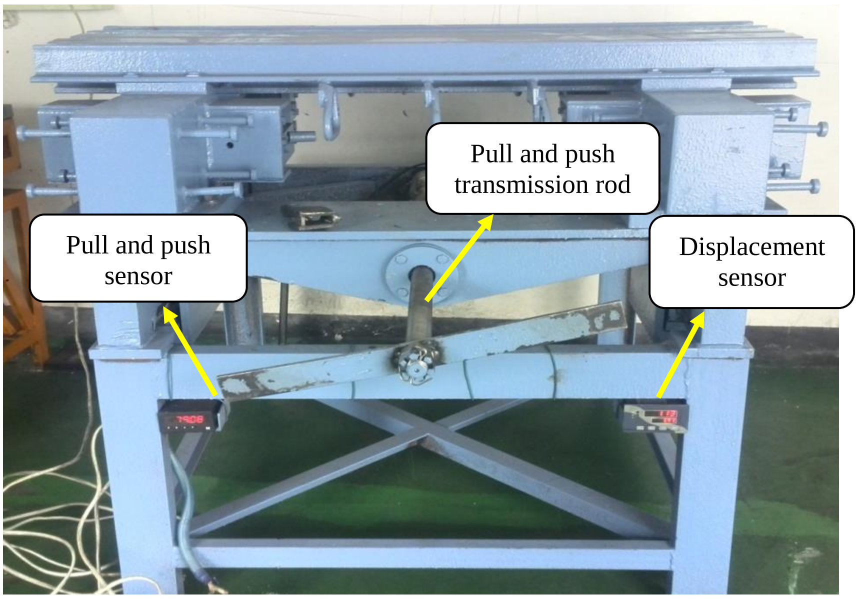


Fig. 4 Schematic diagram of the experimental set-up

The displacement springs use to control the lateral displacement of the device, so centre beam compression is a more realistic simulation for such situation. Moreover, the compression of the centre beams can avoid damages like rebound or disengaging of expansion joint caused by vehicle impact.

### 5.4 Loading systems

At present, there are three kinds of commonly used methods of load control for pseudo-static test: load control, displacement control, hybrid control of load and displacement. In this experiment, we employed equal amplitude displacement control. 0~±160 mm is the equal amplitude displacement control, i.e., for each condition, horizontal load is equal amplitude displacement control. Each 20 mm is a grade, which means a total of 8 levels are ±20 mm, ±40 mm, ±60 mm, ±80 mm, ±100 mm, ±120 mm, ±140 mm, ±160 mm, respectively. Due to restrictions of test equipment, this test adopts manual loading and the loading rate cannot guarantee completely uniform, but workers try to remain nearly the same as machine. For each level of the above displacement amplitude, this test conducts 10 cycles.

Considering the particularity of this test, at first, we do two times back and forth movement, and finally back to the middle. It means that the gap is 40mm (namely expansion joint is in completely squeezed state). Then start the test according to the following steps:

1) The first cycle test

Pulling the expansion device to the outside until the cable is strained, then record the displacement and resistance according to each shift 20mm. The recording points of the return stroke are in agreement with that of the process points. The maximum tension point and the minimum compression point are recorded simultaneously until the expansion joints after a cycle.

2) In accordance with the first cycle test, the next second to tenth cycles are the same.

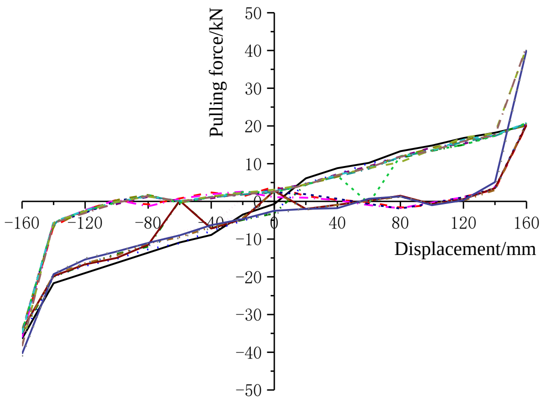


Fig. 5 Hysteresis curves of Condition 1

### 5.5 Test result analysis

#### 5.5.1 Hysteretic curve analysis

The relationship of cable force and displacement of test cases were analyzed. Fig. 5, Fig. 6 and Fig. 7 are hysteresis curves of Condition1, Condition2, Condition3, respectively. These figures and data shown that for each condition, at the beginning of loading, force and displacement fluctuate markedly and result in some jump points. There are two reasons: The one is that there is a certain friction force or cables may be stuck between the support bars and boxes during the tests. The other reason is that pull and push transmission rod is employed by workers, so the speed is not uniform.

