**SIMPLIFIED METHOD OF DESIGNING AN INNOVATIVE SEISMIC IISOLATION SYSTEM FOR HIGHWAY BRIDGE**

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**ABSTRACT**

Since the sliding of laminated-rubber bearings and the concrete shear key failure were mostly observed for small to medium-span highway bridges in the 1999 Chi-Chi earthquake and the 2008 Wenchuan earthquake, an innovative isolation system composed of laminated-rubber bearings and yielding steel dampers was developed, designed and implemented in these bridges to improve their seismic performance during an intense earthquake. This study investigated the seismic performance of the proposed isolation system. By idealizing the bridge system as a simple series-parallel combination of bridge components (e.g. superstructures, bearings, steel dampers, substructures), several new parameters were defined and their correlated parametric formulations were derived accordingly. Based on this, a simple yet efficient step-by-step method of designing this innovative isolation system was presented.

*Keywords: innovative isolation system; highway bridges; simplified design method.*

**1. INTRODUCTION**

Economical laminated-rubber bearings and concrete shear keys have been widely implemented in highway bridges of China, especially those small to medium-span (span length mostly ranging from 10-40 m) ones (Xiang N, 201a). As common practice, the bridge superstructures would be directly placed upon the laminated-rubber bearings through embedded steel plates, and there was no other connection designed except the friction resistance at the contact surface between bearings and steel plates (Xiang N et al, 2017b). Such bridges have suffered from severe damages associated with laminated-rubber bearings and concrete shear keys in the past earthquakes. In the 2008 Wenchuan earthquake, the sliding of laminated-rubber bearings was a common damage phenomenon for highway bridges, which directly led to excessive displacements of the bridge superstructures (Li J et al，2008). The bearing sliding was also the source of many other damages, such as concrete shear keys failure, damages to abutments and expansion joints due to pounding, bearing unseating, and even span collapse. However, the post-earthquake investigation reported that most of bridge substructures (e.g. piers, foundations) were found to be damage free, or only experience minor damage without seriously affecting their load-carrying capacities. Although the sliding of laminated-rubber bearings might result in undesirable excessive superstructure displacements, it could actually act as fuses to limit the seismic forces transmitted from the superstructures to the substructures, thus protecting the substructures from severe earthquake damage.

In order to improve the seismic performance of these small to medium-span highway bridges with laminated-rubber bearings, an innovative seismic isolation system for small to medium-span highway bridges with economic laminated-rubber bearings is proposed. The objective of this study is to develop a simple and efficient design method for designing the innovative isolation system. For this purpose, parametric formulations were firstly derived to reveal the coupling effect of different parameters on seismic performances of the isolation system and the whole bridge system. Simplified design procedures were the presented to assist in designing this isolation system for highway bridges step by step on the premise of design requirements. A design example on a typical highway bridge was subsequently illustrated to validate the feasibility and practicability of the design procedures.

**2. INNOVATIVE ISOLATION SYSTEM**

For small to medium-span highway bridges with laminated-rubber bearings, an innovative isolation system is proposed to improve the seismic performance of these bridges. This proposed isolation system is composed of the sliding of laminated-rubber bearings and yielding steel dampers as shown in Figure 1. Under service or minor earthquake conditions, horizontal stiffness of bearings and steel dampers can provide sufficient elastic support to avoid excessive superstructure displacements induced by vehicle actions, wind actions, and minor earthquake loadings. When the bridge is subjected to medium to large earthquakes, the bearings are permitted to slide, producing a seismically isolated response for the bridge. Simultaneously, the steel dampers will yield and undergo large inelastic deformations to dissipate substantial earthquake energy, and thus effectively limit the bearing sliding displacements to prevent bridge unseating.



Figure 1. Configuration of the innovative isolation system

***2.1 Bearing sliding***

As there are normally no connecting components between the bridge girder and the laminated-rubber bearings for bridges in China, the bearing movement is prone to occur when the critical friction force at the contact surface is reached during the earthquake. Quasi-static experiments were carried out to investigate the movement behavior of laminated-rubber bearings upon steel plate. Figure 2 plots the setup of friction tests for the bearing, which is specifically designed to realistically reflect field conditions for the full-scale bridge bearing test specimen. Vertical loading was imposed on the bearing specimen using a actuator to simulate the gravity load. Cyclic lateral displacements were then applied to the bearing specimen with the constant vertical loading to provide the bearing-steel friction response.





