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COLLAPSE OF BAIHUA BRIDGE DURING THE 2008 WENCHUAN EARTHQUAKE: FINITE ELEMENT ANALYSIS WITH A MULTI-SCALE MODEL

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Abstract

Baihua Bridge, a RC multi-span girder bridge located in the near fault region, collapsed in the curved spans and damaged seriously in the straight spans during the Wenchuan, China earthquake of May 12, 2008. In order to investigate the failure mechanism and reveal the collapse process, the finite element analysis with a multi-scale microstructure model is established for the curved girder segments of Baihua Bridge with consideration of the nonlinear behaviors of piers, bearings and contact impact. A three component accelerogram of ground motion observed only 3 kilometers far from the bridge site in the Wenchuan earthquake is selected as the seismic excitation for the finite element model. The process of damage accumulation and collapse of the bridge structure is analyzed and simulated, and compared with the failure solutions from the post-earthquake investigation. The numerical results show that one side of the girder of the fifth continuous span dropped first from the bracket expansion joint due to excessive movement, and the falling girder hit against the pier. This leads to further damages and final collapse of the pier, then overall progressive collapse of the fifth continuous span. Furthermore, the collapse mechanism of the curved girder bridge are also investigated, they will contribute to explanation why the curved spans rather than the straight spans collapsed during the earthquake.

Keywords: Baihua Bridge; Wenchuan earthquake; Collapse analysis; Multi-scale finite element model; Numerical simulation

1. Introduction

On May 12, 2008 at 2:28 p.m., a magnitude 8.0 earthquake struck a wide area throughout Sichuan, Shanxi, and Gansu Provinces, China. Epicentered in the Yingxiu Town of Wenchuan County, the earthquake caused serious damage to buildings and infrastructural facilities. As a consequence, 24 expressways, 161 national or provincial highways, another 8618 county roads, and 156 tunnels and 6140 bridges were declared destructive till June 19, 2008, according to announcement of China's Ministry of Transport. Direct economic losses due to earthquake damage of transportation facilities were estimated at over 67 billion RMB Yuan. Among all the damaged bridges during the Wenchuan earthquake, Baihua bridge suffered partial collapse locates in the epicentral region and is close to the ruptured fault. It was surveyed and examined deeply after the earthquake (see references [1]-[9]), and tried to explain the collapse mechanism of Baihua bridge.

There is no doubt that strong earthquake is the most direct reason causing destruction of numerous bridges in seismic region including Baihua bridge. However, how did serious damage or even collapse of bridges happen under the action of such strong earthquake? What is its root cause? Are there some lessons worth summarized and improved? Clear judgment and analysis of these questions is the problem that complicated bridge collapse resistance research must face. It is also necessary premise to improve bridge seismic design method and construction measures in order to prevent or mitigate damage and collapse of bridges in earthquakes. Therefore, it has important theoretical significance and engineering application value.

To factually reproduce the seismic damage and collapse process of engineering structure by numerical simulation method is an effective measure to reveal the structural earthquake-induced collapse mechanism. As an engineering example of Baihua bridge collapsed in Wenchuan earthquake, a multi-scale microstructure model of curved girder segment of Baihua bridge is established based on finite element software ABAQUS with considering the nonlinear behaviors of pier, bearing and contact impact. And the Wolong seismic wave record is taken as the earthquake-induced ground motion input for structure. Furthermore, the numerical simulation on earthquake damage and progressive collapse process of bridge are performed according to time history analysis method. Finally, the numerical simulation results are compared to the actual seismic damage to verify the accuracy of numerical model and simulation results. On the basis of numerical simulation results and field seismic investigation, the failure cause and mechanism of seismic damage and progressive collapse of Baihua bridge during Wenchuan earthquake are revealed.

2. Baihua Bridge and seismic damages

2.1 Details of the bridge

Baihua Bridge is located in the place of N31.044º, E103.475º on the National Highway G213 between Dujiangyan City and Yingxiu Town, 10.6 km from the epicenter (N31.021º, E103.367º). Fig.1 shows the location of the bridge, it is noted that the bridge is close to the Beichuan Fault which triggered a 240-km-long surface rupture zone.