However, with the increase of cycles, the more test platform is operated, the less error is found. Figs. 8-13 is the hysteresis curves of the ninth and tenth cycles of Condition1, Condition2, Condition3, respectively. From these figures, it can be seen that the curve pattern is obvious and the error is very small. When the length of the cable is within the free movement, cable forces are very small, and grow slowly with the increase of displacement. However, when the displacement is larger than the free movement, a small

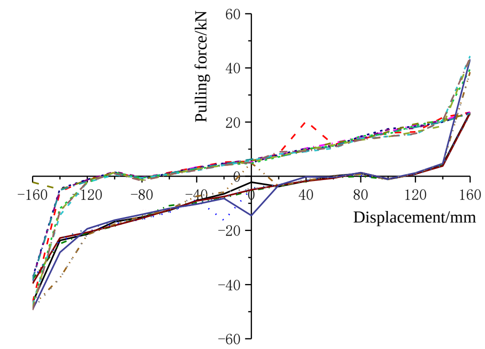


Fig. 6 Hysteresis curves of Condition 2

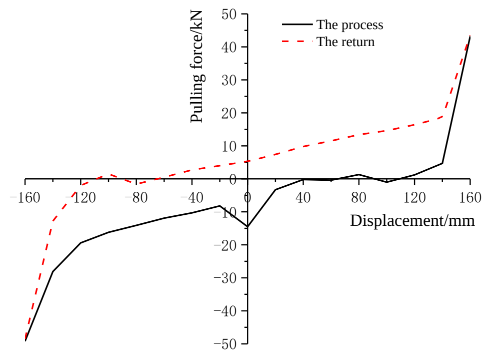


Fig. 10 Hysteresis curves of the ninth cycle of Condition 2

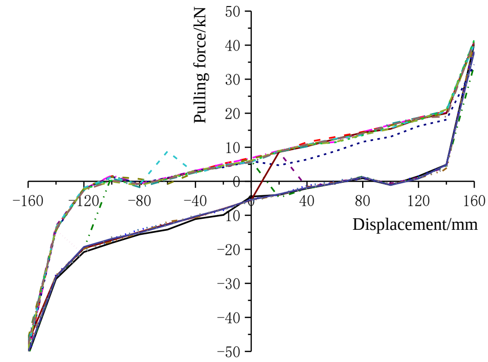


Fig. 7 Hysteresis curves of Condition 3

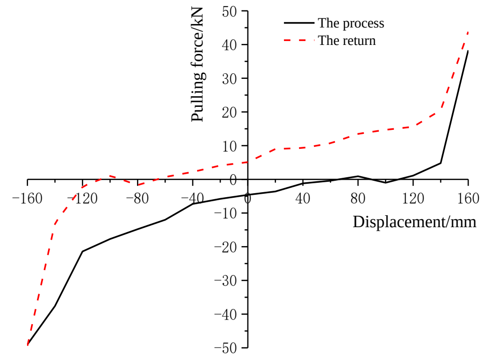


Fig. 11 Hysteresis curves of the tenth cycle of Condition 2

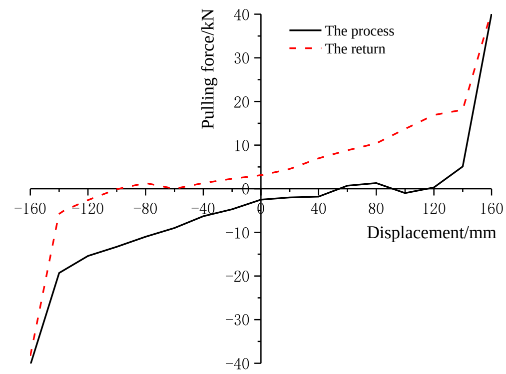


Fig. 8 Hysteresis curves of the ninth cycle of Condition 1

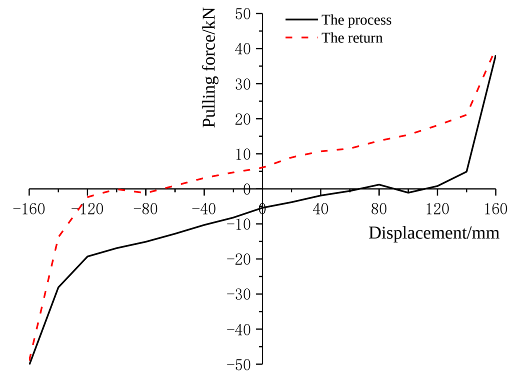


Fig. 12 Hysteresis curves of the ninth cycle of Condition 3

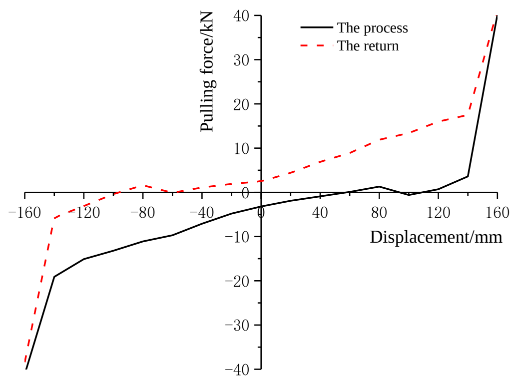


Fig. 9 Hysteresis curves of the tenth cycle of Condition 1

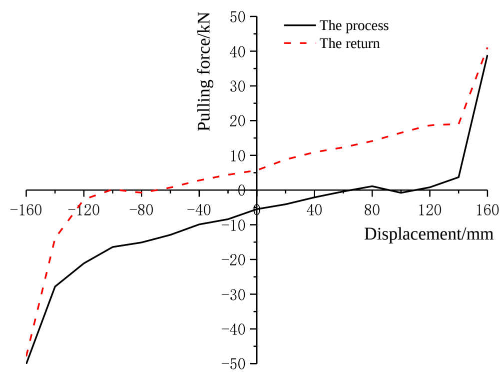


Fig. 13 Hysteresis curves of the tenth cycle of Condition 3

amount of displacement increase leads to the increase of pulling forces. Thus, cables play an effective role in limiting the displacement.

