A Study on Multi-level Control System for Unseating Failure Prevention of Concrete Girder Bridges during Earthquake

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SUMMARY:
Based on the conceptions of energy dissipation, multi-failure and safety protection of structure, a new energy dissipation-based multi-level control system for unseating failure prevention of concrete girder bridges subjected to earthquake is proposed. The control system provides respectively two different functions including energy dissipation-based displacement restriction and unseating prevention, and the two level control functions can be automatically transformed according to the preset threshold value. Firstly, the model of multi-level control system is established and the working mechanism is revealed. Furthermore, the seismic responses of a concrete girder bridge equipped with multi-level control system are analyzed by using nonlinear dynamic analysis method based on a simplified mechanical model to examine the control effectiveness of multi-level control system. Finally, parametric study is performed. It is found that the multi-level unseating prevention system presented in this paper can achieve unseating failure prevention and structure safety protection effectively for girder bridges during earthquake.

Keywords: concrete girder bridge; earthquake; unseating failure; multi-level control; safety protection

1. INTRODUCTION

Among many structural damages of bridges during past earthquakes, the unseating failure is one of the most severe and ubiquity damages of concrete girder bridges (Copper, 1994). During seismic excitations, bridges may give rise to large relative displacement between superstructure and substructure. When the relative displacement exceeds the pre-assigned seating length, the unseating of span will then take place. So how to prevent bridge unseating failure is an important issue for seismic design of bridges.

Following the collapses of a large number of bridges during the 1971 San Fernando earthquake in US, the unseating problem has been attracting many major concerns and after that many state and local agencies began installing seismic restrainers in existing and new bridges to prevent excessive relative movements of bridges. Many researches have been carried out to provide appropriate design procedure for restrainers and to understand the influencing factors on the behavior of restrainers through parametric studies (Abdel-Ghaffar et al. 1997; DesRoches et al. 2003; Hao et al. 1998; Kim et al. 2000; Saiidi et al. 1996; Selna et al. 1989; Trochalakis et al. 1997; Vlassis et al. 2004; Won et al. 2008). During the 1995 Kobe earthquake in Japan and the 1999 Chi-Chi earthquake in Chinese Taiwan, a number of destructive bridges also indicated that bridges are vulnerable to unseating problems. Since then, different retrofit programs and unseating prevention devices have been generally applied to prevent unseating of span for existing and new bridges in Japan and Chinese Taiwan. As for the current structural modes of unseating prevention systems, the connection mode between girder and pier of bridges is usually applied in US and the connection mode between adjacent girders of bridges is usually applied in Japan. The connection mode between girder and pier of bridges can reduce the relative displacement between upper part structure and lower part structure effectively, however, the seismic load transferred from upper part structure into pier due to application of girder-pier restrainers may aggravate the damage of lower part structure leading to unrepairable damage or even collapse of bridges. The connection mode between adjacent vibration spans of bridges does not basically change the interaction behavior between upper part structure and lower part structure, therefore, the excessive relative displacement between span and pier can not be controlled effectively.

With this background, the purpose of this paper is to propose a new type control system for unseating failure prevention of concrete girder bridges subjected to earthquakes, by which the philosophies of energy dissipation, multi-failure prevention and structural safety protection are considered respectively. The working mechanism of the proposed unseating failure prevention system is researched. Furthmore, case studies and parameter studies are performed to evaluate its effectiveness in preventing the span of bridges from unseating failure and protecting the pier of bridges from damage.

