AN IMPROVED SEISMIC DESIGN STRATEGY OF LAMINATED RUBBER BEARINGS FOR ELEVATED-GIRDER BRIDGES IN JAPAN

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1. INTRODUCTION

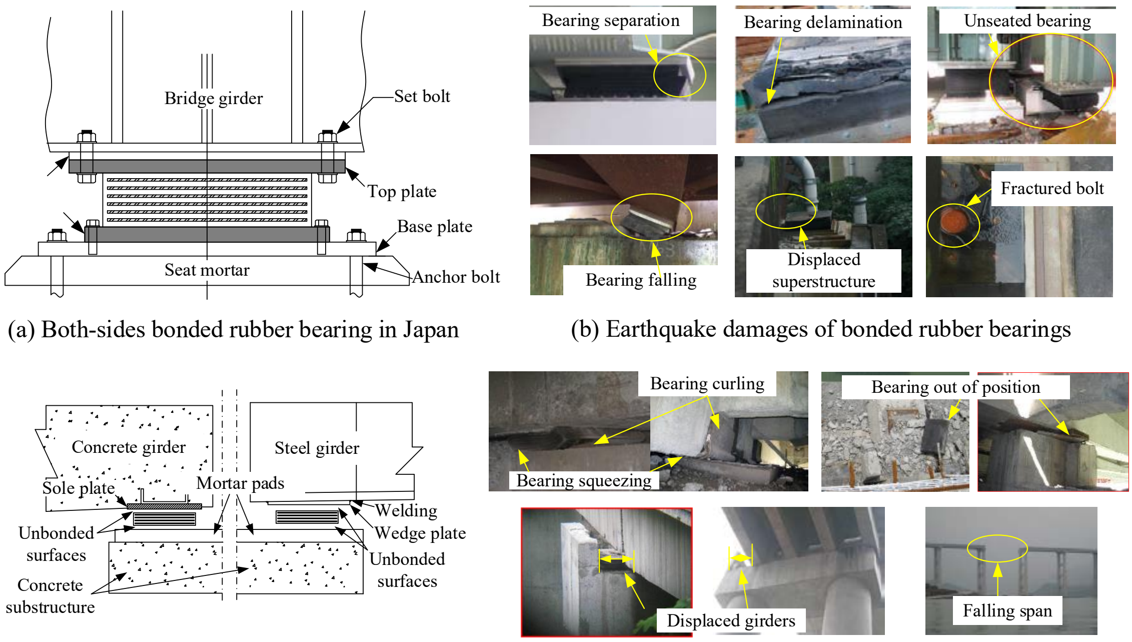
Since the 1995 Kobe earthquake, laminated rubber bearings have started to be widely implemented in bridges to replace the conventional steel bearings. The effectiveness of rubber bearings as horizontal force distribution or isolation devices in mitigating the seismic damages of bridge piers has been verified in the past earthquakes following the 1995 Kobe earthquake. However, during the recent 2011 Great East Japan earthquake (Kawashima 2012) and the 2016 Kumamoto earthquake, such rubber bearings were subjected to challenges, where extensive bearing damage/failure were observed at several bridges occurring before the damage of bridge piers. Such an unexpected damage phenomenon attracted the attention of researchers to rethink the current design strategy of bridge rubber bearings in Japan (Goto et al. 2017).

As common practice, the installation configuration of rubber bearings in Japanese bridges is typically described as follows: both top and bottom surfaces of a rubber bearing is bonded to external plates, which are then bolted to superstructure and substructure of bridges, respectively (called the both-sides bonded). Such a practice ensures the normal function of a rubber bearing to generate adequate shear deformations, which has been initially expected to be satisfactory during earthquakes. The current design method of rubber bearings in Japan is carried out based on such an installation by considering the force components of vertical force, shear force, and shear force-induced moments (P-delta effect). Different from that, some countries around the world adopt different installations for bridge laminated rubber bearings, such as the both-side unbonded in China, and the one-side bonded in several states of the United States.

This study first reviews the typical damage patterns for bridge rubber bearings in the past earthquakes in Japan and some other areas globally, from which the different damage/failure process resulted from different bearing installations are summarized and highlighted. Considering the exposed seismic deficiencies of bridge rubber bearings, an improved bearing design strategy is then proposed for elevated-girder bridges in Japan to resist super-large magnitudes of earthquakes. Critical design issues regarding the proposed strategy are pointed out and discussed.

2. TYPICAL EARTHQUAKE DAMAGES OF BRIDGE RUBBER BEARINGS

The past earthquakes occurred in the recent two decades have revealed the extensive damage patterns of bridge laminated rubber bearings, including the ones with both-sides bonded and unbonded installation configurations. For the bonded case (Fig. 1a), as is commonly adopted in Japan, the damages of rubber bearings include the rupture of bearing bodies and the fracture of connecting bolts, which were typically observed in the 2011 Great East Japan earthquake and the 2016 Kumamoto earthquake, respectively. The damages of fully bonded rubber bearings resulted from the complicated combined force components acting on bearings, which made it highly vulnerable for bearings to reach their ultimate limit



(a) Both-sides bonded rubber bearing in Japan
(b) Earthquake damages of bonded rubber bearings
(c) Both-sides unbonded configuration in China
(d) Earthquake damages of unbonded rubber bearings