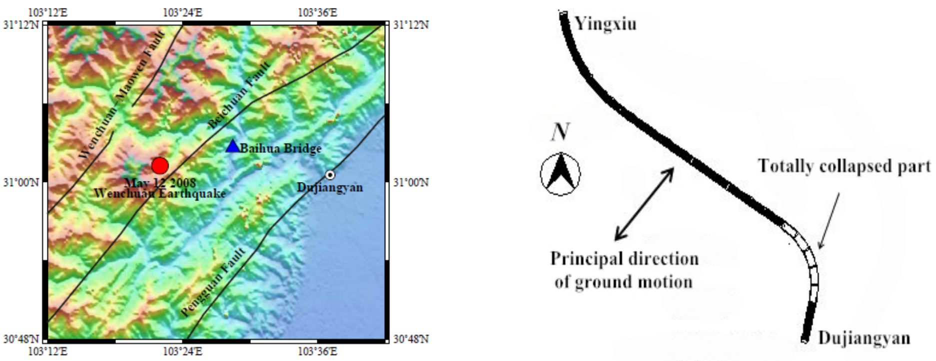


Fig. 1 – Location of Baihua Bridge

Baihua Bridge is a prestressed concrete girder bridge with total 495.6 m in length and 8 m in width, and completed in 2004. The superstructure is composed of 6 units with a span distribution of 4×25m+5×25m+ 1×50m+3×25m+5×20m+2×20m (as shown in Fig.2), and supported by twin-column piers connected together by collar beams. The highest and shortest piers are respectively 30.3 m and 7.1 m. The continuous girders with box section are adopted for all the units except the third unit in which a T-shaped simply supported beam is used. The first unit is within a 150 m radial circlar curve by left side while the fifth unit 66 m right side from a bird's eye view.

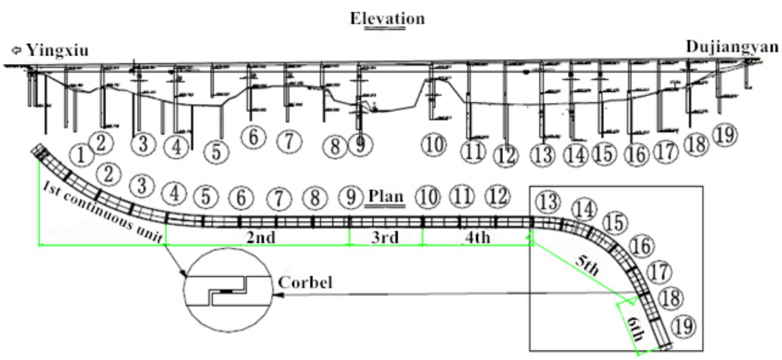
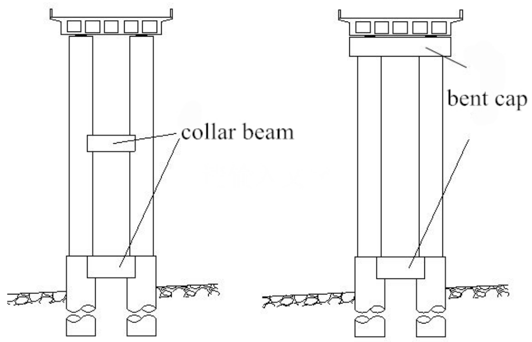


Fig. 2 – General plan and elevation

The piers of Baihua Bridge includes two types of structures, as shown in Fig.3. Most have no bent caps and only collar beams set in the middle part of the columns but transition piers between the second and third units, the third and fourth units, and the fourth and fifth units.

The pot rubber bearings are set on the top of all the fixed piers (2, 7, 12, 16 and 19 piers), while the bi-directional sliding bearings on the transition piers (including the brackets), in which lateral displacement of the girders is limited relying on stop blocks, and laminated rubber bearings on the rest of piers.