2. ESTABLISHMENT OF MULTI-LEVEL CONTROL SYSTEM OF UNSEATING FAILURE

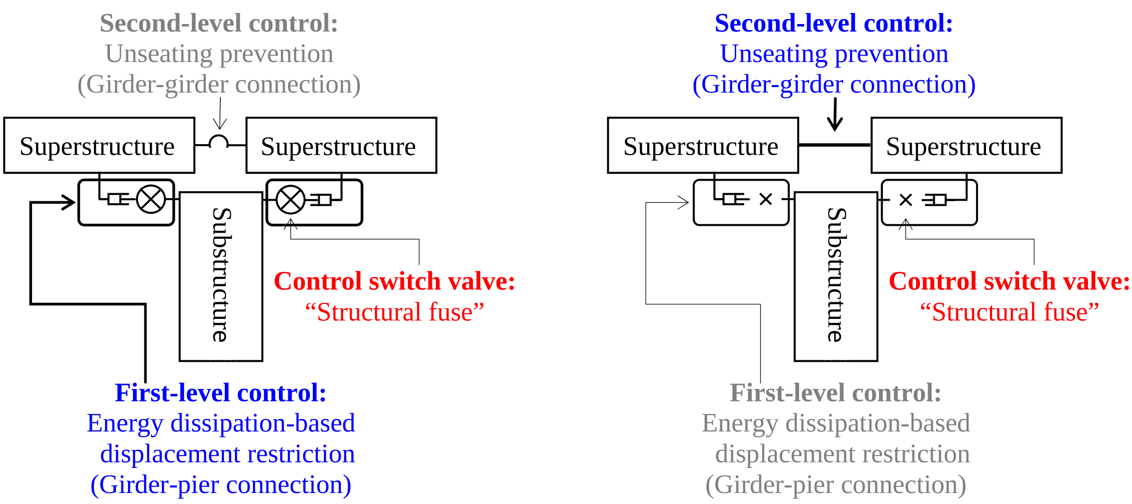
According to both the unseating failure mechanism of concrete girder bridge and the deficiency of existing structural mode of unseating prevention systems, the new type unseating failure prevention system in this paper is created considering the following three aspects:

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

- According to different earthquake action levels to determine different performance control objectives realizing multi-failure criteria.

- Through setting “structural fuse” to attain change of multi-level control state and avoid unrepairable damage of important components due to application of restrainer realizing damage reduction philosophy.

On the basis of the above mentioned factors, the new energy dissipation-based multi-level control system for unseating failure prevention can be established as shown in Fig. 2.1.



(a) During moderate earthquakes (b) During strong earthquakes

Figure 2.1. Illustration of working mechanism of multi-level control system of unseating failure

In the multi-level unseating prevention system herein, 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.

3. NUMERICAL ANALYSIS AND DISSCUSSION

A two adjoining continuous concrete girder bridge is analyzed to investigate the working mechanism and the effectiveness of multi-level control system of unseating failure. Two multi-level unseating prevention devices are installed at the expansion joint respectively between the left and right span and transition pier. In order to examine the behaviours of the multi-level control system described before with better efficiency, a simplified mechanical model of unseating failure control for adjacent spans of concrete girder bridge is proposed using the lumped mass system, which is depicted in Fig. 3.1.

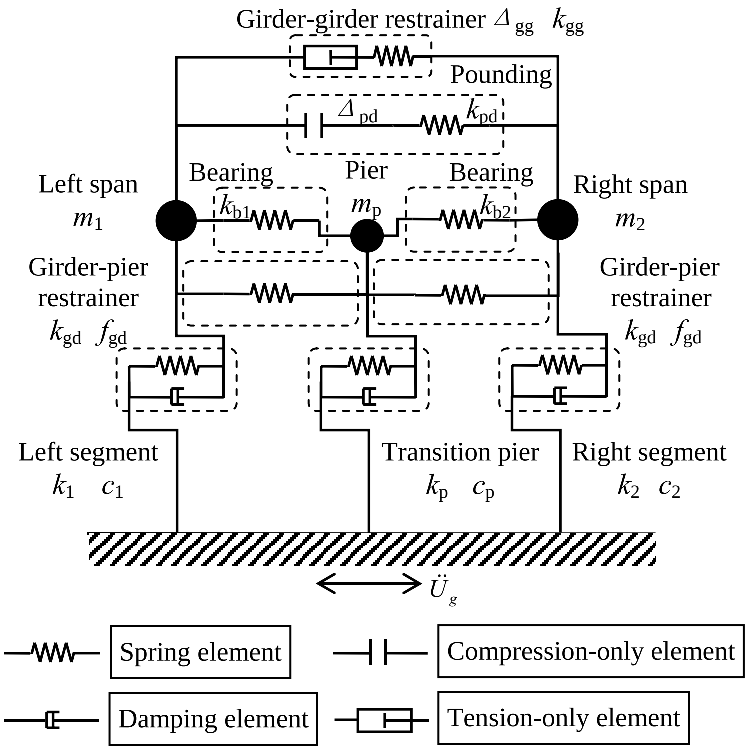


Figure 3.1. Simplified mechanical model of multi-level control system of unseating failure

In this simplified model, the pounding interaction between adjacent spans (pounding unit), the bearing horizontal force between superstructure and substructure (bearing unit), the nonlinear behavior of substructure (left and right segment units, transition pier unit), the first-level control action (girder-pier restrainer unit) and the second-level control action (girder-girder restrainer unit) are respectively considered by the combination of spring element, damping element, compression-only element and tension-only element.

