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NONLINEAR SEISMIC RESPONSE ANALYSIS OF CURVED GIRDER BRIDGE WITH TWO-LEVEL UNSEATING FAILURE CONTROL SYSTEM

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Abstract

The bridge unseating failure will lead to transportation interruptions, and it is one of the most serious and common bridge damages during earthquakes. Firstly, a new two-level control system for seismic unseating failure of curved girder bridges was proposed according to the conceptions of passive energy dissipation, multi-failure and damage reduction in this paper. The system characteristics and working mechanism were introduced. Then, the nonlinear responses of a curved girder bridge with two-level unseating failure control system under the action of three different earthquake ground motions were carried out respectively by numerical simulation. In addition, the response results were compared with the same curved girder bridge without control system to examine the control effectiveness. Finally, the control system response behaviors in different control states were revealed. It is concluded that the proposed two-level control system for seismic unseating failure provides displacement restriction by pier-girder connection mode and unseating prevention by girder-girder connection mode respectively. The two-level control mode is automatically transformed according to the preset threshold value of structural damage reduction fuse. The system can achieve complementary advantages between pier-girder connection and girder-girder connection control mode, which may provide reliable guarantee for unseating-failure prevention and safety protection of bridge pier subjected to strong earthquake.

Keywords: earthquake, curved girder bridge, unseating, two-level control, numerical simulation

1. Introduction

The earthquake damages at home and abroad show that bridges are easy to destroy or fail in earthquakes. Among the many earthquake failures that may occur in the bridge, the most common and serious one is the bridge unseating (see references [1]). On one hand, bridge unseating will cause traffic interruption, seriously affect the post-earthquake rescue, and it is very difficult to repair after the earthquakes. On the other hand, the end of the girder is likely to impact the pier, resulting in the greater earthquake damage, such as overall collapse of the bridge.

At present, there are three kinds of main technical ways to realize unseating prevention: construction measures, seismic isolation passive control and unseating control system. The construction measures mainly adopt the qualitative design based on the experience of earthquake damage, so it is difficult to really play the effect of unseating prevention in the earthquake. The seismic isolation technology has some limitations and cannot completely solve the problem of unseating control. So, the scientific and reasonable unseating control system is the most effective way to reduce the earthquake unseating disaster of the bridge.

The bridge unseating systems have been widely used in many earthquake countries and regions, such as the United States, Japan, Taiwan and so on. The structures of the control system are also various. The United States and Japan are the first to carry out a series of studies on the bridge seismic unseating failure control system, including the on-the-spot investigation of the effectiveness of the unseating control system after the earthquakes, the experimental study and parameter analysis of various systems, the evaluation of existing design methods and the exploration of new design methods (see references [2] to [6]). These studies show that the unseating prevention systems with different structural forms are quite different in terms of technical maturity, functional characteristics, construction convenience, applicability and cost.

In this paper, a new two-level seismic unseating failure control system is proposed firstly. Then, the nonlinear earthquake responses of a curved girder bridge with two-level unseating failure control system are carried out and compared with the same curved girder bridge without control system to examine the control effectiveness. Finally, the control system response behaviors in different control states are revealed.

2. Establishment of a two-level unseating control system

As for the current control modes of bridge unseating failure (see references [7]), the pier-girder connection control mode can reduce the pier-girder relative displacement effectively. However, the seismic load transferred from superstructure into pier by pier-girder restrainers may aggravate the damage of substructure leading to an unrepairable damage or even collapse of bridges. The girder-girder connection control mode does not basically change the interaction behavior between superstructure and substructure. Therefore, the excessive pier-girder relative displacement cannot be controlled effectively.

According to both the unseating failure mechanism of concrete girder bridge and the deficiency of existing control mode of unseating prevention systems, a new type seismic unseating failure prevention system is proposed in this paper considering the following three aspects:

(1) Through passive energy dissipation mechanism to reduce the structural earthquake responses, realizing seismic energy dissipation design philosophy.

(2) According to different earthquake action levels to determine different performance control objectives realizing two-failure criteria.

