Assessment of seismic responses of skewed bridges with bidirectional collision effect

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Abstract. Unbonded laminated elastomeric bearings have been used widely for skewed highway bridges in China. This type bearing is likely to slip during an earthquake, which will lead to large girder displacement and collision phenomenon. In order to discuss the effect of different collision models and design parameters on the seismic response of skewed bridges in China, 3D beam-stick models of three-span highway bridges with skew angles varying from 0° to 60° are developed in this paper. The results show that the collision effect is the principal contributor to girder rotation. The collision model considered nonlinear property in this paper can capture the irregular behavior of skewed bridges correctly. The uneven collision phenomenon will be more obvious for changing the initial gap of shear keys, and the overall seismic responses are likely to become complicated. Then, an appropriate gap is recommended to reduce the seismic damage of skewed bridges.

1 Instructions
Since the late 1980s, the design principles of highway bridges in China compliance with the policy of “bridge following road-trend” [1]. The varied skew angles make skewed bridges fit road-trend easily, so a number of skewed highway bridges were constructed in Chinese, its quantitative proportion even reach to 40%-50% in some highways. However, the seismic response of skewed bridges become more complicated for the varied skew angles, and the lack of detailed design procedures increases uncertainty with regard to the seismic response of skewed bridges.

Post-earthquake investigations show that skewed bridges are vulnerable to severe damage. Foothill Boulevard Undercrossing occurred large girders displacement, and the pier performed shear failure during the 1971 San Fernando earthquake [2]. Gavin Canyon Undercrossing occurred girders falling for large girders displacement in 1994 Northridge earthquake [3]. Most skewed bridges existed girders rotation, shear keys and expansion joints failure during the 2008 Wenchuan earthquake, such as Duxiufeng Bridge on the national highway Route 213 [4,5]. Recently, some researchers studied the seismic performance of skewed bridges. [6-8] conducted parametric study on the seismic response of two-span skewed bridges, the collision effect between girders and abutment and the collision effect between girders and shear keys were also considered. While the researched skewed bridges were fixed between girders and piers, this was obviously differing from the skewed bridges in China, which using unbonded laminated elastomeric bearings between superstructure and substructure. [8] investigated the effect of the arrangement and stiffness of collision element on seismic response. However, the research was only considering the collision effect between girders and abutment, and linear elastic collision...
model was used. [9] studied the rotation mechanism of simply-support bridges. A double broken line model was used to simulate the pounding behavior in the study, but it did not include shear keys failure.

From what has been discussed above, the skew angle and collision effect are the main factors to make the seismic response of skewed bridges differ from regular bridges. In order to investigate the seismic response of skewed bridges with unbonded laminated elastomeric bearings in China, three-dimensional beam-stick models of three-span highway bridges with skew angles varying from 0° to 60° are developed. Subsequently, results of a comprehensive study on the effect of skewed angle, collision models and shear keys design parameters, are discussed.

2 Modeling methods

2.1 Modeling of skewed bridge

The benchmark bridge is a three-span skewed bridge with skew angle of 45° in Sichuan province of China. Each span length is 25m. The superstructure consists of four precast concrete box girders with height of 1.4m. Three-column bent is constructed with diameter of 1.3m, the reinforcement ratios and stirrup ratios are 1.25% and 0.87%, respectively. The height of the columns from the top of the footing to the bottom of the cap is 5 m. The unbonded laminated elastomeric bearings are placed directly between superstructure and substructure without any anchoring. The site class of the bridge is Type II in Chinese Standard [10].

SAP2000 program was used to develop detailed nonlinear 3D model (Figure 1). The linear elastic beam-column elements were selected to simulate the superstructure since it is not expected to damage during an earthquake. The plastic hinges were assumed to form at the top and bottom of the columns, the fiber P-M2-M3 (PMM) type hinge was used to define the characteristics of the plastic hinges. The cross section should be divided into enough fibers so that the properties difference between column cross section and fiber section are not more than 10%, and then the reasonable plastic hinge length and the position of the plastic hinges are determined [11]. The collision effects between girders and abutments as well as this between girders and shear keys were simulated using a combination of link elements and GAP element, which would be activated/inactivated through the gap element closing/opening. Soil-structure interaction was not taken into account. The benchmark bridge model was altered to develop models with various skew angles.