(a) Without bent cap (b) With bent cap

Fig. 3 – Twin-column pier of Baihua Bridge

2.2 Main damages due to the earthquake

Baihua Bridge suffered major damage during the Wenchuan earthquake. As shown in Fig.4 and Fig.5, the whole five spans (spans 14, 15, 16, 17 and 18) in unit 5 collapsed completely, all twin-columns from pier 14 to pier 17 suffered shear cracking, crushing of concrete, destroying of collar beams. It may be observed that pier 17 toppled backwards while other piers, i.e., piers 14, 15 and 16 to opposite direction. The deck of the bridge fell off in unit 5. Seismic damages of collapsed piers mainly include pier breaking, concrete crushing, collar beam destruction and shear failure, etc. Seismic damages of piers not collapsed include concrete crushing, collar beam cracking, stop block destruction and superstructure shifting , etc., as shown in Fig.6.

Fig. 4 – Aerial view of collapse of the bridge

Fig. 5 – Collapsed spans in unit 5 after demolition

(a) Concrete crushing (b) Collar beam cracking (c) Stop block destruction and girder shifting

Fig. 6 – Seismic damages of piers not collapsed

Furthermore, seismic damage investigation shows that the first to fourth continuous units are basically intact. Earthquake damages are mainly presented as overall transverse movement, plane rotation and transverse stress damage in substructure. The seismic damages of substructure of the fifth and sixth continuous units are mainly presented as longitudinal stress damage. Transverse relative sliping occurred between some bridge piers and girders. For piers installed with laminated rubber bearings, the relative displacement between girder and pier is large but damage of pier is slight. However, piers installed with fixed bearings are all damaged seriously.

3. Finite element modeling for collapse analysis

3.1 Determination of ground motion input

The site of Baihua Bridge is about 10.6 km away from epicenter and the closest distance between bridge and surface rupture zone is about 1.5 km. The relationship of bridge site, microscopic epicenter and surface rupture zone is shown in Fig.7 and the relationship between bridge site and principal direction of ground motion is shown in Fig.1.

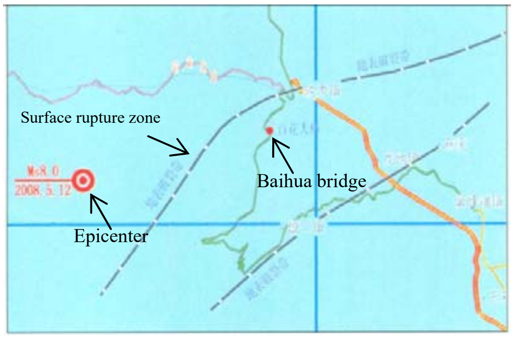
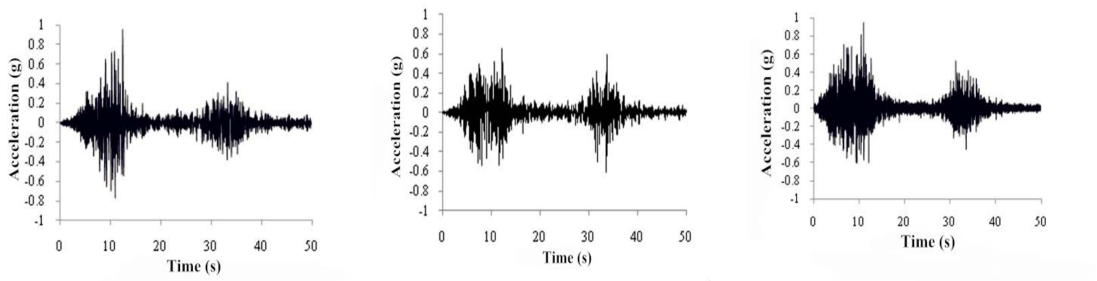


Fig. 7 – Relationship of bridge site, microscopic epicenter and surface rupture zone

It can be seen from Fig.1 and Fig.7 that ground motion input of the first to fourth continuous units is mainly transverse action, however, the ground motion input of the fifth and sixth continuous units is mainly longitudinal action. In addition, because Baihua Bridge is near to fault zone, the vertical earthquake input is also considerable. Therefore, a three component accelerogram of ground motion is considered as ground motion input for bridge model in this paper.