(3) Through setting "structural fuse" to attain change of two-level control state and avoid unrepairable damage of important components due to application of restrainers realizing damage reduction philosophy.

On the basis of the above, the new two-level control system for unseating failure prevention can be established as shown in Fig. 1. As can be seen from Fig. 1, in the two-level seismic unseating prevention system, the first-level control function is energy dissipation-based displacement restriction and, when the small earthquakes and moderate earthquakes happen, relative displacement between span and pier of bridges can be reduced by restrainer device between girder and pier. While the threshold value of control switch valve is reached, the unseating prevention system can be transformed automatically to the second-level prevention mode. Thus, the control switch valve is also regarded as a "structural fuse" to avoid unrepairable damage of structure due to excessively large load transferred into pier. The second-level control function is unseating prevention and the span collapse can be prevented by mechanical connection between adjacent girders during strong earthquakes.

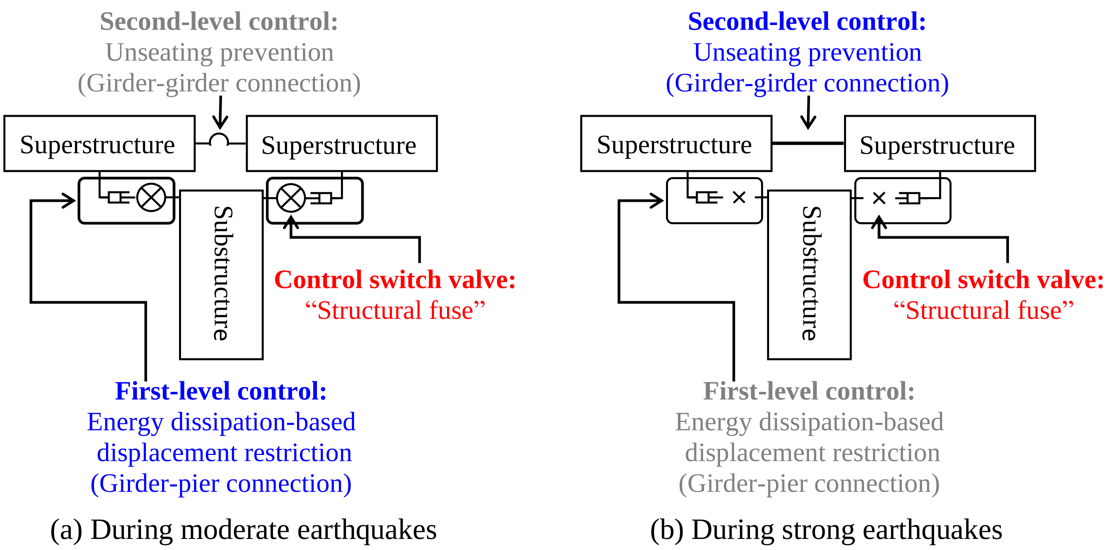


Fig. 1 – Illustration of working mechanism of two-level control system of seismic unseating failure

3. Multi-scale finite element modeling of curved girder bridge with two-level seismic unseating failure control system

3.1 Finite element model of bridge

In this paper, a two units with three-span reinforced concrete curved bridge is selected as the object of this study. The span length of curved bridge is 3×25m with a radius of curvature of 47.75m and the corresponding center angle is 30 degrees. The bridge deck width is 9.2m and the height is 0.86m. Pier height is 30m and diameter of single pier is 1.4m, spacing between two piers is 5.0m, as shown in Fig. 2. Sliding bearing is put in the bottom of No.1 pier and fixed bearing is put in No. 2 pier.