In order to better explore the experimental results, we carry on the scientific treatment to deal with the experimental data. In general, the arithmetic average (i.e.,

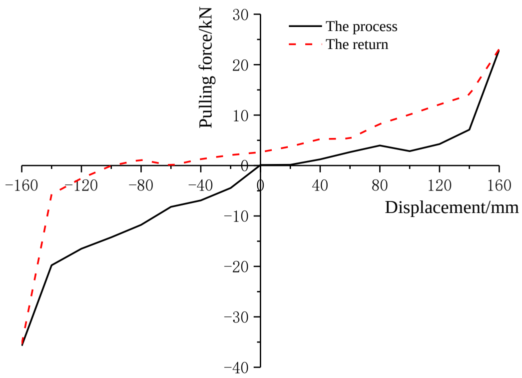


Fig. 14 Hysteresis curves of trimmed mean method of Condition 1

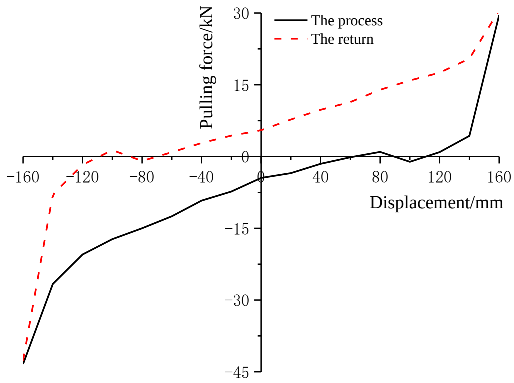


Fig. 15 Hysteresis curves of trimmed mean method of Condition 2

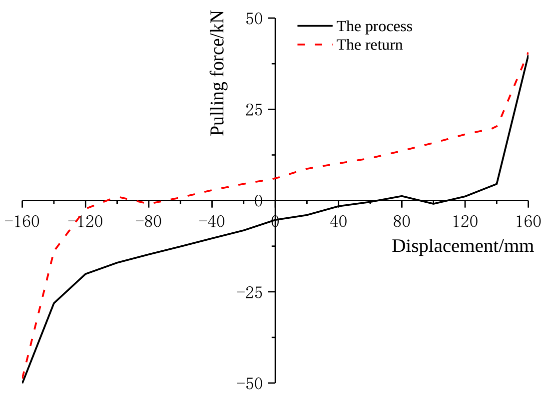


Fig. 16 Hysteresis curves of trimmed mean method of Condition 3

the average value of all cycles) is used to reduce the error. But the test platform has friction, especially in the initial stage of the test and the unavoidable defects of CMEJs, so these reasons can result in the unstable relationship between force and displacement during the first few cycles. Therefore, Trimmed Mean Method is more close to the reality (that is, the average value of removing a maximum and a minimum value for all measurements). As shown in Figs. 14-16.

### *5.5.2 Restoring force curve and cable stiffness*

From the previous sections, the relationship between

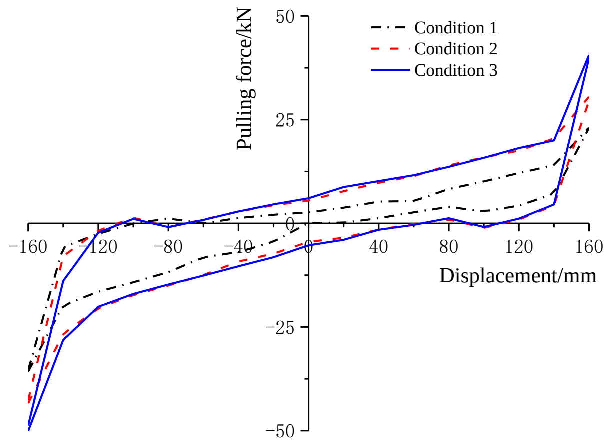


Fig. 17 Hysteresis curves of trimmed mean method of different conditions

Table 2 Cable stiffness

| Items | Cable stiffness *K* (kN/m) | |
|---|---|---|
| | The process | The return |
| Condition 1 | 793.125 | 1485.625 |
| Condition 2 | 1262.5 | 1736.25 |
| Condition 3 | 1765 | 1743.75 |

*The process is from negative to positive direction; The return is from positive to negative direction

force and displacement is more close to the reality when we used Trimmed mean method and error is reduced. Fig. 17 is the Hysteresis curves of Trimmed mean method of Condition 1, Condition 2 and Condition 3.

As can be seen from these figures, there exists errors and different conditions have different results. Calculated by regression analysis, cable stiffness is shown in Table 2. As we can see from the table, cable stiffness is significantly different from different conditions. But with the increase of the compression of the centre beam, the results tend to be true, and the stiffness value of the process and the return is symmetry.

## 6. Case study

Fig. 18 is a 3D model of a triple continuous beam bridge (4×30 m+36+56+36+4×30 m). According to the structure design, a three-dimensional dynamic finite element model is established and girders, piers are simulated as space beam and column element.

In general, the expansion joint's clearance is determined by static calculation. The number is 10cm in this paper. Fig. 20 is the recovery force model of bearings and CMEJs.