In order to accurately simulate collapse process of Baihua Bridge, the determination of earthquak ground motion record considers the following two factors: (1) Seismic stations should be close to the bridge site; (2) Seismic stations should be close to the fault in order to reflect the influence of fault on earthquake ground motion characteristics.

Therefore, the acceleration record obtained at Wenchuan wolong seismic station in Wenchuan earthquake (called Wolong seismic wave) is determined as the ground motion input for bridge model, as shown in Fig.8.



(a) East-west direction (b) North-south direction (c) Vertical

Fig. 8 – Time history of earthquake ground motion acceleration (Wolong seismic wave)

3.2 Multi-scale microstructure model of bridge

In order to improve computation efficiency of numerical simulation and accurately reflect the damage process and failure mechanism of structure, the finite element microstructure model of Baihua Bridge is established considering the following effective measures:

(1) Only the rightmost three continuous units (from the fourth to sixth continuous units) of Baihua Bridge is modeled and the influence of other parts are considered as boundary conditions.

(2) In order to simultaneously analyze the whole mechanical behavior and local damage process of structure and to fatherly reveal the properties and failure mechanism of structure, different-scale model are chosen according to the complex degree and nonlinear behavior of structural components or joints.

Therefore, the finite element model of Baihua Bridge established in this paper is shown in Fig.9.

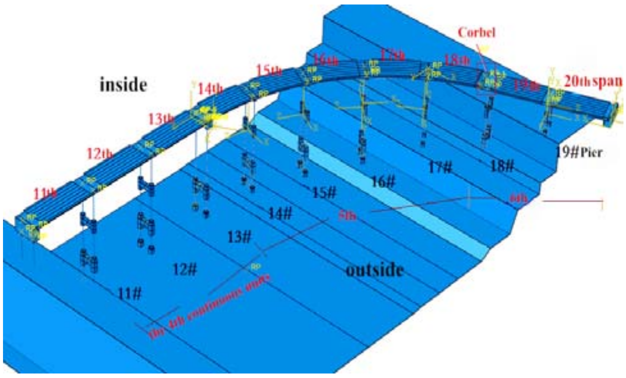


Fig. 9 – Multi-scale finite element model of Baihua Bridge

According to the seismic damage investigation and the numerical simulation result using solid element model, the main damaged parts mostly locate in the collar beam, collar beam-pier joint and pier bottom of bridge, as shown in Fig.10.

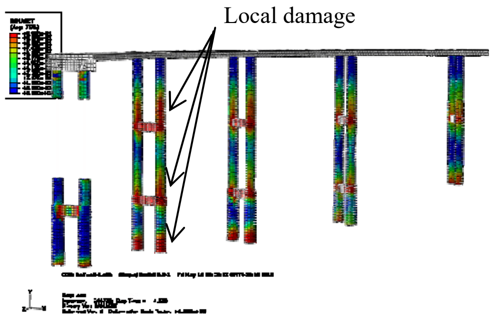


Fig. 10 – Numerical simulation result of bridge pier damage using solid element model

Therefore, the damaged parts of bridge pier are modeled by solid element and others are modeled by beam element. The multi-scale finite element of pier is shown as Fig.11. In the bridge model, the material of beam element is assumed to be elastic and the reinforce concrete of solid element is simulated by a separate plastic model. The Jeeho Lee plastic damage model of concrete (see references [10]) and bilinear model considering strength degradation of steel bar (see references [11]) are applied respectively. The treatment scheme with force equilibrium condition is applied to deal with the coupling problem at the interface between solid model and beam model (see references [12]).

