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Seismic Design Method of Small and Medium Spans Bridge Considering Bearing Friction Slipping

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Abstract

According to the comparison with bridge structural system between China and American/Japan, the difference of bridge damages in Wenchuan earthquake, American Northridge earthquake and Japan Kobe earthquake are proposed. The reasons of the damage rate at the bottom of piers in Wenchuan earthquake are also analyzed. Furthermore, the difference of the seismic load transmission path and the energy dissipation mechanism should be paid attention when the modifications and suggests of seismic specifications citing directly from the provisions of American or Japan. Combining with the difference on seismic performance of elastomeric pad bearing, lead rubber bearings, high damping rubber bearing, friction pendulum system, the view that bearings should be used as fuse-like elements in the seismic design is proposed. Referred to the design method of American and Japan, seismic design method of small and medium spans bridge considering bearing friction slipping is given in this paper. Seismic design methods of multilevel fortification and hierarchical energy dissipation are also suggested. Finally, the corresponding failure modes in longitudinal and transverse direction are proposed and some questions need to be studied are also discussed.

Keywords: elastomeric pad bearing, friction slipping, fuse-like element, minimum support length, failure mode

1. Introduction

A devastating earthquake with a magnitude of 8.0 on the Richter scale struck the Wenchuan area of the Sichuan Province in China. Comparing with the Northridge earthquake in 1994 and the Kobe earthquake in 1995, different characteristics appeared in the bridge seismic hazard. In Wenchuan earthquake, the number of severely damaged bridge columns was relatively fewer. It is significantly different from the bridge columns in Northridge earthquake and Kobe earthquake. 958 simply supported girder bridges were surveyed in the seismic intensity Ⅶ ~Ⅺ area, and only 2.8% (27) of the bridges damaged severely or lose failure. In this area, there were 3298 bridge spans, 19.5% (643) of the bridges suffered superstructures movement. Most of the bridges used elastomeric pad bearings: 16.6% (1092) of them (6596) damaged, and 16.8% (720) concrete shear keys damaged of all (4283). Only 2.4% (56) of the bridges piers (2316) suffered minor to moderate damage. Most of the earthquake bridge hazard is the movement of superstructure, and the damages in bearings or concrete shear keys. Piers are only slight damaged, which is mainly due to the sliding or dislocation of the elastomeric pad bearing. The mechanism of friction and sliding can greatly reduce the seismic force transmitted from the superstructure to substructure. Therefore, it can be used in the seismic design of small and medium spans bridges. In this paper, by comparing the structure systems in China with those in American and Japan, the characteristics of the seismic hazard in the Wenchuan earthquake, the Northridge earthquake, and the Kobe earthquake disclose the problems in citing foreign seismic codes or standards directly.

2. Comparison of Bridge Systems, Seismic Hazard and Specifications

2.1 American

The damaged piers in the 1994 Northridge earthquake are shown in Figure 1[2]. The top or bottom of pier suffered severe damage because of the insufficient stirrup and lack of ductility. Due to the reason that the costs of labor is relatively higher than the steel in North America, the integral abutment bridges with steel piles are common used, as shown in Figure 2. These bridges are similar to the rigid frame bridges whose pier and girder are consolidated together, and the sliding bearings with small friction coefficient are installed at the abutment. Once earthquake occurs, relative displacement will accumulate at the expansion joints of the abutment, which has enough support length or unseating prevention device to prevent superstructure falling. The most unfavorable position is located at the top or bottom of the piers which can perform as plastic hinges to dissipate earthquake energy in severe earthquake.

（a）Venice Boulevard overpass bridge

（b）Venice Boulevard overpass bridge

Fig. 1 –Damage of the piers

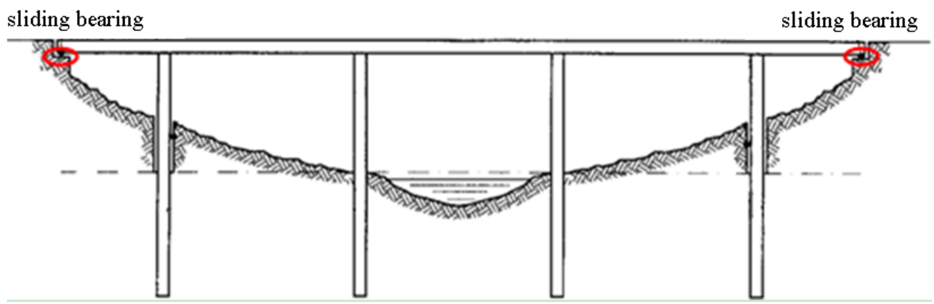


Fig. 2– Common structural style of bridges in U.S.