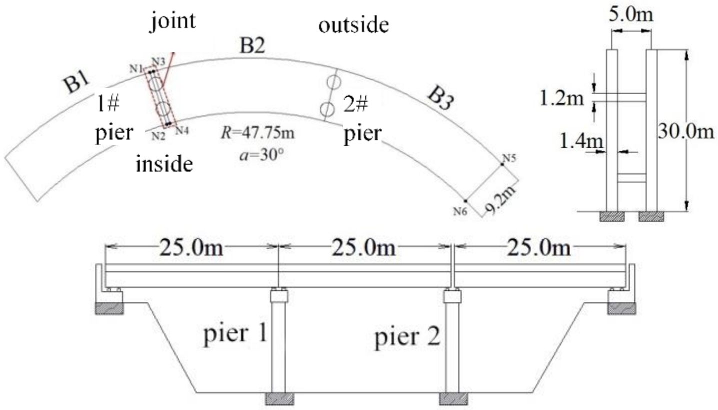


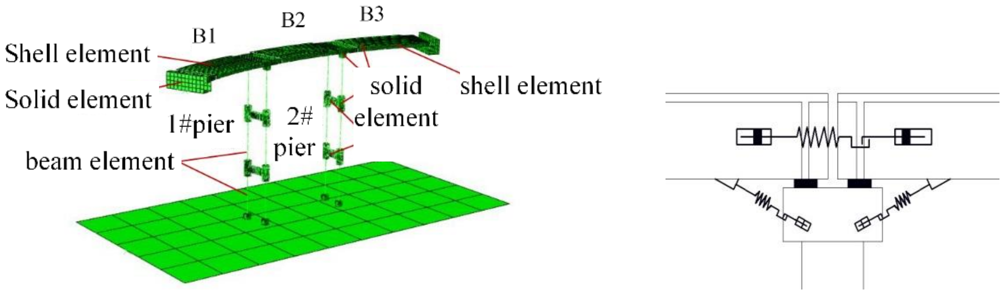
Fig. 2 – Structural parameter of the curved girder bridge

The finite element model of the reinforced concrete curved girder bridge is established using the general purpose FE program ABAQUS, which contains a comprehensive nonlinear analysis capacity. In order to reflect the damage of bridge and reduce the amount of calculation, multi-scale modeling method is used in this paper. Solid element is used to model the parts easy to appear nonlinear deformation and damage such as top and bottom of piers, connection part of pier such as collar beam. Other components of bridge are modeled by using beam element and shell element. The force equilibrium condition is applied to the interface connection of different scale elements (see references [8]). The multi-scale finite element model of bridge is shown in Fig. 3 (a).

The concrete of superstructure and piers is modeled using plastic damage constitutive model proposed by McKenna F T (see references [9]). Steel bar are modeled using multi-line constitutive model considering the degeneration of the flexural capacity caused by the accumulation damage (see references [10]). The parameter values of finite element model of bridge are given in references [11].

Fixed bearing is modeled by using elastic connection element. Sliding bearing is idealized as coulomb friction model and simulated by using bilinear connection element. Three-dimensional contact-friction model combined with explicit dynamic contact algorithm is used to model adjacent girder pounding of the curved bridge. The stiffness of pounding takes 0.5 times the axial stiffness of the girder.

The two-level unseating failure control system proposed in this paper is installed at the expansion joint of the curved girder bridge. The restrainer between adjacent spans is modeled by using "axial" type connector element in ABAQUS and the restrainer between span and pier is modeled by using "axial+align" type connector element as shown in Fig. 3 (b).



(a) Curved girder bridge (b) Unseating failure control system

Fig. 3 – Finite element model of the curved girder bridge with unseating failure control system

3.2 Parameters of two-level unseating failure control system

The first-level control requires that the relative displacement between the pier and girder should be limited under small and moderate earthquakes, and break under large earthquakes. It is suggested that the design value of ultimate failure force F_a of the first-level connection is the design value of yield force of piers F_q multiplied by the reduction coefficient γ_a generally taken as 0.8, that is:

$$F_a=\gamma_a \times F_q \tag{1}$$

The second-level control requires that it does not work under small and moderate earthquakes and ties up the girders under large earthquakes to prevent unseating. According to W/2 method (see references [2]) and referring to the relevant foreign standards, it is suggested that the design bearing capacity of the second level connection F_b is:

$$F_b=\gamma_b \times R_d \tag{2}$$

where, F_b is the design value of the ultimate failure force of the second-level connection, γ_b is the safety factor which is generally taken as 1.5, R_d is the dead load reaction force of the superstructure.