### *6.1 Input of ground motions*

In order to analysis the effects of CMEJs under different ground motions, the maximum multitude of each seismic wave provided by the report of seismic evaluation is changed to 0.2 g, 0.4 g, 0.6 g, 0.8 g, respectively, and the

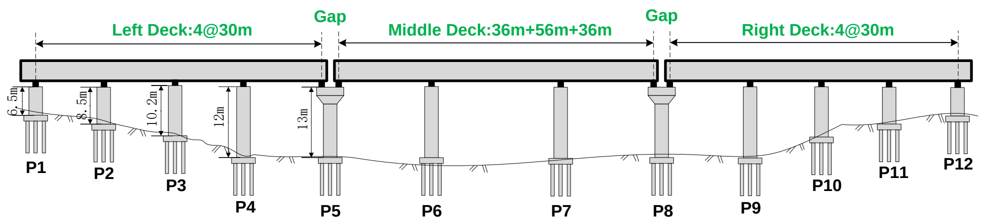


Fig. 18 Target bridge

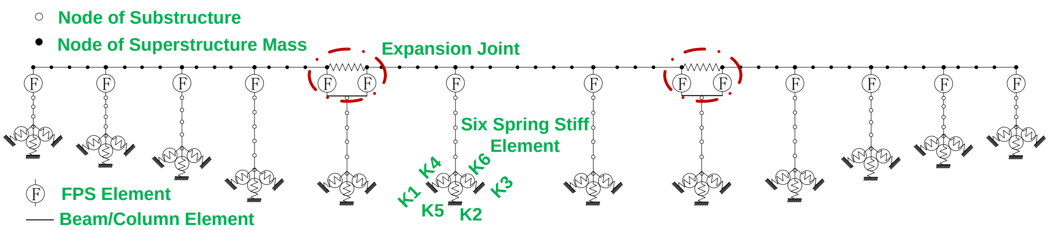


Fig. 19 Finite element model of isolated bridge with FPS bearings and CMEJs

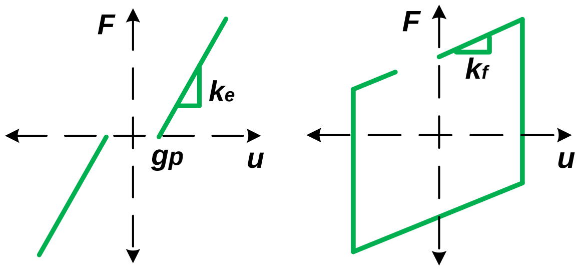


Fig. 20 Recovery force model of CMEJ and FPS

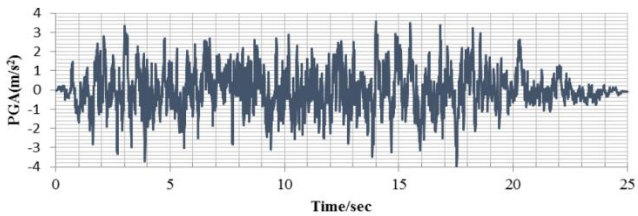


Fig. 22 Seismic wave

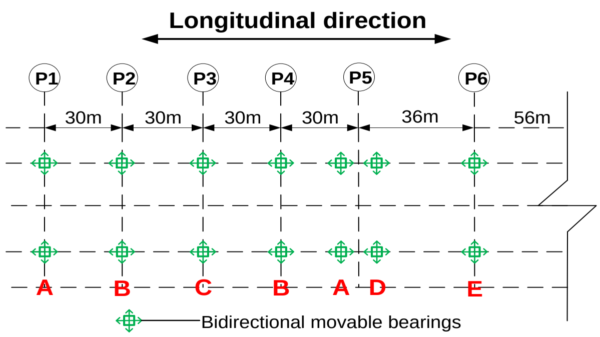


Fig. 21 Distribution diagram of bearings

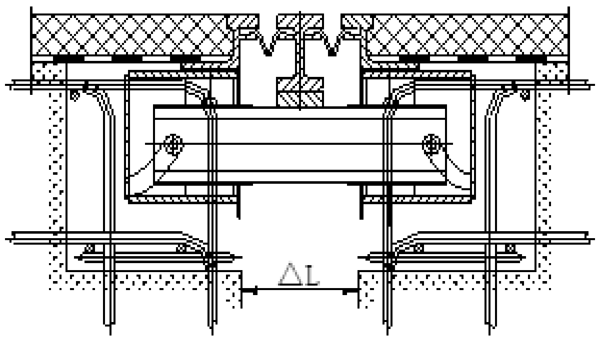


Fig. 23 Schematic diagram of CMEJs

more severe middle 25s are selected for the purpose of analyzing with filtering the beginning and end time history. It is can be summarized that pounding, unseating *et al.* usually occur in the longitudinal direction of bridges under the analysis of previous earthquakes. Therefore, this paper only considers the input of longitudinal direction. Time history analysis is used to evaluate the seismic responses of structures by adopting the method of direct integration and transient is selected for the type of time history. Calculation results choose the maximum of three seismic waves. Fig. 22 is one of the seismic waves.

The seismic response of the target model was investigated by SAP2000 V15.1 in this paper. The damping ratio of the concrete structure is 5%. The damping mechanism is introduced in the analysis through the Rayleigh damping matrix.