2.2 Shear keys behavior

Shear keys can restrict girder displacement effectively, but the collision effect between girders and shear keys may increase the seismic force in substructure. The commonly used shear keys mechanism models are linear elastic model and elastic-plastic model.

2.2.1 Linear elastic model. This model supposes the force - displacement relationship of shear keys following linear elastic rule, as shown in Figure 2.

2.2.2 Elastic-plastic model. [12] conducted experimental research earlier on the nonlinear characteristics of shear keys. They found that the shear keys performed five working levels under collision effect and put forward two spring hysteresis model by separating the contribution of concrete and steel skeleton respectively. [13] modified the Megally model by considering with shear keys construction characteristics in China, the hysteresis rule is shown in Figure 2, and the related parameters definition can refer to [13].
2.2.3 *Abutment behavior*. Linear elastic model and elastic-plastic model were used to consider the abutment-soil interaction. The elastic-plastic model referred to the experimental study results of [14], as shown in Figure 3. The stiffness of linear elastic model equals to the tangent stiffness of the elastic-plastic model. The collision effect between girders and abutment was simulated using a combination of link element and GAP element.
2.2.4 Selection and input of ground motions. According to site conditions and Chinese Standard [10], the target spectrum was established. Then three artificial ground motions were generated and four real ground motions were selected from PEER database. The match status between the average response spectrum of the seven ground motions and the target spectrum is shown in Figure 4. The PGA levels were amplified to 0.4g, and all ground motions were input along the longitudinal and transverse directions (X and Y) respectively.

![Figure 4: Response spectrum match](image)

3 Seismic response of skewed bridge with collision effect

3.1 The influence of different collision models

Collision effect is the main factor influencing the seismic responses of the skew bridge. Three finite element models taking longitudinal and transverse collision effect into account were built to investigate the influence on the seismic response of the skewed bridge, so as to determine reasonable collision analysis model:

(1) Model 1: Assuming that the gap is large enough so that no pounding effects happen.

(2) Model 2: It is supposed that shear keys would failure if its ultimate capacity has been reached, its function to restrict girders displacement would degrade, and abutment-soil interaction may perform nonlinear property under collision effect. The hysteresis rules are shown in Figure2 and Figure3. A combination of link elements considered nonlinear property and GAP element was used to simulate the collision effect.

(3) Model 3: The behavior of abutments-soil interaction and shear keys are linear elastic under collision effect. The line elastic rules are shown in Figure2 and Figure3. A combination of link elements considered linear property and GAP element was used to simulate the collision effect.
3.1.1 Girder rotation. Figure 5 presents the variation of girder rotation as skew angle increasing for different collision models. For the bridge with skew angle of 0° (regular bridge), there is no girder rotation occurring under any cases. For skewed bridges (skew angle larger than 0°), the girders perform small rotation without considering collision effect. While after taking collision effect into account, different levels of girder rotation occurs, and the rotation angle varies for different collision effect. The girder rotation angles of model 2, which considered nonlinear property of shear keys and abutments, were larger than that of model 3 considered linear property of shear keys and abutments. The ration between two models reached 3.02 times under the skew angle of 30°, which shows that collision effect plays an important role in the girder rotation of skew bridges. This can reasonably explain the common girder rotation of skewed bridges, which is often accompanied by the expansion joints and shear keys failure during the 2008 Wenchuan earthquake. In Figure 5, it also can be seen that the girder rotation angle increases as skewed angle increases, but does not increase linearly, which indicates skew angle complicates the seismic response of skewed bridges.

![Figure 5: Girder rotation](image)

3.1.2 Uneven pounding effect between girders and abutments. Figure 6 shows the impact force at 1# (obtuse corner) and 2# (acute corner) of right abutment. When skew angle less than 45°, the impact force at 1# (obtuse corner) and 2# (acute corner) are almost equal. Once skew angle reaches to 45°, the differences between the two impact forces get larger, especially for the model considered collision effect with nonlinear property of shear keys and abutments, the uneven collision phenomenon is obvious. To describe the uneven collision phenomenon between girders and abutment, impact coefficient k is defined as the ratio of the impact force at obtuse corner to the impact force at acute corner.