Initial development of Earthquake-Resisting System (ERS) strategy by the Illinois Dept. of Transportation (IDOT) began in 2005[3]. It was initially implemented in the end of 2006 and revised in the end of 2007 to reflect increased design accelerations being adopted in the American Association of State Highway and Transportation Official's bridge design code. A new seismic bridge design guide specification was published in 2007, which plays emphasis on the reliable, uninterrupted load path and the integrity of the Bridges. Therefore, the ERS of bridge structural system was divided into three types [4, 5]:

Type 1-Ductile substructure with essentially elastic superstructure: this category includes conventional plastic hinging in columns, walls and abutments which can limit inertial forces by full mobilization of passive soil resistance. Also included are foundations that may limit inertial forces by in-ground hinging. This is actually the ductility seismic design that uses plastic hinges in piers during an earthquake dissipating seismic energy. Caltrans firstly introduced this design approach in 1973 following the 1971 San Fernando earthquake. It was further refined and applied nationally in the 1983 AASHTO Guide Specification for Seismic Design of Highway Bridges which was adopted directly from the ATC-6 reports: Seismic Design Guidelines for Highway Bridges (ATC, 1981). These provisions were adopted by AASHTO in 1991 as their standard seismic provisions [4].

Type 2-Essentially Elastic Substructure with ductile superstructure: this category only applies in steel superstructures.

Type 3-Elastic superstructure and substructure with a fusing mechanism between the two: this category includes seismically isolated structures and structures in which supplementing energy-dissipation devices. The two parts are used to control inertial forces transferred between the superstructure and substructure. The last one is an emerging technology and has not been widely used as a design strategy in new construction [5].

Before 2007, the concept of bearings and their connections being designed as fuses was not fully endorsed by the AASHTO. However, the notion that connections between superstructures and substructures remain elastic during an earthquake was endorsed. In mid-2007, AASHTO approved some significant updates to Section 14 in the LRFD Code that deal with the design of joints and bearings. For extreme event loadings, clarification and expansion of the notion that bearings and their connections may be designed as sacrificial elements [3]. The primary objective of IDOT's ERS strategy is to prevent span loss. This is achieved through three levels of seismic structural redundancy: bearing as fuse-like element, the adequate support lengths and the plastic hinges in bridge columns or piles.

2.2 Japan

The severely damaged piers in the 1995 Kobe earthquake are shown in Figure 3 [6]. The bridges were devastated severely and it was similar to the piers in Northridge earthquake. The reason is the inadequate ductility of piers which leads to brittle failure. It was also found that the columns with sliding bearings suffered more serious damage than those with fixed bearings [7]. Steel bearings are widely used in Japan [8]. Once steel bearings damaged, movable bearings lost their sliding function and turned into the fixed support, then the inertia load of the superstructure would directly applied on the piers, as shown in Figure 4. Therefore, the piers were damaged since they had not been designed to resist large horizontal loads, as shown in Figure 5.

After the Kobe earthquake, the bridge seismic design code was revised in Japan. Special considerations were given to the seismic performance of the whole bridge system. Bearings and unseating prevention devices are also designed as main structural components, which could clearly reveal the seismic intensity relationship between piers and pile foundations. The seismic intensity of pile foundation should have more capacity than piers to make sure the plastic damage emerged in piers, which would reduce the inertia force in foundation transmitted from the superstructure [9].