According to the Eq. (1), Eq. (2) and the results of collapse analysis of curved girder bridge (see references [11]), the parameters of finite element model of control system can be calculated and is shown in Table 1

Table 1 – Parameters of two-level unseating failure control system

Control level	**Stiffness** (kN/m)	**Damping** (N·s/m)	**Initial gap** (cm)
First-level control	5.0×10^3	600	0
Second-level control	1.8×10^4	600	3

3.3 Earthquake ground motion input

To analyze the proposed model, three different kinds of earthquake ground motion records are selected respectively as the input of the curved girder bridge. The three seismic waves are respectively: (1) ground motion record of Wenchuan Wolong seismic wave in three directions (peak acceleration is 0.98g), (2) EL-Centro seismic wave (peak acceleration is 0.31g); (3) Taft seismic wave (peak acceleration is 0.16g). Among them, the last two seismic waves are input in three directions, and the peak acceleration ratio of ground motions in three directions is 1: 0.8: 0.6. The three kinds of seismic waves are all input along the connecting direction of the piers and other two vertical directions.

4. Seismic response analysis of curved girder bridge with two-level unseating failure control system

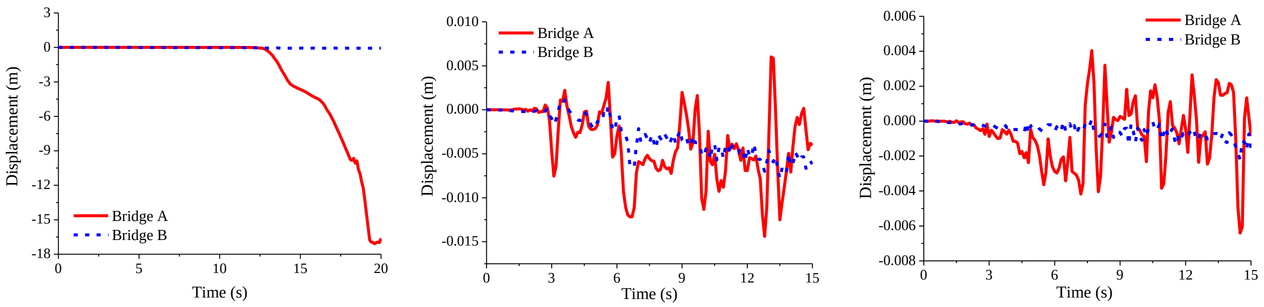
4.1 Seismic response analysis of curved girder bridge

The responses of curved girder bridge due to earthquake ground motions are computed with nonlinear time history analysis method. In order to evaluate the effectiveness of two-level unseating failure control system, the nonlinear time history analysis is carried out for two analysis cases in this study:

(1) Bridge A: a bridge without unseating prevention system.

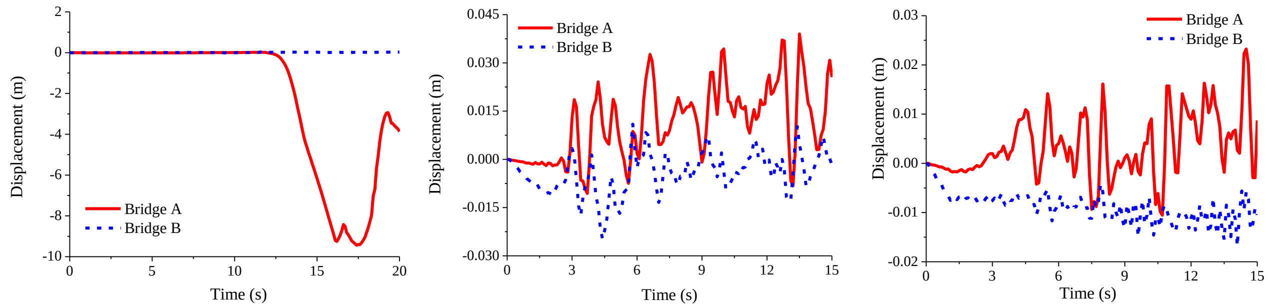
(2) Bridge B: a bridge with two-level unseating failure prevention system.