![Figure 6: Impact abutment force at 1# and 2#](image)
Figure 7: Impact coefficient $k$ of right abutment

The impact coefficient $k$ of both side abutments changing along with skew angle increases is illustrated in Figure 7. The impact coefficient $k$ increases obviously with the increases of skew angle. For model 2, which considered nonlinear property of shear keys and abutments, the impact coefficient $k$ of right abutment is nearly 1.0 when the skew angle was 0°, and reached to 2.44 at skew angle of 60°, which shows that the uneven collision phenomenon between girders and abutments occurs significantly. The different collision models used in modeling skewed bridges will result in different collision effect, the degree of uneven collision of model 2 was greater than that of model 3. The differences between two models get larger with the increases of skew angle. In summary, the model 3 considered linear property of shear keys and abutments significantly overestimates the impact force between girders and abutment, and it weaken the uneven collision effect, which cannot accurately reflect the rotation features of the skewed bridges girders.

3.1.3 The moment of bents. Figure 8 shows the base moment for bent 1-1. It can be observed that the base moments (Mx and My) of bent 1-1 increase with the skew angle under all cases. By comparison the base moments (Mx and My) of bent 1-1 of the three model, it indicates that the base moments get larger under the collision effect, which suggests that the collision effect enlarges the seismic response of skewed bridges. The influence on seismic response of skewed bridges considered linear property of shear keys and abutments is more obvious, the base moment Mx of bent 1-1 of model 3 is larger than that of model 2 by a factor of 2.2 (Figure 8(b)), which overestimated significantly the seismic responses at substructure.

Figure 8: Moment for bent 1-1
3.2 Effect of the initial gap of shear keys

The initial gap of shear keys is an important parameter of the collision effect between girders and shear keys, which plays significant role in restricting the superstructure displacement and influencing bridges seismic response. Based on the finite model considered nonlinear property of shear keys and abutments (model 2), the influence of shear keys design parameters on seismic response of skewed bridges is investigated by changing the initial gap of 5cm, 8cm, 12cm and 15cm.

![Figure 9: Girder rotation](image)

The girder rotation angles against with the initial gap are plotted in Figure 9. As can be seen from Figure 9, the trends of the rotation angles with the initial gap first decrease and then increase, especially for skew angle reaches to 45°. When the initial gap was 5cm, the impact force between girders and shear keys is large enough to make shear keys failure, then it loss the function of displacement restricting. While the initial gap was 15cm, the girders have enough space to move, meanwhile, the earthquake energy could be dissipated through unbonded laminated elastomeric bearings sliding and bents yielding, while the shear keys would remain elastic under collision effect, the displacement restricting function of shear keys could not work well, and the girder rotation angle is large enough. So, it is important to select an appropriate gap to assure shear keys restrict girder displacement effectively, but not increase the seismic force in substructure.

![Figure 10: Impact abutment force](image)

**Figure 10:** Impact abutment force: (a) at 1# (obtuse corner); (b) at 2# (acute corner)
The uneven collision phenomenon at right abutment under the application of different initial gap with 5cm, 8cm, 12cm and 15cm are investigated. As can be seen in figure 10, both impact forces at 1# (obtuse corner) and 2# (acute corner) decrease with skew angles increase, and it decreases more obvious at 2# (acute corner). When skew angle is the same, the impact forces at 1# (obtuse corner) under different initial gap are essentially equal, the maximum difference happened at the skew angle of 30° with the value of 2.1%. While the impact forces at 2# (acute corner) under different initial gap decreased significantly with the increases of the initial gap, the impact force for 5cm gap was 1.96 times larger than that for 15cm at the skew angle of 60°. According to the previous analysis of the girder rotation, the girders is induced to rotate anticlockwise firstly by the impact abutment force at obtuse corner, while the shear keys in transverse direction limit this rotation, and push the girders rotate clockwise, which increases the impact force at acute corner. It can be concluded that the impact effects in longitudinal and transverse directions influence each other and change the girder rotation mechanism. The interaction of collision effects in two directions will weak with the increase of the initial gap, the impact force decreases gradually at acute corner and lead to impact coefficient $k$ increase, the larger the skew angle is, the more impact coefficient $k$ increases (Figure 11), which indicates the irregular behavior of skewed bridges increase.