Fig. 3–Pier damage in Kobe viaduct bridge

Fig. 4–Failure mode of bearings

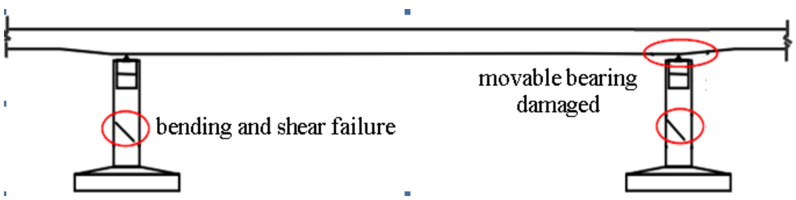


Fig. 5–Failure mechanism of bridges in Japan

2.3 China

In China, the bridge system which transforming from simple-supported girder into continuous girder is widely used in small and medium spans bridges. The PTFE sliding rubber bearings are proposed at expansion joints or abutments while elastomeric pad bearing are proposed on the top of piers. Also, this kind of structure system is partly used in continuous girder bridge. The common layout is shown in Figure 6. In Wenchuan earthquake, most bridges only suffered minor damage. The relative movements between the superstructure and the substructure are shown in Figure 7. Compared with the bridge systems in American and Japan, the bridge system in China is quite different from them. The bearings in China are usually placed on the top of piers directly without anchorage measures, so the link between superstructure and substructure is weak and damageable during earthquakes which could lead to the superstructure movement in the transverse and longitudinal direction [10]. The bearing sliding which could reduce the inertia force transmitted to substructure was taken as fuse-like elements [11-13]. These elements could protect piers and other major components.

After the Wenchuan earthquake, the new bridge seismic code "Guidelines for seismic design of highway Bridges" (JTG/T B02-01-2008) ("08 rules" for short) was promulgated [14]. Seismic design philosophy of “two stage fortification, two stage design” was adopted in the guidelines, and ductility seismic design and capacity design were also added in it. In the bridge ductility seismic design, the piers are ductile components, and the upper or the lower part of the piers are designed as plastic hinge zone which could use the plastic rotation of plastic hinge to dissipate seismic energy. Bases, cap beams, the superstructure and bearings are designed as capacity protected members. Bearings should meet the requirements of deformation and anti-sliding stability during strong earthquakes, but it is unreasonable to the use of elastomeric pad bearing in small and medium spans bridges in China. The concept that bearings should meet the requirements of anti-sliding is not suitable for the seismic design of Highway Bridge in China.

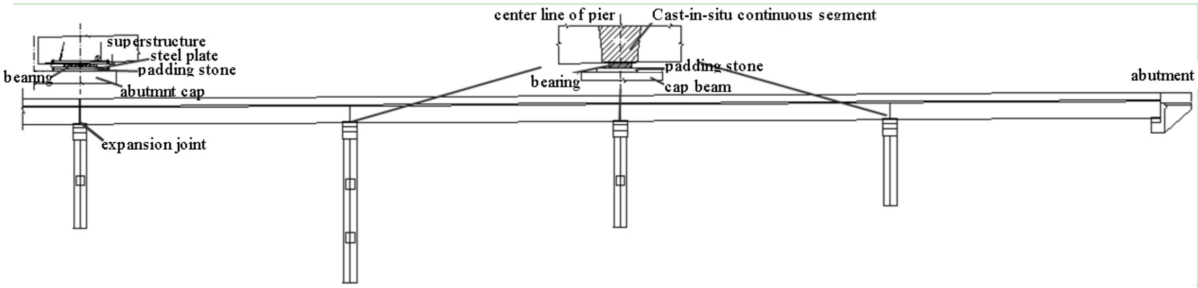


Fig. 6–Common bridge structural style in China

（a）bearings slipping and damaged shear key （b）movement of superstructure

Fig. 7 –Wen Chuan Earthquake

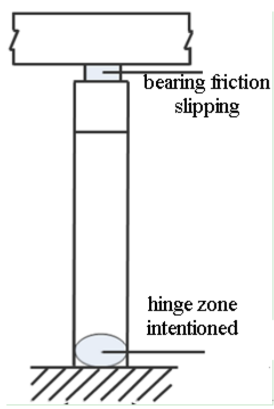


Fig. 8 –Wenchuan Earthquake

The connection between the superstructure and substructure is weak in small and medium spans bridges in China. Compared with that in American, there is a fundamental difference in the transmission path and the energy dissipation mechanism of the bridge structure system. Bearings are easy to slip during strong earthquakes. The transmission path will be interrupted after sliding, and the inertia force in the piers will be greatly reduced which mainly relying on bearing friction slipping to dissipate energy. Type 1 of ERS in AASHTO specifications is not suitable for the bridges that arranging elastomeric pad bearings in simply supported girder bridge or continuous girder bridge. This system is only suitable for pier girder consolidation system (including rigid frame bridge, fixed support or pier girder consolidation in continuous girder bridge or other bridges). Structure differences lead to different earthquake damage. Therefore, the seismic design code cannot cite directly from the code in American. Instead, the characteristics of bridges in China should be considered, and more attention should be given to the mechanism of bearing slipping in dissipating energy. In the seismic design, it can refer to the manual of IDOT [16] or the design method that unseating prevention device in Japan. Figure 8 shows the mechanism that uses the friction and sliding of elastomeric pad bearing to dissipate earthquake energy, and the provision for adequate support lengths to guarantee the integrity of bridges. If the seismic force is too large, it could serve as plastic energy dissipation mechanism of pier. The well performed bridges in Wenchuan earthquake also illustrated the advantages of elastomeric pad bearing. The friction slipping of these bearings could effectively dissipate inertia force in substructure and have a better damping effect.