Figure 2. Setup of friction tests for the bearing Figure 3. Force-displacement curves of bearing sliding

The force-displacement curves for the bearing specimen are shown in Figure 3. Furthermore, test results also revealed that the sliding coefficient of friction *μ*s between the laminated-rubber bearing and the steel plate was inversely related to the normal pressure *p* (MPa), and had a positive relationship with velocity *v* (mm/s), which could be expressed as(Xiang N et al, 2017b)

 (1)

***2.2 X-shaped steel damper***

X-shaped steel damper （Xu Y et al, 2016）is one type of the energy dissipation devices which has been widely used to decrease dynamic response of buildings subjected to earthquake excitation, as shown in Figure 4. The experimental tests were performed at Tongji University to investigate the mechanical behavior of X-shaped steel dampers. Figure 5 plots the typical force-displacement hysteretic curves of a sample specimen. It was observed that the X-shaped steel damper exhibits stable hysteretic behaviors and could sustain large numbers of yielding cycles without obvious stiffness degradation. The mechanic behavior of a X-shaped steel damper can be modeled by a bilinear model, which is characterized by the yield force, the yield displacement, and the strain hardening ratio of the damper.

 

Figure 4. Configuration of X-shaped steel damper Figure. 5. Force-displacement curves for X-shaped steel damper

**3. PARAMETRIC FORMULATION FOR THIS ISOLATION SYSTEM**

***3.1 Simplified model and controlling parameters***

Figure 6 schematically shows a simply supported bridge with the proposed isolation system, followed by an idealized model systematically representing the parallel-series combination of different bridge components. For laminated-rubber bearings, a simplified bilinear model characterized by an initial shear stiffness *Kb*, a sliding frictional force *Fyb* and a critical sliding displacement Δ*yb* (the displacement indicating the initiation of bearing sliding) is used to approximately simulate the bearing sliding behavior. The seismic behavior of yielding steel dampers is represented by an idealized bilinear model with an initial stiffness *Kd*, a yield force *Fyd*, a yield displacement Δ*yd* and a strain hardening ratio *β* (also referred as the ratio of post-yield stiffness to initial stiffness). The bridge substructure is assumed to remain essentially elastic during an earthquake, with an elastic lateral stiffness denoted as *Kp*.

The force-displacement relationships of the proposed isolation system (bearing-damper parallel system) and the whole bridge system are plotted in Figure 7. From the Figure, the initial stiffness of the isolation system *Kbd* and the initial stiffness of the whole bridge system *Ktot* can be respectively expressed as

 (2)

 (3)

*δt* is defined as the maximum displacement of the isolation system for design-level earthquakes, which is equal to the maximum displacement of individual components (bearing or steel damper). This parameter is of great importance, as it is generally used to assess the seismic risk of bridge unseating. Based on this, the maximum bearing displacement ductility *μb* is calculated by the ratio between *δt* and Δ*yb* as

 (4)

The maximum displacement ductility of the steel damper, *μd*, is given by

 (5)

The maximum displacement of the bridge system, or more specifically, the maximum substructure displacement for the design earthquake is denoted as *d*. If the bridge structure has a long natural period that lies in the constant-displacement region of the response spectrum, the equal displacement principle (Clough RW et al, 2003) [5] assuming that the maximum displacement of an elastoplastic system is the same as that of a corresponding elastic system could be applied, and *d* and *δt* are calculated as:

 (6)

 (7)

where *Fe* denotes the maximum inertial force of superstructure for the design earthquake by assuming an elastic seismic response for the bridge system. *Fe* can be easily calculated as the product of superstructure mass and spectral acceleration. In particular, as the isolation system is in series with the substructure, the superstructure inertial force sustained by the isolation system will be equal to the substructure base shear when the contribution of substructure mass is ignored.