The relative displacement responses between N1 and N3 under three kinds of seismic waves are shown in the Fig. 4 and Fig. 5. The relative displacement response results between N2 and N4 are similar to Fig. 4 and Fig. 5.



(a) Wolong seismic wave (b) EL-Centro seismic wave (c) Taft seismic wave

Fig. 4 – Radial relative displacement between N1 and N3 under three kinds of earthquakes



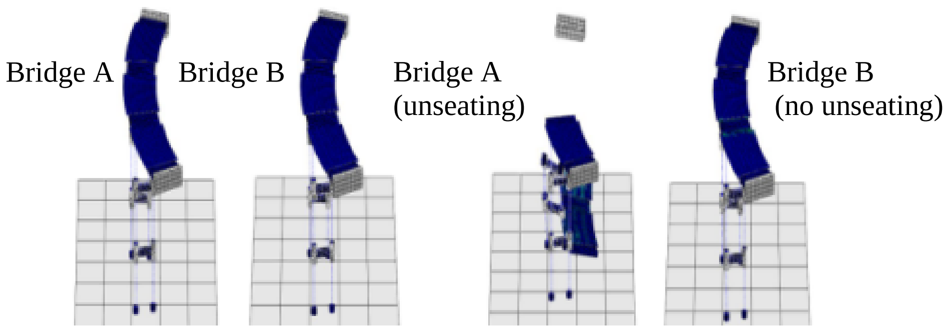
(a) Wolong seismic wave (b) EL-Centro seismic wave (c) Taft seismic wave

Fig. 5 – Tangential relative displacement between N1 and N3 under three kinds of earthquakes

It can be seen from Fig. 4 and Fig. 5 that the relative displacements between the adjacent girders at the expansion joint are well controlled. Under the Wolong seismic wave, bridge A (uncontrolled bridge) occurs unseating failure. However, bridge B (controlled bridge) does not occur unseating failure. Under the EL-Centro seismic wave and Taft seismic wave respectively, no unseating occurs both in bridge A and bridge B. The displacement limit effect under three kinds of earthquake ground motions is shown in Table 2. The comparison of response processes of bridge A and bridge B due to Wolong seismic wave is shown in Fig. 6.

Table 2 – Limit effect of unseating failure control system

Analysis cases and limit effect	**Tangential relative displacement of girder at expansion joint** (mm)		
	Wolong seismic wave	EL-Centro seismic wave	Taft seismic wave
Without unseating control system	unseating	41	24.1
With unseating control system	no unseating	24.7	16.8
Limit effect	/	39.76%	30.29%



(a) t=0s (b) t=20s

Fig. 6 – Comparison of response process of bridge A and bridge B under Wolong seismic wave

Due to the unseating failure of the bridge under the Wolong seismic wave, the responses of the bridge pier under this analysis case is mainly investigated. The peak value of internal force at the bottom of the pier is shown in Table 3.

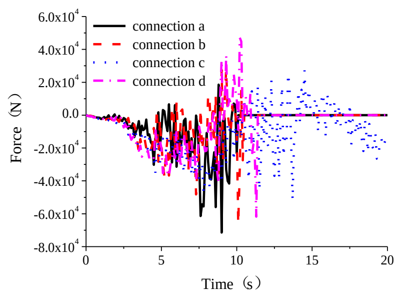
Table 3 – Peak value of internal force at the bottom of the pier