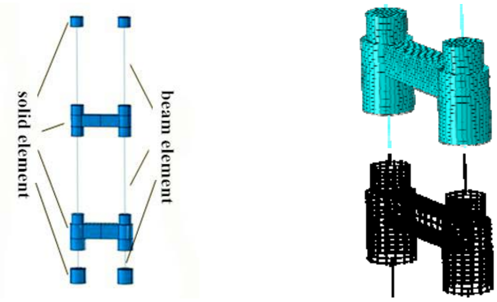
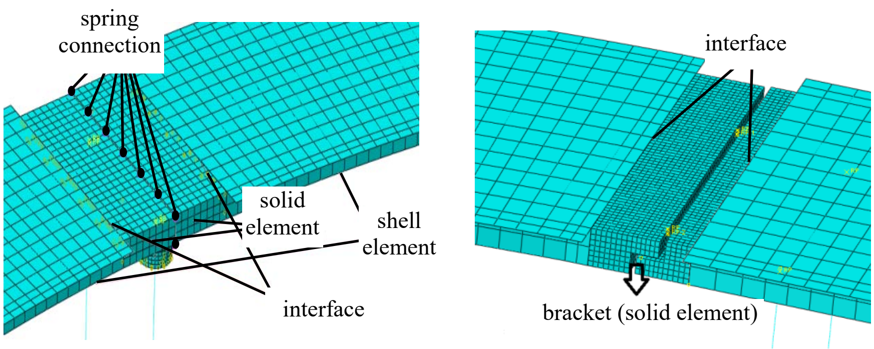


Fig. 11 – Multi-scale model of bridge pier

According to the seismic damage investigation, the damaged parts of superstructure mainly locate in the girder on top of bearing due to collision and unseating. Therefore, the girder model is divided into two parts, the parts on the top of bearing are modeled by solid element and others are modeled by shell element, as shown in Fig.12(a). The plastic damage constitutive relation is adopted in solid model and the elastic constitutive relation is adopted in shell model respectively. The tensile and compressive effects of steel bar in girder are simulated by nonlinear spring. The treatment scheme with force equilibrium condition is applied to deal with the interface coupling the between solid model and shell model.

In addition, the collision occurred at the bracket connection of girder during earthquake, so the bracket is modeled also by solid element and local mesh refinement is applied, as shown in Fig.12(b).



(a) Girder (b) Bracket

Fig. 12 – Multi-scale finite element model of girder

Bearings of Baihua Bridge include laminated rubber bearing, fixed bearing, bi-directional sliding bearing and unidirectional (longitudinal) sliding bearing as shown in Fig.13. Bearing is simulated by the link element and contact friction element as shown in Fig.14.

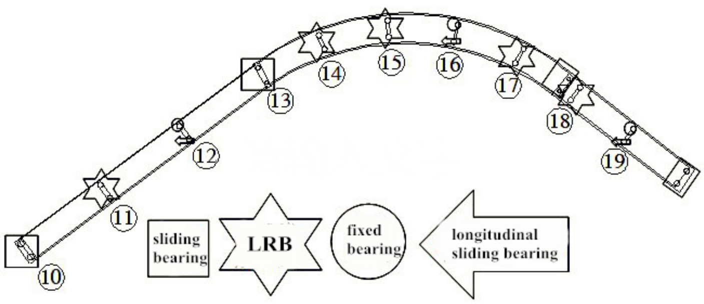
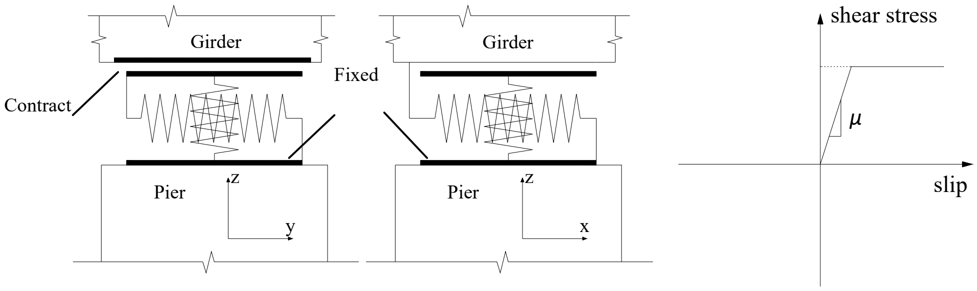
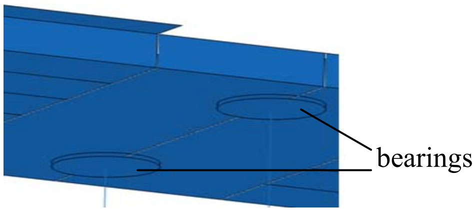