The material nonlinear of the RC pier of bridge is modeled by bilinear hysteresis model. The pounding is modeled by using impact element which consists of a linear spring and a compression-only gap. The bearing is modeled by friction element to describe the friction force between superstructure and support. The restrainer between adjacent spans is modeled by using a linear spring and a tension-only gap. The restrainer between span and pier is modeled by using bilinear hysteresis model to describe the energy dissipation properties and by using valve element to implement the control switch. The earthquake input motion is the N-S component of the 1940 El Centro earthquake, multiplied by a factor of 2.0 to give a peak acceleration of 0.7g. The viscous damping ratio of structure is assumed to be 5%. The parameter values of the simplified model are given in Table 3.1.

Table 3.1. Parameter values of the simplified model

Parameter	Value
Mass of bridge span, m_1, m_2	2×10^6 kg
Stiffness of bridge span, k_1, k_2	1×10^8 N/m
Mass of transition pier, m_p	1×10^5 kg
Stiffness of transition pier, k_p	1×10^8 N/m
Stiffness of bearing, k_{b1}, k_{b2}	2.63×10^7 N/m
Stiffness of pounding, k_{pd}	1.75×10^{10} N/m
Gap of pounding, Δ_{pd}	2.5×10^{-2}m
Stiffness of girder-girder restrainer, k_{gg}	1.75×10^8 N/m
Gap of girder-girder restrainer, Δ_{gg}	5×10^{-2}m
Stiffness of girder-pier restrainer, k_{gp}	1.75×10^8 N/m
Strength of girder-pier restrainer, f_{gp}	1.8×10^6 N

The responses of analytical model due to earthquake ground motion are computed with nonlinear time history analysis method. In order to evaluate the effectiveness of multi-level unseating prevention system, the nonlinear time history analysis is carried out for four analysis cases in this study: (a) a bridge without unseating prevention device, (b) a bridge only with unseating prevention restrainer between adjacent spans, (c) a bridge only with unseating prevention restrainer between span and pier, (d) a bridge with multi-level unseating prevention restrainer. Because the relative displacement between span and pier and the seismic force of pier are the main causes affecting the unseating of span and the damage of pier, the response results are respectively given in this paper. The time history responses of the relative displacement between left span and transition pier D_{r1}, the relative displacement between right span and transition pier D_{r2}, the horizontal seismic force of transition pier F_p and the horizontal control forces of girder-pier connection restrainers F_{gp} are shown in Fig. 3.2~Fig. 3.5 respectively.

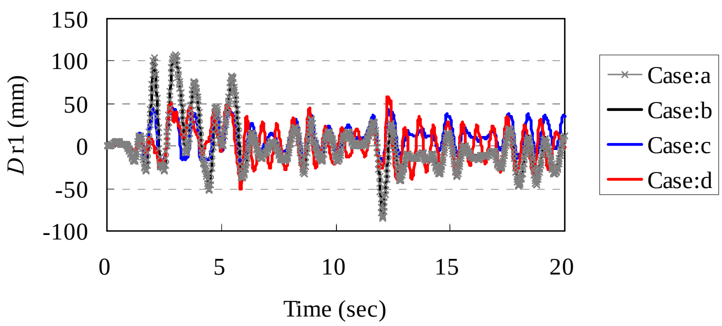


Figure 3.2. Time history of relative displacement between left span and transition pier

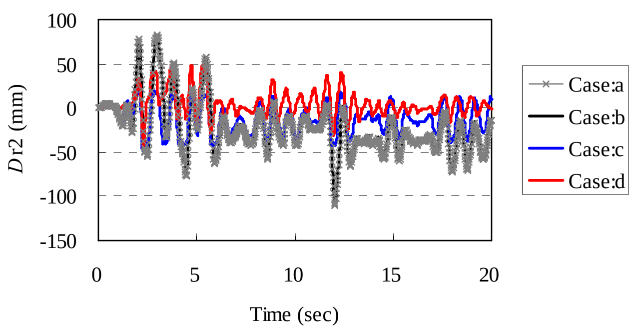


Figure 3.3. Time history of relative displacement between right span and transition pier