3. Seismic Design Method Considering Bearing Friction Slipping

3.1 Characteristics of bearing energy dissipation

In Anti-seismic device (EN 15129-2009) [17], elastomeric pad bearings were regarded as isolated damping bearing. Compared with lead rubber bearing (LRB) , high damping rubber bearing (HDRB) and friction pendulum bearing (FPB), the elastomeric pad bearing has smaller damping (only about 5%). But when the earthquake force is greater than the friction force, bearings begin to slip and have good effects in energy dissipation. The isolation device requires a restoring force to reduce or eliminate the permanent lateral displacement. AASHTO adopted the regulation of the isolation device without the ability to reset, which defined the displacement capacity must be 3 times of design displacement in Guide Specifications for Seismic Isolation Design (1991). Guide Specifications for Seismic Isolation Design in 1999 cancel this provision. Instead, it defined that the isolation device should have self-resetting ability and the minimum restoring force. Also, the restoring force at dt shall be greater than the restoring force at 0.5dt with a difference not less than W/40 (AASHTO 2010,1.25%)[18,19], as shown in Figure 9. This provision in AASHTO had been cited directly by the code for seismic design of urban bridges (CJJ 166-2011).

Compared with the other bearings, elastomeric pad bearing don't have the minimum self-resetting ability and minimum restoring force, but it has its own advantages, such as manufacture convenient, mechanical property stable, low cost and easy installation [20]. Also, other types of bearings have different shortcomings: the lead in lead rubber bearing would cause irreversible environmental pollution during producing and using; the mechanical properties of high damping rubber bearing is greatly influenced by the rubber material, and its actual structural behavior needs further verification. For the friction pendulum bearings, scholars from New Zealand and Japan considered there are many problems need to be further studied, and this type of bearings were only used in bridge retrofit in the United States. For example, as the displacements of bearings are not identical; when displacements change, elevation changes will occur in the support, thus additional force will be produced. The friction pendulum bearings used in Sutong Approach Bridge are cylindrical in the longitudinal bridge, and they are effective only in transversely [7]. Therefore, the application of elastomeric pad bearings in small and medium span bridges is more suitable. But the inability to reset of these bearings should be noticed, and large permanent deformation may occur during strong earthquakes. According to the characteristics of this supporting system, it had been defined as "quasi-isolated system" by the United States IDOT.

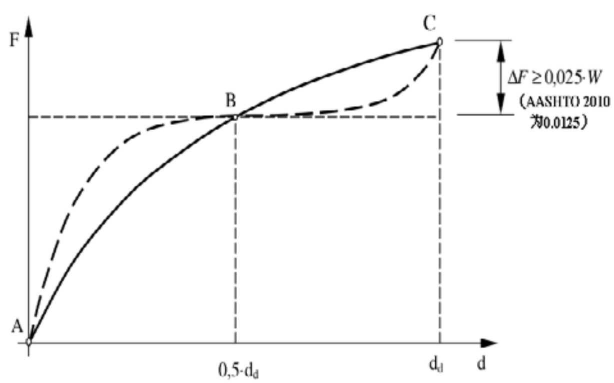


Fig. 9 –Graphical representation of the re-centering capability of an isolation system

3.2 Design methods

Since the 1960s, elastomeric pad bearings were widely used in multi-span highway small and medium spans bridges. According to the characteristics of this system, Wang Kehai[11-13] suggested that the damage of bearings acting as fuse elements should be priority during devastating earthquake, repairable plastic hinges could appeared in piers, and piles should be intact. In order to avoid bearing separation or slide during an earthquake, it should be anchored between the top of the pedestal and the pier or between the bottom of the pedestal and the girder in order to provide a relatively stable sliding surface. Therefore, when designing the small and medium spans bridges in China, the seismic performance of bearing and bridge pier should be comprehensive considered. According to design principle of "Multichannel fortification, Hierarchical energy dissipation", three-level redundancy was given:

Level 1 redundancy: bearing. Bearing damage should occur before the development of plastic hinges in pier, and after bearing sliding, with the limiting structure devices beginning to take effect.