Fig. 13 – Bearing arrangement



(a) Sliding direction (b) Constraint direction (c) Coulomb friction model



(d) Finite element model

Fig. 14 – Finite element model of bearing

In addition, collision effect is simulated by three-dimensional contact friction element through search algorithm, parameter selection is shown in Table 1. The ground is regarded as a rigid body and the effect of structure-pier-soil mutual interaction and seismic traveling wave effect are not considered.

Table 1 – Selection of collision contact parameters

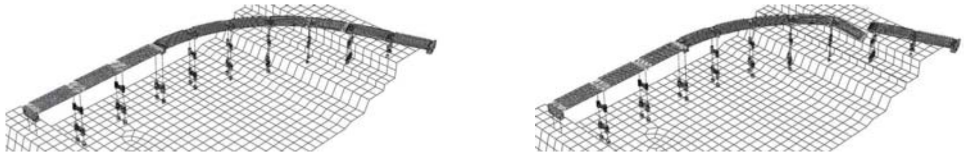
		Contact between girders, girder and abutment, girder and bent cap	Contact between girder and bearing	Pounding of girder to pier	Pounding of girder to ground
Surface to surface contact		√	√		
General contact				√	√
Dynamic mechanical contact method		√			
Penalty function contact method			√	√	√
Contact properties	"Hard" contact				√
	"Soft" contact	√	√	√	
	Whether considering the friction	YES	YES	YES	NO
Slip calculation	Finite sliding	√	√	√	√
	Small sliding				
Master-slave contact	Pure				
	Equilibrium	√	√	√	√
Searching method	Overall search				
	Local search	√	√	√	√

4. Numerical simulation of damage and collapse process

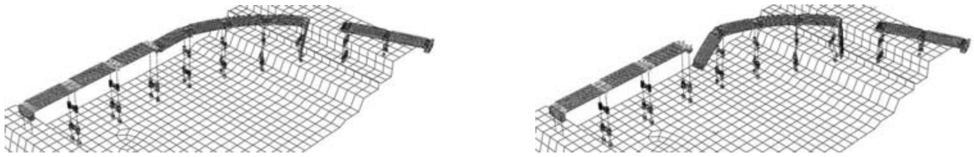
4.1 Damage and collapse process analysis

Based on the multi-scale finite element model, the numerical simulation is carried out by explicit nonlinear dynamic analysis method and compared with the actual seismic damage.

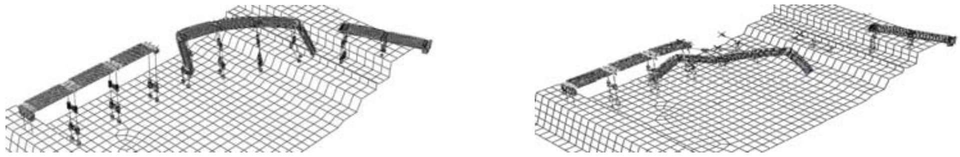
Numerical simulation results of progressive collapse process of Baihua Bridge are shown in Fig.15. It can be seen from results that bridge collapse process is as follows.



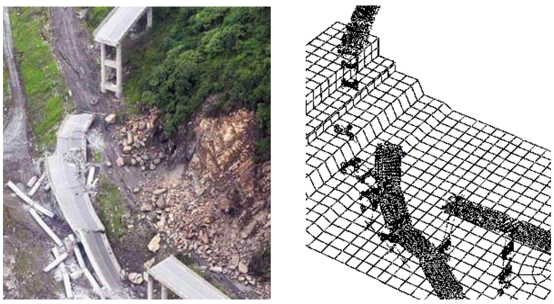
(a)10s: initial state (b) 33s: span dropped from the bracket expansion joint



(c) 35s: falling girder hit against the pier (d) 36s: span near the 4th continuous unit dropped



(e) 38s: falling girder hit against the pier (f) 43s: overall collapse of the 5th continuous unit



(g) Comparison of actual seismic damage and numerical simulation result

Fig. 15 –Progressive collapse process numerical simulation of Baihua Bridge

(1) One side of the 18th girder of the fifth continuous span dropped first from the bracket expansion joint due to excessive movement, as shown in Fig.15(b).