Bridge pier		**Shearing force** (kN)			**Axial force** (kN)	**Bending moment** (kN·m)			**Torque** (kN·m)
		Radial	Tangential	Combination		Radial	Tangential	Combination	
Bridge A	No.1 inside	283.6	332.7	409.5	4873.4	2652.3	2173.6	3184.2	454.4
	No.1 outside	425.8	263.0	499.2	5360.8	2281.4	1905.1	2801.8	488.1
	No.2 inside	770.4	3049.2	3145.0	9467.3	4431.1	1616.3	4503.3	1228.3
	No.2 outside	425.3	554.8	568.7	7432.2	2887.9	1491.2	2888.5	1293.1
Bridge A	No.1 inside	394.8	688.9	779.6	7957.5	2791.3	2756.9	3786.6	392.7
	No.1 outside	499.8	452.5	575.1	8247.5	2735.8	3429.3	4340.8	351.1
	No.2 inside	416.1	464.7	465.5	5344.1	2970.6	1726.1	3007.4	217.3
	No.2 outside	357.1	644.4	690.3	7856.2	3534.1	1603.3	3593.8	239.6

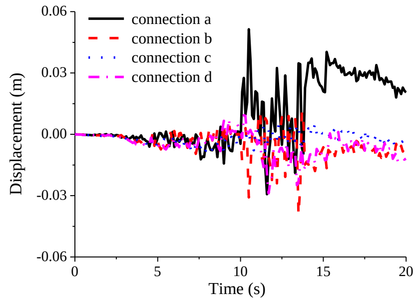
It can be seen from Table 1 that with the two-level unseating failure control system, the bottom shear force, axial force and bending moment of No. 1 bridge pier are obviously increased, while the torque is reduced. This shows that the unseating failure control system not only limits the relative displacement of the expansion joint, but also increases the internal force response of the pier, reduces the torque of the curved girder bridge, and limits the torsion of the girder to a certain extent. Before the girder of bridge A falls to impact the pier, the internal force of the No. 2 pier of bridge B is higher than that of bridge A; after the girder of bridge A falls to the pier, due to the impact of the girder, the peak force at the bottom of the No.2 pier of bridge A is higher than that of bridge B. Overall, with the two-level unseating failure control system, the internal force response at the bottom of the No. 2 pier is also increased. In addition, under the action of unseating control system, the girder does not collapse and the torsion of the girder is well controlled.

4.2 Seismic response analysis of two-level unseating failure control system

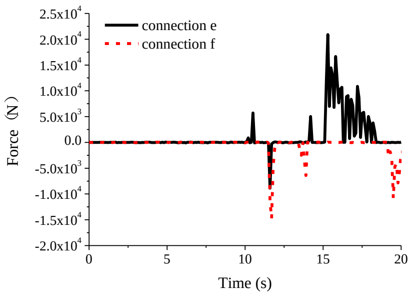
For the convenience of analysis, the first-level connection of the two-level unseating failure control system is numbered as “a” (between No. 1 inner pier and B1 girder), “b” (between No. 1 inner pier and B2 girder), “c” (between No. 1 outer pier and B1 girder) and “d” (between No. 1 outer pier and B2 girder) respectively; the second level connections are numbered “e” (inside of B1 girder and B2 girder) and “f” (outside of B1 girder and B2 girder). The response of the two-level unseating failure control system under the Wolong seismic wave is shown in Fig. 7.



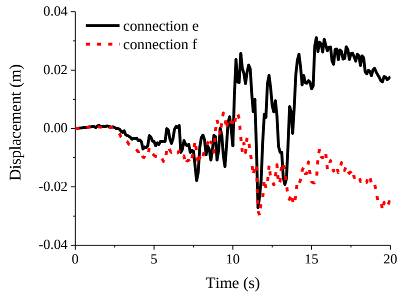
(a) First-level control force



(b) First-level control displacement



(c) Second-level control force



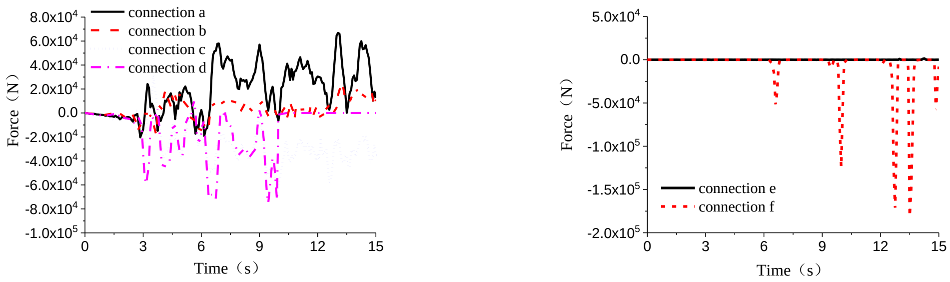
(d) Second-level control displacement

Fig. 7 – Responses of two-level unseating failure control system under Wolong seismic wave