Level 2 redundancy: minimum support length. When the limiting structure devices losing efficacy, bearing sliding could be allowed, but the overlapped length must meet requirements.

Level 3 redundancy: shear key and unseating prevention device. Double-layer shear keys can be used in bridges [24-26]. The inboard shear keys are used as sacrificial components which have the effect of buffering and energy dissipation. The outboard shear keys are designed to prevent falling beams.

(1) Level 1 redundancy

If do not consider the effect of vertical ground motion, x should be $x=\mu_d R_b/K$. Where μ_d is the dynamic friction coefficient of bearing; the dynamic coefficient of friction between neoprene and concrete is 0.15; the dynamic coefficient of friction between steel and neoprene is 0.10 (compared with Caltrans seismic design criteria [23], the coefficient of friction in China is more smaller while Caltrans is 0.4 and 0.35 respectively). R_b is reaction force in the bearing produced by the gravity of the superstructure. K is the shear stiffness of elastomeric pad bearing.

If the bearing deformation is less than x, sliding will not occur; if the bearing deformation is larger than x, sliding will occur in this bearing. Therefore, focus should be put on the influence factors of slipping resistance under the vertical load and friction slipping mechanism.

(2) Level 2 redundancy

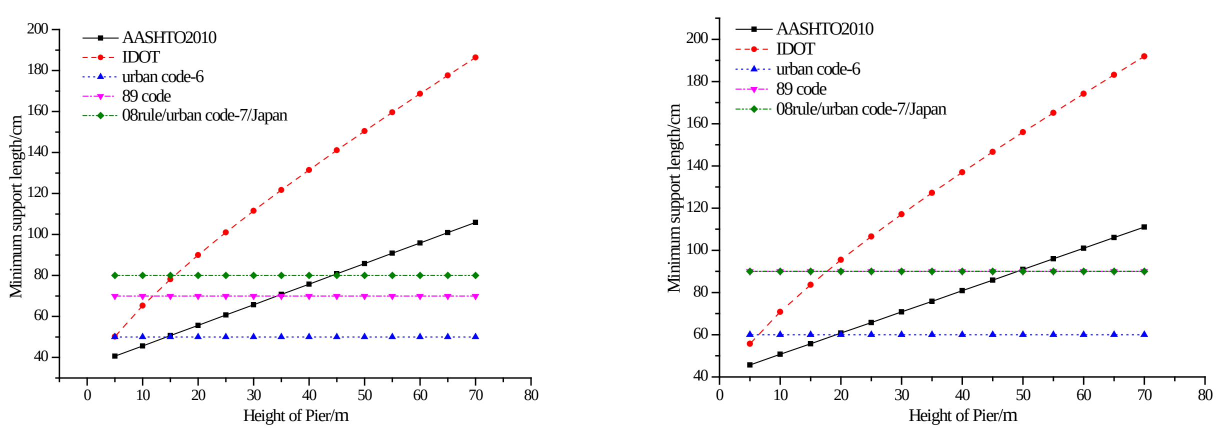
The minimum support length is a distance that prevent superstructure falling caused by accumulative displacement during strong earthquakes. It is the length from beam-end to the substructure bearing edge. The expression of the minimum support length in codes or manuals of American, Japan and China are shown in Table 1. The support lengths in skew bridge, curved bridge and high pier bridge are larger than those in the regular bridges, and the minimum support length of straight bridge is shown in Table 1.

The minimum support lengths of Code for seismic design of urban bridges (urban code for short) in region with intensity 6 or 7 of Chinese intensity scale are shown in Figure 10. It can be noticed that the minimum support length of urban code and 08rule is identical in the region with intensity 7 of Chinese intensity scale. For the spans less than 40 m, the minimum support length in 89code is less than that in 08 rules. For spans greater than 40 m, the minimum support length in 89code is equal to that in 08 rules. Compared with the minimum support length of America and Japan, it can be found that IDOT design manual is the most conservative when the height of piers less than 50 meters. The minimum support length of the AASHTO code was the least, but it is larger than the value in China code when the height of piers larger than 50 meters. The AASHTO code and the IDOT design manual had considered the influence factors of span and height of piers. The bridges in west of China cross deep gorges in heavy mountainous have high piers. For example, the span of a bridge is L=40 meters, the average piers height is 60 m, width-span ratio is 3/8, α=0°, FvS1=0.5; the minimum support length of the bridge is 0.9 m according to Japan code or 08rules, 1.01 m according to AASHTO code, 1.74 meters according to IDOT design manual. It can be noticed that the lengths in AASHTO code and IDOT design manual are larger than the value in China code. The reason is that the minimum support length in China code is cited from the Japan code which relying on experience mostly and some key factors are not considered in it.