Figure 6. Schematic representation of a simply supported bridge retrofitted with the proposed isolation system and its correlated structural components

 

(a) Proposed isolation system (b) Whole bridge system

Figure 7. Force-displacement relationships of the idealized bridge system

For simplicity, three dimensionless parameters are introduced for the proposed isolation system to illustrate the correlation between laminated-rubber bearings and yielding steel dampers, namely the bearing strength ratio *α*, defined as the ratio of the inertial force *Fe* to the bearing frictional sliding force *Fyb*; the damper strength ratio of *λ* that is the ratio between the inertial force *Fe* and the damper yield force *Fyd*; the stiffness ratio *γ* which is given by the initial stiffness of the damper, *Kd*, divided by the initial shear stiffness of the bearing *Kb*. The expressions of these three new parameters are listed as follows:

 (8)

 (9)

 (10)

Putting Equations (2), (4), (5), (7), (8), (9) and (10) together, *μb* and *μd* can be rewritten as

 (11)

 (12)

Thus, the values of *μd* and *μb* can be determined alternatively by the newly defined *α*, *λ* and *γ*. Taking *μd* as an example, Figure8 shows the diagrams representing the values of *μd* versus different values of *λ* and *γ*. The vertical axis represents the values of *μd*, whereas the horizontal axis shows the stiffness ratio *γ*. The solid line in the figure depicts the variation of *μd* against *γ* for a given *λ*. The horizontal and vertical dashed lines correspond to the thresholds of *μd* and *μb*, respectively, which can be specified according to the design objectives. Note that the correspondence between *μd* and *μb* can be established by the stiffness ratio *γ*, as presented in Equation (11) and (12).

 

(a) α=2 (b) α=6

 

(c) *α*=10 (d) *α*=14

Figure 8. Influences of *α*, *λ* and *γ* on the seismic response of the proposed isolation system

The shaded areas generated by the horizontal and vertical dashed lines, as plotted in Figure 8a-d, represent the admissible values of *λ* and *γ*. In this particular example, *μd*=1 is the lower bound value below which the yielding steel dampers will behave elastically without displaying the benefits of energy dissipation, while *μd*=6 denotes the upper bound value indicating the maximum allowable ductility of the dampers. *μb*=1 is the lower bound value of bearing displacement ductility above which the bearings are expected to slide during the earthquake, and *μb*=1.5 acts as the upper bound value which indicates that the maximum bearing sliding displacement should not exceed 50% of the critical sliding displacement Δ*yb*. These bound values for dampers and bearings are initially set to ensure a satisfactory seismic performance in these components. It is generally required that the bearings are permitted to slide during a major earthquake but with their sliding displacements being controlled within limit to prevent unseating, and the dampers are forced to yield to dissipate seismic energy while not exceeding their design ductility limit.

**4. SIMPLIFIED DESIGN METHOD AND STEP-BY-STEP PROCEDURES**

The previous studies revealed that for the proposed isolation system, the displacement ductility demands of yielding steel dampers and laminated-rubber bearings could be reliably predicted by some simple equations which were expressed by three key parameters, namely, the bearing strength ratio *α*, the damper strength ratio *λ* and the stiffness ratio *γ*. This is quite important for the seismic design of highway bridges with this proposed isolation system, as the suitable parameter values of yielding steel dampers can be easily selected to ensure that the maximum displacement demand of bearings for design earthquakes are controlled within design limit. For this purpose, a simplified design method and the corresponding step-by-step procedures were proposed based on the previous parametric formulation, to provide guidelines for the seismic design or retrofit of highway bridges with the proposed isolation system.

1. According to the design details of laminated-rubber bearings, calculate its sliding frictional force *Fyb* under dead loads and the initial shear stiffness *Kb* as:

 (13)

 (14)

where *m* is the superstructure mass, *g* is the acceleration of gravity, *G* is the shear modulus of rubber, *A* is the plan area of bearing, and *t* is the total height of rubber.

1. Calculate the lateral stiffness of pier substructure *Kp* using a static pushover analysis.
2. Select the maximum allowable displacement ductility of the yielding steel dampers, a value of 6 is recommended.
3. Calculate the fundamental period of the bridge without yielding steel dampers, which is used to obtain the spectral acceleration *Sa* from the design spectrum.
4. Assume a value of spectral acceleration *Si* for the bridge with yielding steel dampers. The assumed *Si* should be generally larger than the *Sa* obtained from Step (4), as the incorporation of yielding steel dampers will stiffen the bridge structure.
5. Calculate the initial value of *αi* by using Equation (8).
6. Choose a maximum allowable displacement for laminated-rubber bearings to avoid unseating, and then calculate its maximum displacement ductility *μb\_max*. The value of *γ* corresponding to *μb\_max* is calculated according to Equation (11).
7. According to the *α*-*λ*-*γ*-*μd* curves plotted in Figure 8, determine the suitable value of damper strength ratio *λi* that lies within the admissible areas (shaded area in the *α*-*λ*-*γ*-*μd* charts).
8. Calculate the required stiffness and yield force of the yielding steel dampers as follows:

 (15)

 (16)

1. Calculate the actual stiffness, the actual period *Ti+1* and the corresponding spectral acceleration *Si+1* of the bridge.
2. Determine if the calculated spectral acceleration *Si+1* equal to *Si+1*. If not, assume a new spectral acceleration and go back to Step (5) and then iterate until the actual value equals to the assumed one.
3. Calculate the values of *μb* and *μd* according to Equation (10) and (11), respectively. If the actual period of the bridge does not fall in the constant displacement region of spectrum, the displacement magnification factor *Rd* should be applied to correct the values of *μb* and *μd*.
4. Design the yielding steel dampers by specifying suitable geometric parameters (e.g. height, thickness and width of steel plates), to correspond to the calculated values of damper yield force and stiffness.
5. Design the longitudinal reinforcement in the pier substructure to ensure that the lateral strength of the pier structure, *Fyp*, complies with the following equation:

 (17)

**5. CASE STUDY: A DESIGN EXAMPLE**

***5.1 Bridge description***

A multi-span, simply supported T-girder highway bridge with a span length of 25 m was selected as the design example. The transverse view of the bridge was previously shown in Figure 6. Only transverse seismic design of the bridge example was considered in this study. The total mass of a single span superstructure is 568 ton. The substructures are double-column concrete bents with equal height of 8 m and equal column diameter of 1.4 m. Static pushover analysis was performed to obtain the transverse stiffness of a single bent as *Kp*=105000 kN/m. For preliminary design, there are five laminated-rubber bearings implemented under the bridge girders for a single bent, and these bearings have a sum shear stiffness of *Kb*=20970 kN/m. If the sliding coefficient of friction between the bearings and the steel plates embedded in the bridge girders is assumed to be 0.45, the sum of sliding frictional forces for the five bearings in a bent can be calculated as *Fyb*=2505 kN. The critical sliding displacement of bearing, Δ*yb*, is then obtained as the sliding frictional force divided by the shear stiffness of bearings, which equals to 0.122 m. The design acceleration spectrum used for this design example is shown in Figure 9. The spectral acceleration corresponding to the constant acceleration region of the spectrum is 1.575 g, and the characteristic period for this design spectrum is 0.9 s. For the design-level earthquake, design objectives of this bridge example can be illustrated as: the maximum displacement of the laminated-rubber bearings does not exceed 0.2 m, or the maximum allowable bearing displacement ductility is 1.64, while simultaneously, the pier bent displays an essentially elastic seismic response. Therefore, design process on how to easily select the suitable parameters of yielding steel dampers and design the substructure reinforcement in order to achieve these design objectives were presented in the following section.



Figure 9. Overview of the input earthquake excitations

***5.2 Design process using the proposed procedures***

For the bridge without yielding steel dampers, the fundamental period of the structure was calculated as 1.13 s according to the mass and stiffness properties, which lied in the constant displacement region of the spectrum. Based on the equal displacement principle, the maximum bearing displacement considering bearing sliding could be simply obtained from the response spectrum analysis on the corresponding elastic structure as 0.34 m, indicating that the bearing displacement would not satisfy the design requirements if yielding steel dampers were not incorporated.

For the bridge with yielding steel dampers, it was initially assumed that the spectral acceleration of the structure *Si* fell in the constant acceleration region of spectrum as 1.575 g. The superstructure inertial force of the elastic retrofitted structure was then calculated as *Fei*=8767 kN. According to Equation (8), the value of bearing strength ratio was obtained as *αi*=3.43. Considering the possible increase in ductility accounting for the magnification factor, the target displacement ductility of bearings was initially taken as *μb*=1.4, slightly lower than the limit value of 1.64. Further, the stiffness ratio *γi* could be calculated as 1.45 by Equation (11). For the displacement ductility of yielding steel dampers *μd*, a target value of 4.5 was set, which was lower than the upper bound value of 6. Accordingly, the value of damper strength ratio was calculated as *λi*=7.6 based on Equation (9). Then, the required values of the initial stiffness *Kdi* and the yield strength *Fydi* for the yielding steel dampers were obtained from Equation (15) and (16) as 30407 kN/m and 1154 kN, respectively. Other response paramters were finally calcualted as follows: *Ktot*=34497 kN/m，*T*=0.81 s，*Si+1*=1.575 g，*Fei+1*=8767 kN，*Rd*×*μb*=1.56＜1.64, *Rd*×*μd*=5.01＜6. As the actual *Si+1* were equal to the assumed *Si*, no further iterations were needed.