It can be seen from Fig. 7(a) and Fig. 7(b) that the first-level pier-girder connection plays the role of displacement restriction under earthquake and works well. Among them, the control force of the connection is gradually increasing, and when the strength failure threshold is reached, the pier-girder connection fails to quit the work, while the connection “c” plays the role of displacement restriction in the whole process because it does not reach the failure threshold. On the inside of the girder of the curved girder bridge, the control force and displacement of connection “a” is greater than that of connection “b”, while on the outside, the control force and displacement of connection “d” is greater than that of connection “c”. Through the analysis of the first-level connection control force and displacement time history of the bridge pier and the same girder, it can be concluded that the control force and displacement of connection “a” is greater than that of connection “c”, and that of connection “b” is greater than that of connection “d”. This shows that with the two-level unseating failure control system, due to the bending-torsion coupling effect of the curved girder bridge, the force of the first-level connection at the expansion joint position of the curved girder bridge is not the same.

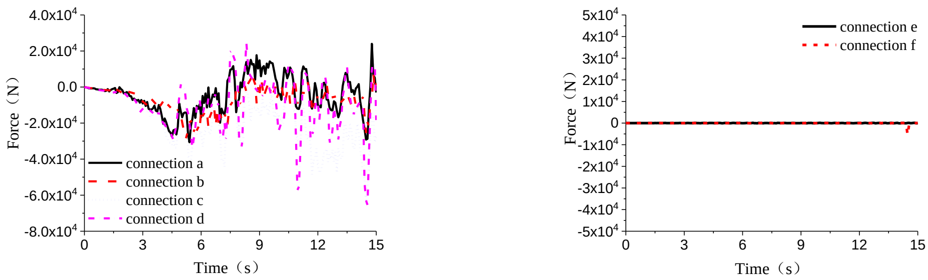
It can be seen from Fig. 7(c) and Fig. 7(d) that in the unseating control process, the second-level connection control does not work at the beginning, the connection displacement is within the initial clearance limit, and the connection almost has no force. As the first-level connection reaches the preset strength threshold and withdraws from the work one by one, the second-level girder-girder connection begins to work, which ensures the continuity of the superstructure system. It can be seen from the figure that the peak value of control force and displacement of the inside connection of the second-level is slightly larger than that of the outside, which is due to the first failure of the inside connection “a” and “b” of the first level, while there is still a connection “c” on the outside to ensure the pier-girder connection. In addition, because the stiffness of the second-level girder-girder connection is greater than that of the first-level, the effect of the second-level girder-girder connection is obvious, which limits the relative displacement of the girder and prevents the girder from unseating.

The time history of the control force of the two-level unseating failure control system under EL-Centro wave and Taft wave are shown in Fig. 8 and Fig. 9 respectively.



(a) First-level control (b) Second-level control

Fig. 8 – Responses of two-level unseating failure control system under EL-Centro seismic wave



(a) First-level control (b) Second-level control

Fig. 9 – Responses of two-level unseating failure control system under Taft seismic wave

It can be seen from Fig. 8 that under the EL-Centro seismic wave, the first and second level connections of the two-level unseating failure control system are involved in the work. Among them, due to the obvious earthquake response on the outside of the curved girder bridge, the control force of the first-level connection “d” connected to the B2 girder reaches the strength threshold and fails to quit the work. Due to the failure and withdrawal of the first-level outer connection “d”, the second-level outer connection “f” enters the work, while the second-level inner connection “e” does not enter the working state.