### *6.2 Calculation method of bridge expanded size*

Table 3 is the calculation method of the expansion joints of the model used in this paper. According to Fig. 2, the cable parameters of the target model can be calculated. A total of eight cable devices are set up at the expansion joints symmetrically. It is assumed that when the earthquake occurs, these cables are uniformly stressed.

Considering the elongation and compression length of CMEJs itself (compression length and telescopic length are different) and does not affect by the normal temperature change and the impact of vehicles. This paper chooses the CMEJs in Fig. 23. Which minimum compression is 11 cm and the maximum extension length is 27 cm. By analyzing a majority of the expansion joints in middle span bridges, finally this paper sets 10cm as the gap. That is, when the relative displacement between adjacent girders larger than 10 cm, collision occurs and the cable fails.

Table 3 Calculation of expansion joints

| Parameter series | | Values |
|---|---|---|
| The length of the calculated expanded length | $L$ | 64 m |
| Temperature range | $T_{max}$<br>$T_{min}$ | 35℃<br>-5℃ |
| Linear expansion coefficient of concrete | $a$ | 0.00001 |
| Shrinkage strain of concrete | $\varepsilon_\infty$ | 0.00020 |
| Creep coefficient of concrete | $\varphi_\infty$ | 2 |
| Modulus of elasticity | $E_c$ | 34500 MPa |
| Reduction factor of shrinkage and creep | $\beta$ | 0.6 |
| Average stress of cross section | $\sigma_p$ | 6.5 MPa |
| Installation temperature of expansion joints | $T_{set}$ | 15℃ |
| (1) Expanded length due to temperature change $\Delta L_t$<br>$\Delta L_t = a(T_{max} - T_{min})L$ | $\Delta L_t$ | 25.6 mm |
| (1.1) Elongation of beam due to temperature rise:<br>$\Delta L_t^+ = a(T_{max} - T_{set})L$ | $\Delta L_t^+$ | 12.8 mm |
| (1.2) Shortening amount of beam due to temperature reduction:<br>$\Delta L_t^- = a(T_{set} - T_{\min})L$ | $\Delta L_t^-$ | 12.8 mm |
| (2) Shortening amount of beam caused by Shrinkage of concrete:<br>$\Delta L_s = \varepsilon_\infty L \beta$ | $\Delta L_s$ | 7.7 mm |
| (3) Shortening amount of beam caused by creep of concrete:<br>$\Delta L_c = \sigma_p / E_c \times \varphi_\infty L \beta$ | $\Delta L_c$ | 7.2 mm |
| (4) The displacement of the beam at the expansion joints due to vehicle effect:<br>$R$=0.04 L | $R$ | 2.6 mm |
| (5) Total extension length=(1)+(2)+(3)+(4) | | 43.1 mm |
| (5.1) Total elongation of beam=(1.1) | | 12.8 mm |
| (5.2) Total shortening amount of beam =(5)-(5.1) | | 30.3 mm |
| (6) Design Length (considering 30% of the surplus): 1.3×(5) | | 56.0 mm |
| (6.1) Total design elongation of beam=1.3×(5.1) | | 16.6 mm |
| (6.2) Total design shortening amount of beam=1.3×(5.2) | | 39.4 mm |

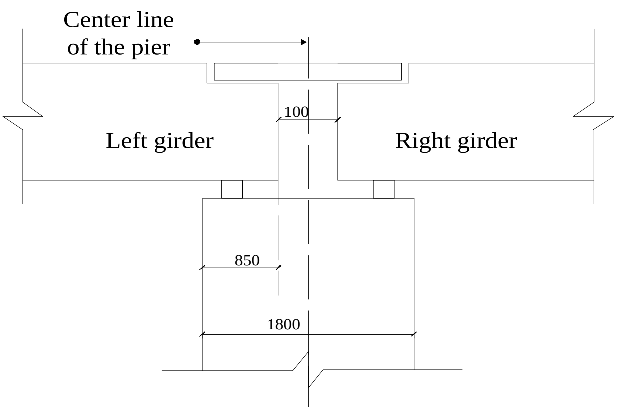


Fig. 24 Overlap length of the transitional piers

For the convenience of the study, we don't consider the failure of CMEJs or the failure of the anchor bolt. Fig. 24 is overlap length of the transitional piers.

Through the preliminary calculation, for conventional system, the free movement of cables is 8cm and the free movement of cables is 4cm in seismic isolation system.

Under normal use, this device can meet the needs of driving and temperature change, etc. After calculation, the total design rigidity of CMEJs is $[K]=5.65\times10^5$ kN/m.

### 6.3 Analysis cases

For the purpose of analyzing seismic responses of CMEJs under different ground motions and systems, two systems are established, Conventional System (using plate-type rubber bearings, noting as CS) and seismic isolation system (using friction pendulum bearings, noting as SIS), respectively. The effects of CMEJs are analyzed under the 0.2 g, 0.4 g, 0.6 g, 0.8 g of ground motions and the effects of pounding between adjacent spans are not considered in this paper.

Case 1: Conventional system (the free movement of cable is 8cm under the consideration of the fixed central piers and the side piers using pot bearings), with or without CMEJs respectively.