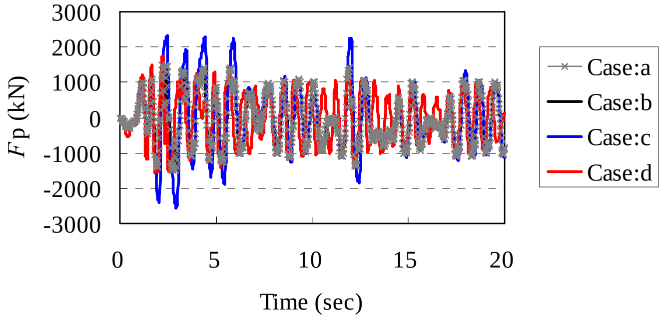


Figure 3.4. Time history of horizontal seismic force of transition pier

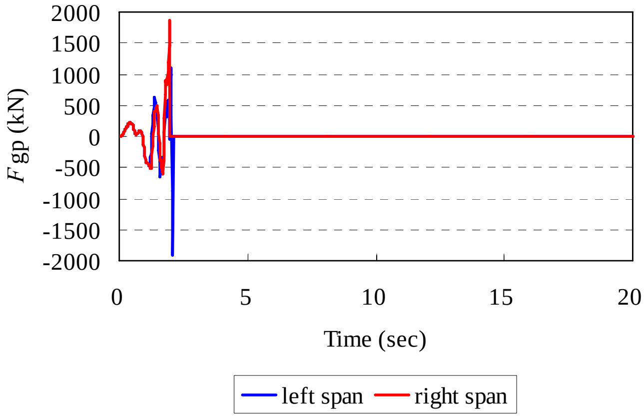
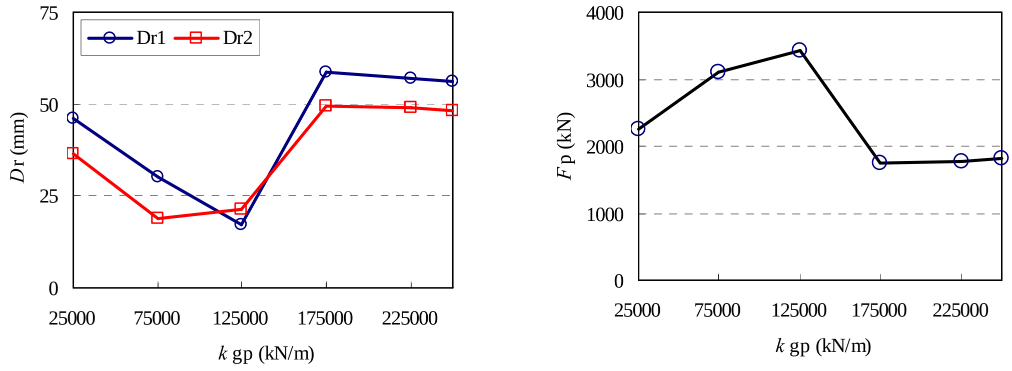


Figure 3.5. Time history of control force of girder-pier connection restrainer

As can be seen in Fig. 3.2 and Fig. 3.3, in the case of bridge without unseating prevention restrainer the relative displacements between superstructures and transition pier are considerably larger and the peak relative displacements of left span and right span are 1.08×10^2 mm and 1.10×10^2 mm respectively leading to the increment of unseating failure probability. The restrainer between adjacent spans nearly can not reduce the relative displacements between superstructures and transition pier, therefore, the time history response curve of the case only with girder-girder connection restrainer is almost coincided with that of the case without unseating prevention device. It is also observed that both the ordinary unseating prevention restrainer between span and pier and the multi-level unseating failure prevention restrainer can reduce the relative displacements between superstructures and transition pier. In the case of bridge only with ordinary unseating prevention restrainer between span and pier, the peak relative displacements of left span and right span are reduced to 4.50×10^1 mm and 4.86×10^1 mm respectively. While in the case of bridge with multi-level unseating failure prevention restrainer, the peak relative displacements of left span and right span are reduced to 5.86×10^1 mm and 4.96×10^1 mm respectively. It seems that the ordinary girder-pier connection restrainer can reduce the relative displacement between span and pier more efficiently than multi-level unseating prevention restrainer. However, due to the connection between span and pier existing in the whole vibration process, the seismic load transferred from the superstructures to the pier by the girder-pier connection will lead to the increment of seismic force of transition pier and the value is increased from 1503.57kN to 2572.52kN as shown in Fig. 3.4. Thus the probability of severe damage or even collapse of pier increases necessarily. While for the multi-level unseating failure prevention restrainer, because the strength valve value of girder-pier connection restrainer is set to 1800kN as shown in Table 3.1, when the threshold value is reached the path of force transfer is interrupted as shown in Fig. 3.5 and a significant redistribution of the seismic force of the transition pier is produced, thus the horizontal seismic force of transition pier can be controlled effectively in the range with the maximum value of 1739.88kN avoiding the damage of the pier as shown in Fig. 3.4. Thus, the multi-level control system can implement effectively both prevention for unseating failure and safety protection for bridges.