Table 1 –Provision minimum support length requirements

codes	The minimum bearing width/cm	note
AASHTO	a=(20+0.0017L+0.067H)(1+0.000125s2) To SDC A，when As<0.05，it was 0.75a; when As≥0.05，1a； To SDC B and SDC C，it was 1.5a or the maximum in the calculated maximum displacements；	H: average height of substructure(m); s: skew angle of support (°); L: length from the bridge deck to the adjacent expansion joint(m); As: acceleration coefficient
08 rules/Japan	a≥70+0.05L	L: length from the bridge deck to the adjacent expansion joint(m);
Urban bridges code	a≥40+0.05L(in area of seismic intensity 6) a≥70+0.05L(in area of seismic intensity 7)	L: length from the bridge deck to the adjacent expansion joint(m);
89code	a≥50+L	L: length from the bridge deck to the adjacent expansion joint(m);
IDOT	$a=[10+0.17L+0.7H+5\sqrt{H}\sqrt{1+(2\frac{B}{L})^2}]\times\frac{1+1.25F_vS_1}{\cos\alpha}$	L: typically length between expansion joints(m); H: height of the tallest pier between expansion joints (m); B: width of superstructure; B/L: should be smaller than 3/8; A: skew angle (°); F_vS_1: spectral response coefficient of 1s period modified for Site Class

89code refer to Specifications of earthquake resistant design for highway engineering (JTJ 004-89);
Urban bridges code refer to Code for seismic design of urban bridges (CJJ 166-2011)



（a）L=20m （b）L=40m

Fig. 10 –Comparison of the minimum support lengths

(3) Level 3 redundancy

If utilizing measures of unseating prevention devices in longitudinal direction and double-layer shear keys in transverse direction [24-26], it is necessary to handle the relationship among the energy dissipation of bearing friction slipping, the minimum support length and the reasonable stiffness of unseating prevention device or shear key, so as to guarantee the displacement of the superstructure in reasonable support length, which could balance the superstructure's movement and the force transmitted to substructure[27-29]. By building the relationships between energy dissipation components of bearing, pier and shear key or unseating prevention device, the performance based seismic design method of multi-level fortification can be formed. But intensively and deeply research is still needed.

4. Failure mode of bridge

The design principle of multilevel fortification and hierarchical energy dissipation is the development direction of the current specifications. Many seismic measures have applied in small and medium spans bridges in China: utilizing elastomeric pad bearings to dissipate seismic energy by friction slipping, limiting displacements by unseating prevention devices or shear keys, allowing them to damage which can avoid large seismic force transmitted to the piers, and providing enough support length to prevent superstructure falling. In seismic design of bridges, the design principle of "controllable, detectable, repairable, replaceable" should be followed, which means the location and degree of damage should be controlled, the injury location should be checked easily, the damage components should be repaired or replaced easily. The failure mechanism of the small and medium spans bridges considering bearing friction slipping is given as follows, as shown in Figure 11 (unseating prevention devices are used in the longitudinal direction and double-layer shear keys are used in the transversal direction):

Under normal operating conditions, elastic shear deformations are produced in bearings.

Under minor earthquakes, elastic shear deformations or small slipping displacements which do not hamper vehicle driving are produced in bearings. Also, there is enough length to prevent slip impact between the superstructure and the unseating prevention devices.

Under moderate earthquakes, the friction slipping occurs in bearings and the inhibiting devices are contributing or yield, but the substructure remains elastic.

Under strong earthquakes, damages in bearings and inhibiting devices are permitted, unseating prevention devices are contributing, and limited ductility in piers are also permitted, but should make sure that there is enough support length to prevent beam falling.

According to the above failure mechanism, the failure modes in longitudinal and transverse direction during earthquakes are shown in figure 11.