Case 2: Seismic isolation system (the free movement of cable is 4cm because of the bidirectional sliding under the nonlinear analysis), with or without CMEJs. Fig. 19 is finite element model of isolated bridge with FPS bearings and CMEJs

## 7. Case study

### 7.1 CMEJs' parameters

According to the formula provided above, the stiffness of the cable can be obtained. Four groups of cable devices (the total number is 8) are symmetrically set up along the width of the bridge spans at expansion joints. It is assumed that these cables are uniformly stretched when an earthquake occurs. Ultimately, the gap size of expansion joints is set to 10c m by analyzing the expansion joints of most of medium span bridges. When the relative displacement between the adjacent girders over 10cm, pounding occurs and means cables fails. Through preliminary calculation, the free movement of cables in conventional system is 8 cm and 4 cm in seismic isolation system. Both of them are meeting the requirements of driving and temperature changing under normal use.

### 7.2 CMEJs in Conventional system

The relative displacement of adjacent girders is the main control parameter of restrainer devices and the amount of reduced displacement is also a measure of the most intuitive effect standard of restrainer devices.

To facilitate the expression, the expansion joints with cable is noted as Y-CS, otherwise, noted as N-CS. Since the model selected in this paper is a symmetrical structure, the first girder and the second girder are selected as analytical elements and piers, central piers are noted as P5, P6, respectively. Fig. 21 is distribution diagram of bearings and Fig. 25 is bearings layout of the main bridge

The relative displacement of adjacent girders with/without CMEJs under different ground motions are shown in Fig. 26. The results show that whether the Y-CS or

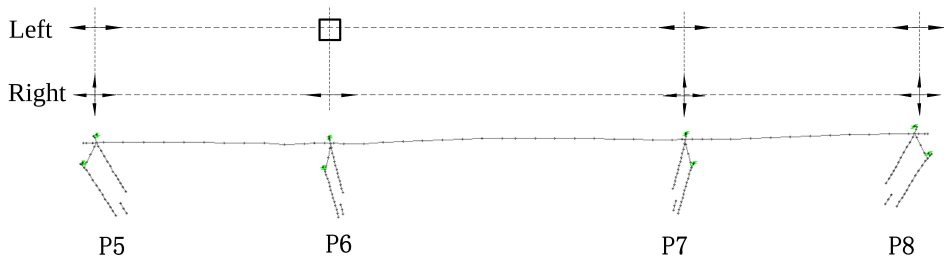


Fig. 25 Bearings layout of the main bridge

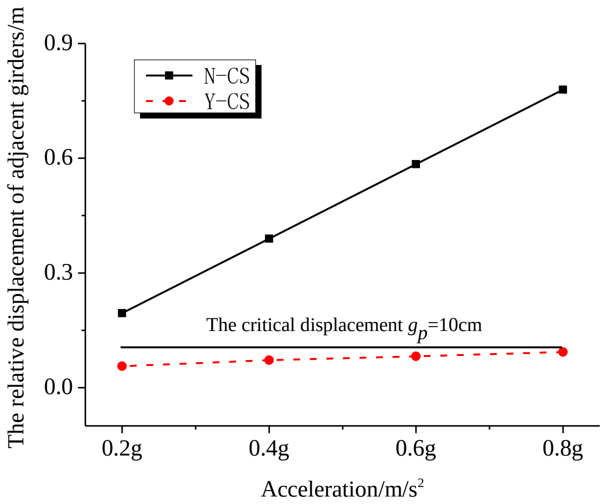


Fig. 26 The relative displacement of adjacent girders with/without CMEJs under different ground motions

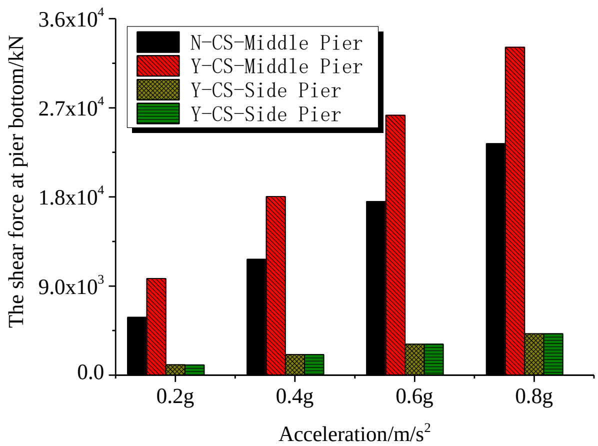


Fig. 28 The shear force at pier bottom with/without CMEJs under different ground motions

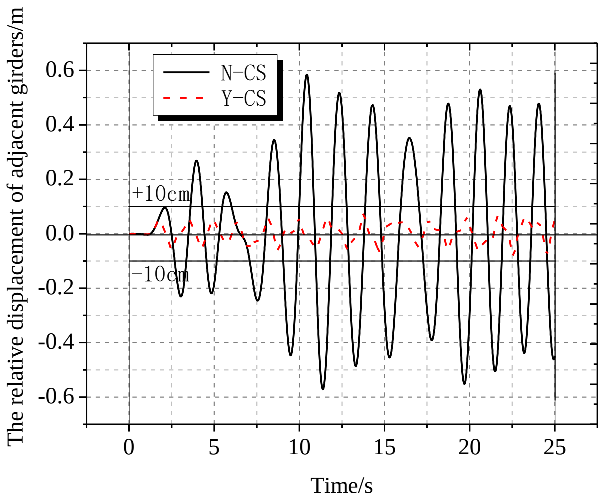


Fig. 27 The relative displacement time history of adjacent girders with/without CMEJs at 0.6 g