4. PARAMETER STUDY

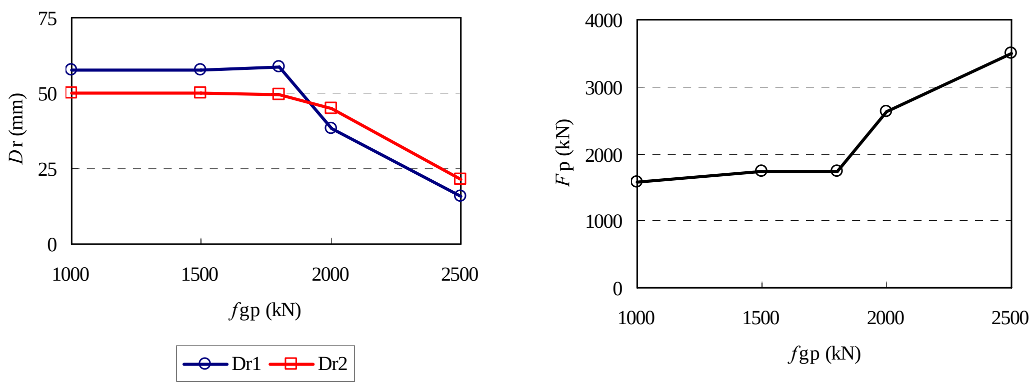
By using the analytical model with the structural and control parameters listed in Table 3.1 as the reference standard model, the parameter influences of the multi-level unseating prevention system are investigated according to change of control parameters including the stiffness of girder-pier connection restrainer k_{gp}, the strength valve value of girder-pier connection restrainer f_{gp}, the stiffness of girder-girder connection restrainer k_{gg}, the gap of girder-girder connection restrainer Δ_{gg} and the stiffness ratio of adjacent spans R_s.



(a) girder-pier relative displacement (b) horizontal seismic force of transition pier

Figure 4.1. Maximum responses of bridge for various stiffnesses of girder-pier restrainer

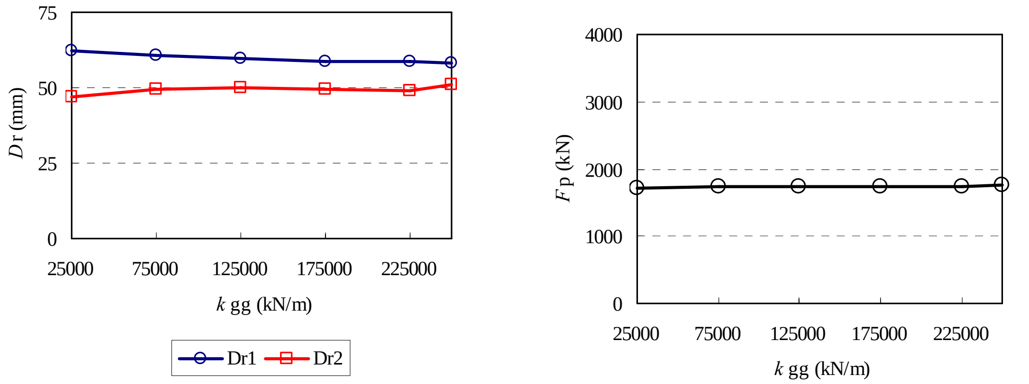
Fig. 4.1 shows the maximum responses of bridge for various stiffnesses of girder-pier restrainer from 2.5×10^7 N/m to 2.5×10^8 N/m. In this figure, it is found that the relative displacement between span and pier D_r changes with the stiffness of restrainer between span and pier k_{gp} in three stages. In the first stage, D_r become considerably smaller as k_g becomes larger in a certain range. When the k_{gp} exceeds the certain value, D_r tends to considerably increase with k_{gp} in the second stage. Then D_r slightly decreases with k_{gp} and tends to stable in the third stage. This can be explained that when the k_{gp} is smaller than a certain critical value a large connection deformation can occurs even due to small seismic force and the girder-pier connection can not be broken down timely, moreover, the smaller the k_{gp}, the more the deformation; when the k_{gp} exceeds one certain value, the connection deformation becomes small and the girder-pier connection can be interrupted while the control switch force which is transferred from the connection reaches the preset value, the girder-pier connection experiences earlier termination with lower ductility as k_{gp} increase, thus the effect of displacement restriction is inadequate. When k_{gp} reaches a value, a further increment of k_{gp} has little influence on the responses of D_r. While the change of seismic force of transition pier F_p with k_{gp} shows a reversed law compared to that of D_r with k_{gp}.