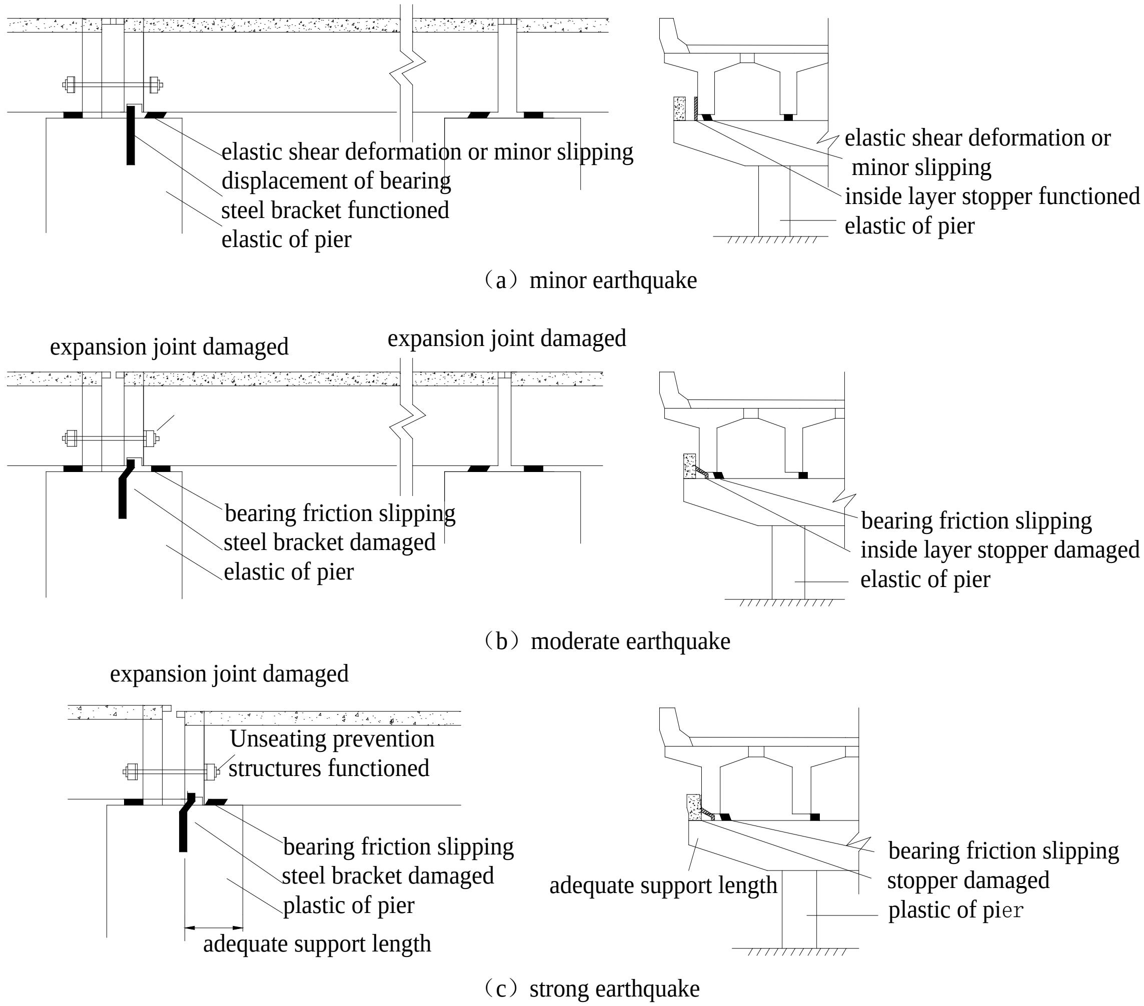


Fig. 11 –Failure modes of bridges

5. Conclusion

Considering that elastomeric pad bearing is the main type of bearings used in medium and small span bridges in China, it is suggested that the characteristics of bearing friction slipping should be considered. Also, integrated design should be given to bearings, shear keys and support length to achieve the principle of multilevel fortification and hierarchical energy dissipation. In the seismic design of bridge, the principle of controllable, detectable, repairable, replaceable should be followed (that is the location and degree of damage should be controlled, the injury location should be checked easily, the damage components should be repaired or replaced easily), to achieve the objective of using the lowest cost to minimize the possible damage in bridges.

6. Acknowledgements

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