4 Conclusions

(1) The skew angle will complicate the seismic response of skewed bridges. As the skew angle increase, the uneven collision phenomenon at abutment become more obvious, and the interaction of collision effect in longitudinal and transverse directions may become closer, which means the irregular behavior of skewed bridges increased significantly.

(2) The collision effect between girders and abutment as well as this between girders and shear keys are the principal contributor to girder rotation. Different collision models lead to significant difference in seismic response. The collision effect considered linear property of shear keys and abutments could be better to restrict girder displacement, but it lead to overestimate the seismic force in substructure, especially for bridge with large skew angle. The collision effect considered nonlinear property of shear keys and abutments has the capability to capture the irregular behavior of skewed bridges. It is recommended that the elastic-plastic collision model should be used in the seismic design of skewed bridges.

(3) The initial gap of shear keys has great impact on the seismic response of skewed bridges. The girder rotation angles first reduce and then increase with the increase of the initial gap. The change of the initial gap will lead to suffer some degree of the uneven collision. An appropriate gap can decrease the seismic damage.

(4) According to previous literature, the soil-structure interaction plays an important role in structural vibration, it will increase structural damping. And some studies also noted that the input angle of ground motion may have great influence on the seismic response of skewed bridges. The further re-

**Figure 11:** Impact coefficient $k$ of right abutment

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search will be focused on the effect of soil-structure interaction and determining the most unfavorable input angle of ground motion of skewed bridges.

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References
[1] Wang, J.W., Wu, T.Y., & Li, S.H., et al. (2016). Refined study on longitudinal seismic pounding response of simply supported skewed girders bridge. Journal of Vibration and Shock 35(8):194-200. (In Chinese)
[2] Ghobarah, A.A. (1974). Seismic analysis of skewed highway bridges with intermediate supports. Earthquake Engineering and Structural Dynamics 2(3):235-240.
[3] Basoz, K. (1997). Risk assessment of bridge and highway systems from the Northridge earthquake. In Proc. The Second National Seismic Conference on Bridge and Highways, Sacramento, CA, pp. 65-79.
[4] Chen, L.S & Zhuang, W.L. (2012). Report on highways’ damage in the Wenchuan earthquake. Beijing: China Communication Press. (In Chinese)
[5] Zhang, H., Li, J.Z., & Saiidi, M. (2012). Evaluation of performance of a skew bridge in Wenchuan 2008 earthquake. In Proc. The International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, Tokyo, Japan, PP.1439-1450.
[6] Abdel-Mohti, A. & Pekcan, G. (2008). Seismic response of skewed RC box-girder bridges. Earthquake Engineering and Engineering Vibration 7(4):415-426.
[7] Abdel-Mohti, A. & Pekcan, G. (2013). Assessment of seismic performance of skew reinforced concrete box girders bridges. International Journal of Advanced Structural Engineering 5:1-18.
[8] Kaviani, P., Zareian, F., & Taciroglu, E. (2014). Performance-Based seismic assessment of skewed bridges. Report PEER 2014/01, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.
[9] He, J. & Ye, A.J. (2012). Seismic response of continuous skew bridges with pounding effect. Journal of Central South University (Science and Technology) 43(4):1476-1481. (In Chinese)
[10] Wang, J.W., Shen, X., & Li, J.Z. (2014). Study of rotation mechanism and skew degree influence of skewed simply-supported beam bridge under earthquake excitation. Bridge Construction 44(3):32-37. (In Chinese)
[11] JTG(2008). Guidelines for seismic design of highway bridges. Beijing: China Communication Press. (In Chinese)
[12] Aviram, A., Mackie, K.R., & Stojadinovic, B. (2008). Guidelines for nonlinear analysis of bridge structures in California. Report PEER 2008/03, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.
[13] Megally, S., Silva, P. F., Seible, F. (2002). Seismic response of sacrificial shear keys in bridge abutments. Report No. SSRP-2001/23, University of California, San Diego, La Jolla, California.
[14] Xu, L.Q., Li, J.Z. (2016). Design and experimental investigation of a new type sliding retainer and its efficacy in seismic fortification. Engineering Mechanics 33(2):111-118. (In Chinese)
[15] Duncan, J.M. & Mokwa, R.L. (2001). Passive earth pressure: theories and test. Journal of Geotechnical and Geoenvironmental Engineering 127(3):248-257.