(a) girder-pier relative displacement (b) horizontal seismic force of transition pier

Figure 4.2. Maximum responses of bridge for various strength valve value of girder-pier restrainer

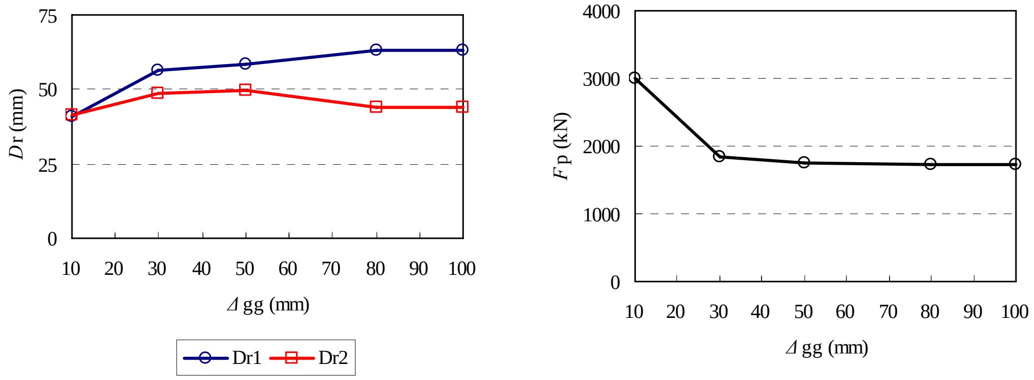
Fig. 4.2 shows the maximum responses of bridge for various strength valve value of girder-pier restrainer from 1.0×10^6 N to 2.5×10^6 N. In this figure, it is found that in a certain range with small strength threshold value of restrainer between span and pier f_{gp} the relative displacements between span and pier D_r and the seismic force of transition pier F_p is not so relative to it, when f_{gp} exceeds the certain value D_r tends to decrease and the seismic force of transition pier F_p tends to increase with the increment of f_{gp}. It is easy understand that when f_{gp} is small the control effect of girder-pier connection is interrupted due to small seismic force at the beginning of earthquake, therefore the girder-pier restriction is almost not available, and when f_{gp} exceeds a certain value the probability of interruption of girder-pier connection gets lower as the threshold value increases, therefore, the effects of displacement restriction and the seismic force increasing in pier is more significant.



(a) girder-pier relative displacement (b) horizontal seismic force of transition pier

Figure 4.3. Maximum responses of bridge for various stiffnesses of girder-girder restrainer