It can be seen from Fig. 9 that under the Taft seismic wave, due to the small peak acceleration of ground motion, only the first-level connection is involved in the work, while the second-level control connection does not work. The first-level to the second-level control conversion does not occur under earthquake, and the first-level connection played the role of displacement restriction, which limits the relative displacement between the girder and pier.

5. Conclusions

Based on the above analysis, it can be concluded that the two-level unseating failure control system proposed in this paper has both the control performance of displacement restriction and unseating prevention. Through effective displacement restriction, reasonable unseating prevention mechanism and clear “disaster fuse” structure to meet the effective control of unseating failure and the safety protection of bridge piers.

Under the strong earthquake such as Wolong seismic wave, the first-level and the second-level connections of the two-level unseating failure control system are involved in the work, which plays the role of displacement restriction and unseating prevention. Among them, the first-level connection works first, and when the connection control force reaches the strength threshold, the failure occurs, and the two-level control system is automatically transferred to the second-level connection control. In the control conversion process, the internal force of the curved girder bridge is redistributed, and the control force of the first-level connection is slightly larger than that of the second-level connection. The whole two-level control system reduces the relative displacement response of the girder, increases the internal force response of the pier, limits the torsion of the girder, and plays a good role in preventing the curved girder bridge from unseating.

The overall control force of the two-level unseating failure control system increases with the increase of the peak acceleration of the ground motion. When the peak acceleration of ground motion is small, only the first-level pier-girder connection takes part in the work. When the peak acceleration is large, the control force and displacement of the two-level unseating control system increase significantly.

The two-level unseating failure control system proposed in this paper does not need the input of external energy. The control state and the conversion of the control level of the system are completely determined by the intensity of the earthquake and the structural seismic response.

6. Acknowledgements

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7. References

[1] Zuo Y, Sun G, Li H (2016): Comparison and research of unseating prevention measures in seismic codes of China and foreign countries. *Journal of Disaster Prevention and Mitigation Engineering*, **36** (4), 617-623/639.

[2] Saiidi M, Randall M, Maragakis E, Isakovic T (2001): Seismic restrainer design methods for simply supported bridges. *Journal of Bridge Engineering*, **6** (5), 307-315.

[3] Andrawes B, DesRoches R (2001): Comparison between shape memory alloy seismic restrainer and other bridge retrofit devices. *Journal of Bridge Engineering*, **12** (6), 700-709.

[4] Ruiz J, Hayashikawa T, Obata T (2007): Seismic performance of isolated curved steel viaducts equipped with deck unseating prevention cable restrainers. *Journal of Constructional Steel Research*, **63** (2), 237-253.

[5] Won J, Mha H, Cho K, Kim S (2008): Effects of the restrainer upon bridge motions under seismic excitations. *Engineering Structures*, **30**, 3532-3544.

[6] Luders C, Criado M (2008): A new design philosophy of seismic anchor elements for bridges. *16th World Conference on Earthquake Engineering 16WCEE*, Santiago, Chile.

[7] Sun G, Li H, Zhao P (2014): Unseating failure control mode for simply supported girder bridge during earthquakes. *Journal of Nanjing Tech University (Natural Science Edition)*, **36**(02), 40-47.

[8] Sun G, Zuo Y, Li H, Luo R, Du X (2014): Application of multi-scale finite element modeling in bridge seismic damage and collapse analysis. *10th Asia Pacific Transportation Development Conference and 27th ICTPA Annual Conference*, Beijing, China.

[9] Mckenna F (1997): Object-oriented finite element programming: frameworks for analysis, algorithms and parallel computing. *Doctoral dissertation*, University of California, Berkeley, USA.

[10] Qu Z (2010): Study on seismic damage mechanism control and design of rocking wall-frame structure. *Doctoral dissertation*, Tsinghua University, Beijing, China.

[11] Zuo Y, Sun G, Jin H, Li H (2018): Analysis of seismic response of curved bridge subjected to near-fault ground motion. *Journal of Vibration, Measurement and Diagnosis*, **18** (4), 687-695.