Fig. 1 Typical earthquake damages for bridge laminated rubber bearings

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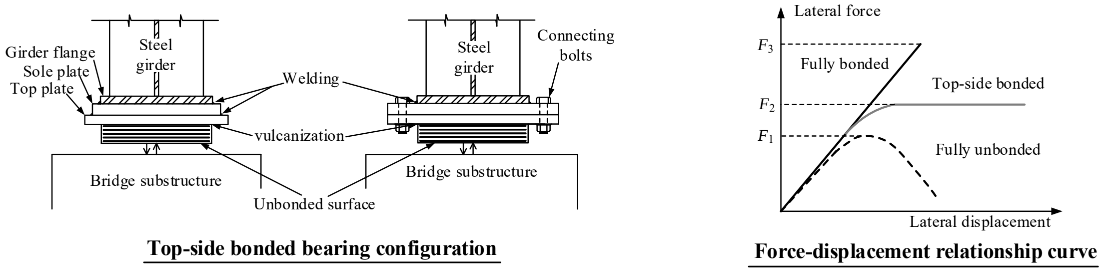
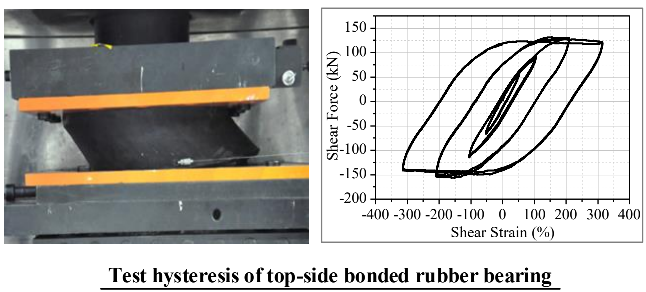
state under large earthquakes. The ultimate consequence of such a failure pattern is always the unseating of bearings (Fig. 1b). For the rubber bearings with fully unbonded configurations, such as those in China (Fig. 1c), although the unseating of such bearings was also common during the past earthquakes (Li et al. 2008), its direct cause, however, is usually attributed to the relative sliding between bearings and bridge superstructure/substructure due to the lack of positive connection measures (Fig. 1d). The bearing unseating of the unbonded case was more serious than that of the bonded case, where the catastrophic span falling was more prone to occur.

By evaluating relative performance between fully bonded and unbonded rubber bearings, it can be concluded that 1) although fully bonded rubber bearings are effective in utilizing the shear deformation of rubber for seismic response mitigation, their performance under larger than expected earthquakes is questionable, where the bearing rupture may still occur due to the complicated force acting. Under large earthquakes, the bonded bearings may generate excessive forces, which will pose adverse effects on bridge substructures. In addition, the design and check of a fully bonded rubber bearing requires a significant amount of effort. 2) If the fully unbonded configuration of rubber bearings is adopted, the transmitted forces through bearings can be effectively limited due to the slippage of bearings when reaching a certain magnitude of earthquake. However, some critical issues are usually found in fully unbonded rubber bearings, such as the unstable behaviors of bearings like curling and squeezing, and the easy movement out of position.

3. TOP-SIDE BONDED BEARING CONFIGURATION TO IMPROVE SEISMIC PERFORMANCE

Considering the deficiencies of fully bonded and unbonded configurations of rubber bearings, an improved top-side bonded bearing configuration is proposed for bridges in Japan. By bonding the top side to the bridge superstructure and releasing the bottom side seated directly upon the substructure, the seismic performance of the rubber bearings can be greatly improved. For one hand, under small earthquakes, the top-side bearings are able to exhibit shear deformations for seismic resistance; when medium and large earthquakes come, the bearing sliding will be initiated and dissipating earthquake energy through friction. The seismic sliding displacement of bearings can be well controlled within a design limit by using proper displacement restrainers. The bearing sliding provides an isolated response for the bridge substructure, whose damages under large earthquakes can be effectively reduced. Compared with the fully unbonded case, the sliding with the one-side bonded configuration is more stable, easy to simulate by using analytical models.





$$\text{Fully bonded}: \quad F_s = K_s d_s, \ K_s = \frac{G_s A}{t}$$

$$\text{Fully unbonded}: \quad F_h = K_h d_s,$$

$$K_h = \frac{G_s A}{t}(1-\gamma\lambda), \ \lambda = \frac{t}{2b}$$

$$\text{Top-side bonded}: \quad F_e = K_e d_s, \ \text{when } d_s < d_c;$$

$$F_e = P\mu, \ \text{when } d_s \ge d_c$$

Formulations of bearing analytical models

Fig. 2 Top-side bonded configuration for bridge laminated rubber bearings

4. CONCLUSIONS

Considering the exposed deficiencies of bridge laminated rubber bearings during the recent earthquake events in Japan and other areas worldwide, an improved installation configuration with top-side bonding is proposed for such rubber bearings. For small earthquakes, the proposed bearings deform elastically for seismic force distribution; When large earthquakes strike, the bearings will be forced to slide, generating sufficient frictional energy dissipation and also providing an isolated seismic response for bridge substructure. Proper displacement restrainers are required along with the bearings to ensure a limited sliding displacement to prevent span unseating.

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