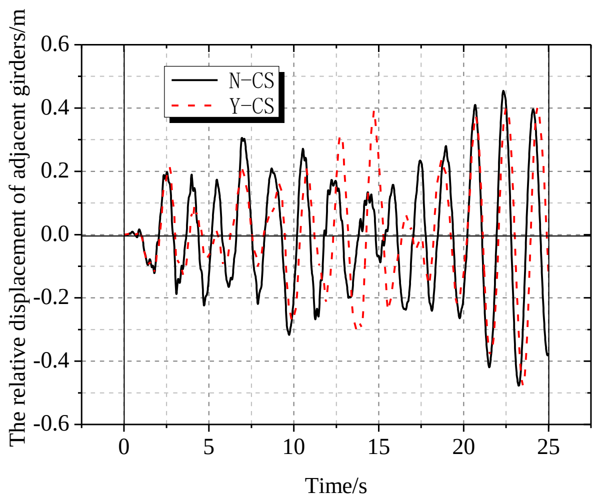


Fig. 29 Time-history of relative displacement between girder and pier at 0.6g with/without CMEJs

N-CS, the relative displacement of adjacent girders changes linearly with the increment of the acceleration of ground motion. However, N-CS increases quickly and Y-CS changes a little. The relative displacement of adjacent girders is controlled under the critical value with CMEJs, which realizes the transformation from passive regulation to active regulation. In addition, the relative displacement of adjacent girders is reduced 3 to 8 times by adopting CMEJs and the more intense of the ground motion it has, the more effective of the device.

On the other hand, Fig. 27 shows that with/without CMEJs has an obvious difference for relative displacement. For case with CMEJs, displacement of adjacent girders ranges within 10cm, which satisfies the requirement of bridges but leads to unintelligible displacement fluctuation. However, when we remove of CMEJs, structure fluctuation becomes obvious.

Fig. 28 shows shear force at pier bottom with/without CMEJs under different ground motions. Shear force at P5 changed little when CMEJs is installed. However, shear

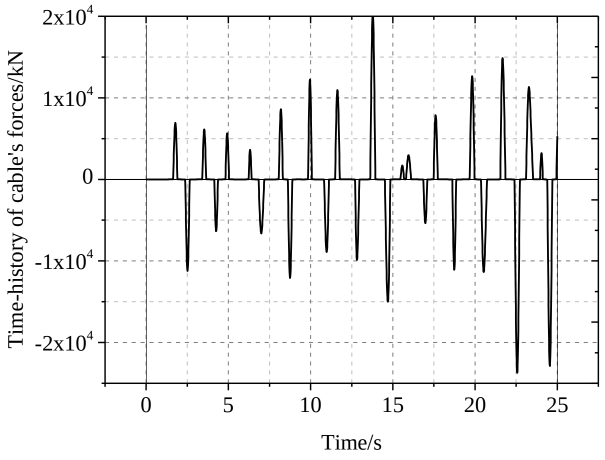


Fig. 30 Time-history of cable's forces at 0.6g

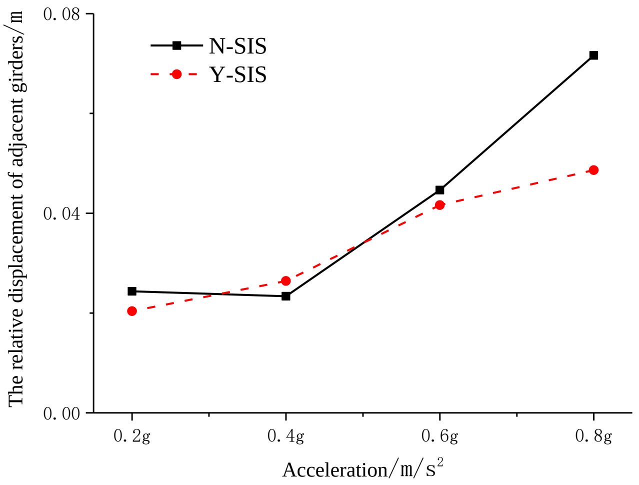


Fig. 31 The relative displacement of adjacent girders with/without CMEJs under different ground motions

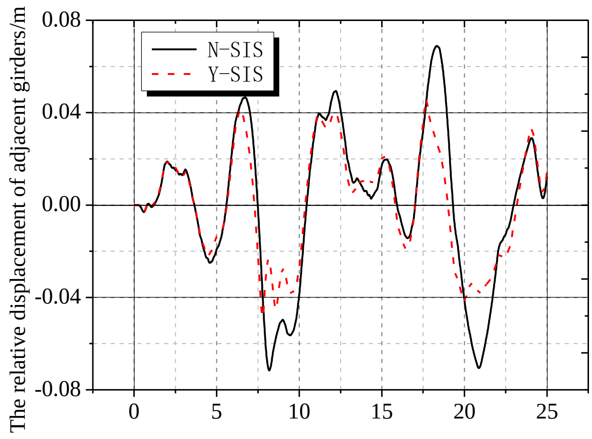


Fig. 32 The relative displacement time history of adjacent girders with/without CMEJs at 0.8g