After obtaining the design parameters of yielding steel dampers, the minimum lateral strength of the pier bent required to maintain an essentially elastic seismic response could be calculated from Equation (17) as *Fyp*=4814 kN. If steel bars with a specified strength of 400 MPa were used as the longitudinal reinforcement in the pier bent, the required reinforcement ratio was calculated as 2.0% for this double-column bent with a height of 8 m, and a column diameter of 1.4 m.

***5.3 Seismic response analysis***

To verify the appropriateness of the obtained parameters for designing the yielding steel damper, nonlinear time history dynamic analyses were performed and seismic responses of the bridge example for the cases with and without yielding steel dampers were then compared. Ten spectrum-compatible artificial waves were used as the earthquake input for the time history analysis. Figure 10(a) shows the maximum bearing displacements obtained from the individual artificial waves for the cases with and without yielding steel dampers, respectively. It can be seen from the figure that the maximum bearing displacements calculated from all the ten artificial waves for the case without yielding steel dampers exceed the design limit, with an average value of 0.345 m. When the properly designed yielding steel dampers are implemented in the bridge, the corresponding values decrease significantly and the average value equal to 0.195 cm is found to be just below the design limit.

Sample time histories of bearing displacement for the two cases are shown in Figure 10(c) and (d). It is seen that the bridge example without yielding steel dampers is subjected to a high risk of unseating as the calculated maximum bearing displacement of 0.343 cm exceeds the design limit of 0.2 m. Moreover, a considerable residual bearing displacement of 0.12 m is observed after the earthquake, which is obvious by considering the lack of re-centering capacity for bearing sliding. Bearing displacement time histories for the bridge with yield dampers show that both the maximum and the residual bearing displacements as 0.195 m and 0.05 m, respectively, can be effectively controlled by the yielding steel dampers.

Figure 10(b) plots the cumulative force-displacement hysteresis of the pier bent for the same artificial wave. The hysteretic curves are relatively narrow, indicating that the pier bent does not undergo large plastic deformations and remains essentially elastic during the earthquake excitations. This proves that the proposed equation (Equation (19)) for designing the longitudinal reinforcement of substructure is feasible and effective, ensuring a satisfactory seismic performance of bridge substructure.



Figure 10. Summary of results from the nonlinear time history analysis

**6. CONCLUSIONS**

This research investigates the seismic performance an innovative isolation system proposed for typical highway bridges with laminated-rubber bearings in China, as well as its simplified design method. A simplified design method based on the parametric formulation is developed. Design example are used to validate the feasibility and efficiency of the proposed design method.

(1) An isolation system composed of laminated-rubber bearings and yielding steel dampers is proposed as an innovative retrofit strategy for highway bridges. In this isolation system, the sliding of laminated-rubber bearings acts as fuses to limit the seismic forces transmitted from superstructure to substructure, and simultaneously yielding steel dampers are expected to control bearing sliding displacements through their powerful energy dissipation.

(2) Three new dimensionless parameters, namely the bearing strength ratio, the damper strength ratio and the stiffness ratio of damper to bearing are defined to describe the correlated relationship of these two components in the proposed isolation system. These parameters can be combined to predict the displacement demands of bearings and dampers with adequate accuracy, which is further validated by nonlinear time history analyses.

(3) Based on the analytical results, step-by-step simplified procedures have been developed to design highway bridges r with this new isolation system. This method is based on the well-known equal displacement principle in structural dynamics, and can be easily implemented following a flow chart presented in this study.

(4) Case studies on a design example have validated the feasibility and effectiveness of the proposed design method. By using the simple procedures instead of complex nonlinear dynamic analyses, optimal parameters of the isolation system to achieve an expected performance can be obtained with a small number of iterations.

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