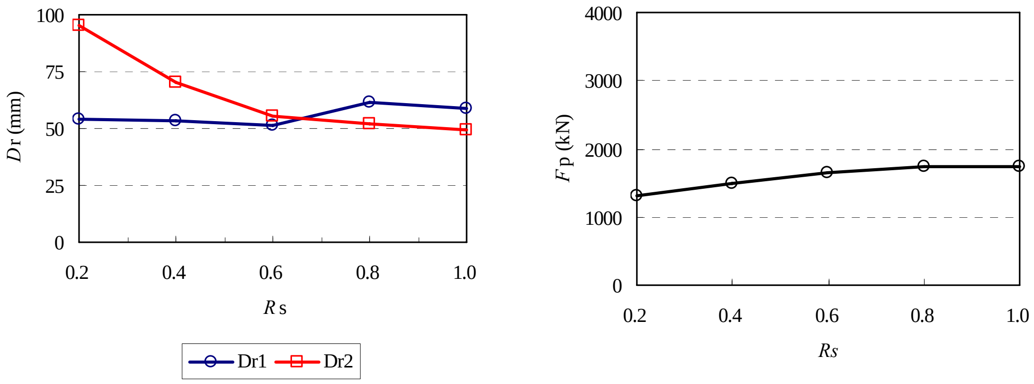
Fig. 4.3 shows the maximum responses of bridge for various stiffnesses of girder-girder restrainer from 2.5×10^7 N/m to 2.5×10^8 N/m. In this figure, it is found that the influence of the stiffnesses of restrainer between adjacent spans k_{gg} both on the relative displacement between span and pier D_r and seismic force of transition pier F_p is not significant because the connection stiffness of restrainer between adjacent spans does not basically change the interaction behavior between upper part structure and lower part structure.



(a) girder-pier relative displacement (b) horizontal seismic force of transition pier

Figure 4.4. Maximum responses of bridge for various gap of girder-girder restrainer

Fig. 4.4 shows the maximum responses of bridge for various gap of girder-girder restrainer from 10mm to 100mm. In this figure, it is found that when the gap of restrainer between adjacent spans Δ_{gg} is in a smaller range the relative displacement between span and pier D_r tends to increase and the seismic force of transition pier F_p tends to decrease with Δ_{gg}, however, when Δ_{gg} exceed a certain length the change of D_r and F_p with Δ_{gg} is not significant. This phenomenon can be explained that when the gap lengths is small the girder-girder connection control play a role together with the girder-pier control simultaneously at the first control stage, thus the responses of bridge system is reduced. However, it is obvious that this control mode is not in conformity with the multi-failure criteria and the girder-girder connection will probably failure untimely. When Δ_{gg} is long enough, the girder-girder connection control occurs only after the termination of girder-pier connection control and the girder-girder connection has little influence on relative displacement of span and pier.



(a) girder-pier relative displacement (b) horizontal seismic force of transition pier

Figure 4.5. Maximum responses of bridge for various stiffness ratio of adjacent spans

Fig. 4.5 shows the maximum responses of bridge for various stiffness ratio of adjacent spans from 0.2 to 1.0. The stiffness ratio of adjacent spans R_s is defined as ratio of the stiffness of right span to the stiffness of left span. In this figure, it is found that R_s has significant influence on the relative displacement between span with small stiffness and pier D_{r2} while the relative displacement between rigid span and pier D_{r1} is not sensitive to R_s. With the decrease of R_s, D_{r2} tends to increase considerably. It is also observed that the seismic force of transition pier F_p tends to decrease with R_s. This can be explained that due to the difference of stiffness of adjacent spans, the adjacent spans vibrate with different phase and the girder-pier control forces transferred from left and right span are counterbalanced to some extent, thus the seismic force of pier is reduced.

5. CONCLUSIONS

In this paper a multi-level control system for unseating failure has been proposed for the seismic retrofit of concrete girder bridges. The working mechanism and the effectiveness of the proposed multi-level unseating failure control system are evaluated and compared with existing structural mode of unseating prevention system through the nonlinear time history analyses on two adjoining continuous concrete girder bridge based on a simplified mechanical model. The results show that the application of multi-level unseating failure control system can significantly reduce the maximum relative displacement between superstructure and pier in bridge with a limited increase of the maximum force experienced by the pier. Therefore, the proposed multi-level control system for unseating failure proves to be effective in preventing span from collapsing and protecting bridge pier from damage. The parameter influence laws are studied in this paper and the analysis results indicates that the control mode and control effect of the multi-level unseating failure prevention system depend on the various parameters of control system including stiffness of girder-pier connection restrainer, preset strength valve value of girder-pier connection restrainer, stiffness of girder-girder connection restrainer, gap of girder-girder connection restrainer and ratio of stiffness of adjacent span. The determination of control parameters should be made by an optimization approach giving consideration to the relative displacement restriction effect and pier internal force control.

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