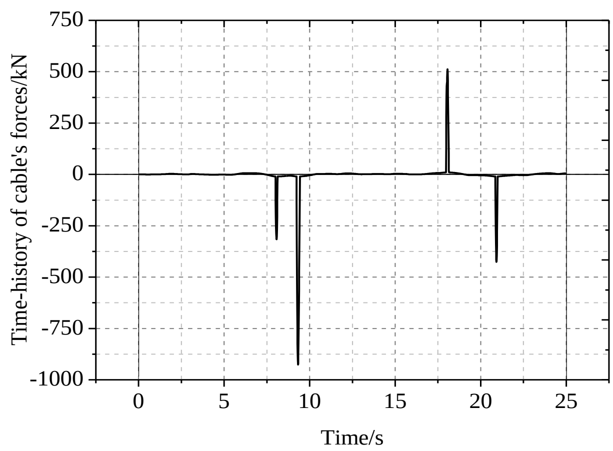


Fig. 33 Time-history of cable's forces at 0.6g

force at P6 with CMEJs is almost twice of that without CMEJs. The main reasons are described below. The one is that P6 uses fixed bearings which cause the shear force change directly. The other is that all the girders are connected together with CMEJs. When earthquake occurs, to some extent, inertial force of first girder transfers to the adjacent one and cause force at P6 change a lot. Seismic isolation system is used to solve the problem, which will be explained in the following text.

Fig. 29 shows the time-history of relative displacement between piers and girders at 0.6 g with/without CMEJs and correspondingly cable's force is described in Fig. 30. The period of structures with CMEJs changes but the max relative displacement remains the same.

The cable operates 26 times in Fig. 30, which contains 14 times for coming together, almost half of all. For acceleration of 0.2 g, 0.4 g, and 0.8 g it shows the same law, meaning that the cable deforms well and satisfies the need of relative displacement between girders. We can also find that the peak cable force is 2500 kN much less than the design load-caring capacity 3738 kN enabling the safety of the cable under various earthquake accelerations. Even at 0.8 g, cable force reaches 3874 kN near the load-caring capacity; it is still safe for the reduction factor of cable is considered when choosing cables.

### *7.3 CMEJs in seismic isolation system*

In seismic isolation system, bearings are in a bi-direction sliding mode. As shown in Fig. 31, For SIS, the relative displacements of adjacent girders are kept in a safe distance (0.1m). In addition, with the increase of the intensity of ground motion, the relative displacements of adjacent girders of the case with CMEJs is growth fading. For without CMEJs, the relative displacements of adjacent girders increase rapidly with the increase of the ground motion.

Fig. 32 shows the time history of relative displacement between adjacent girders with/without CMEJs. The relative displacement is restrained within 4cm after installing the cables and almost half of the displacement when compared with without CMEJs. That means the possibility of pounding is reduced.

Compared Table 4 and Fig. 33, For the seismic isolation system, the structural vibration period is changed due to its own characteristics, which makes the relative displacement of adjacent girders is smaller. What's more, the cable force

Table 4 The effect with CMEJs under different ground motions

| PGA ($m/s^2$) | Number of tensile | Max force (kN) | Max relative displacement between piers and girders(m) | Max relative displacement of adjacent girders(m) | The shear force at pier bottom(kN) | |
|---|---|---|---|---|---|---|
| | | | | | Middle Pier | Side Pier |
| 0.2 g | —— | —— | 0.07 | 0.02 | 1.57E+03 | 9.21E+02 |
| 0.4 g | —— | —— | 0.14 | 0.03 | 1.84E+03 | 1.39E+03 |
| 0.6 g | 4 | 926 | 0.26 | 0.04 | 2.45E+03 | 1.99E+03 |
| 0.8 g | 5 | 4890 | 0.44 | 0.05 | 3.05E+03 | 2.58E+03 |

is too little and can be ignored at 0.2 g and 0.4 g; even when reaches 0.6 g and 0.8 g, the cable force is still very low. Then we can draw a conclusion that the use of CMEJs doesn't reduce the relative displacement between piers and girders and the stress of piers, which well meets the conclusion we have expected. The true reason is that the CMEJs links girders together under SIS. Then the girders vibrate together when earthquake occurs. Because of the advantages of the system itself, the internal force at bottom of P5 and P6 keep in the safety range. The displacement between girders and piers is relatively large at 0.6g and 0.8g but unseating prevention devices can be used to solve this problem.

Therefore, combining isolation technology with CMEJs can be more effective to restrain the relative displacement between adjacent girders.

## 8. Conclusions

This paper introduced a device called CMEJs that can limit the relative displacements between adjacent girders. It not only meets the need of driving and deformation caused by temperature, but also restrains the displacements between girders. Compared the results of with and without CMEJs under CS and SIS, we drew the following conclusions:

(1) CMEJs can effectively control relative displacement between girders of continuous girder bridge and cable stayed bridge. The effect of anti-collision is very obvious.

(2) Then the experiment proves the validity and scientific of this device.

(3) the device combines with seismic isolation bearings, the anti-collision can reach the best. It can not only limit the relative displacement between girders and avoid the occurrence of the collision, but also control the relative displacement between piers and girders and avoid falling beam, which achieves the perfect balance between force and displacement.

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