(2) The 18th falling girder hit against the 17th pier, as shown in Fig.15(c).

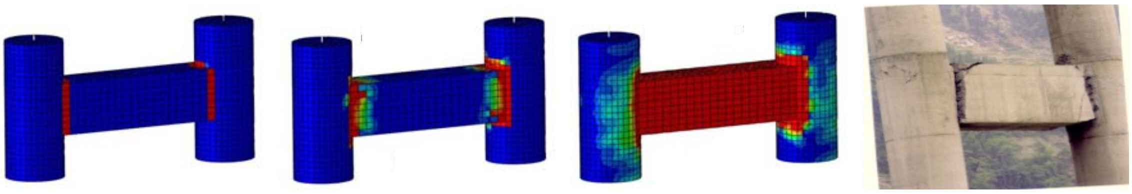
(3) One side of the 14th girder of the fifth continuous span dropped from the 13th transition pier due to excessive movement, as shown in Fig.15(d).

(4) The 14th falling girder hit against the 14th pier, as shown in Fig.15(e).

(5) The 14th and 17th piers collapsed and led to overall collapse of the fifth continuous unit including the 14th to 18th span and the 14th to 17th pier, as shown in Fig.15(f).

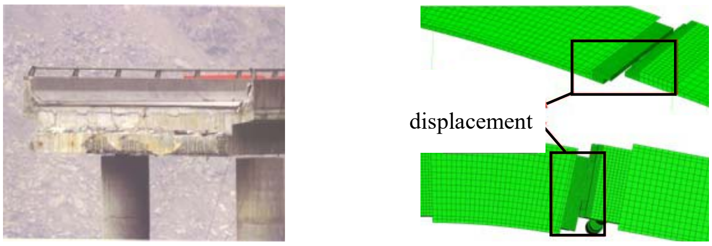
From Fig.15(f), it can be seen that the actual seismic damage and collapse process can be simulated accurately according to the multi-scale modeling in this paper.

In addition, numerical simulation results of local damage process by tension of connection part of collar beam and pier is shown in Fig.16, and the numerical simulation result of longitudinal-transverse coupling displacement of curved girders between bracket expansion is shown in Fig.17.



(a) 9s (b) 10s (c) 11s (d) Actual collar beam damage

Fig. 16 – Pier and collar beam damage process



(a) Actual damage (b) Numerical simulation result

Fig. 17 – Bracket damage

4.2 Collapse mechanism analysis

According to the numerical simulation results and the failure solutions from the post-earthquake, the main reasons and mechanism for the collapse of the fifth continuous unit of Baihua Bridge is presented as follows.

(1) Complex and excessively strong near-fault earthquake action.

Baihua Bridge is close to seismogenic fault zone and the north-south trending fault passes through the collapsed continuous unit. Therefore, the earthquake effect in bridge site is very complex and excessively strong, both the horizontal and vertical peak values of earthquake accelerations reach 1 *g*. The seismic intensity of bridge site reach X to XI degree, however, the fortification intensity of Baihua Bridge is only VII degree.

(2) Dynamic properties difference of adjacent continuous units.

There is a great difference between pier height of the fifth and sixth continuous unit. The height difference of fixed pier is about four times, i.e., the 16th pier is 26.9m in height and the 19th pier is only 7.1m in height. Acoording the numerical simulation results, the longitudinal natural frequency of the fifth and sixth continuous unit is 0.45Hz and 0.64Hz respectively. The displacement of girders at bracket expansion is shown in Fig.18, it is indicated that movement in an opposite direction of the fifth and sixth continuous unit occurred at about 9.5s during earthquake, leading to the excessive relative displacemen and collision between bracket expansion.

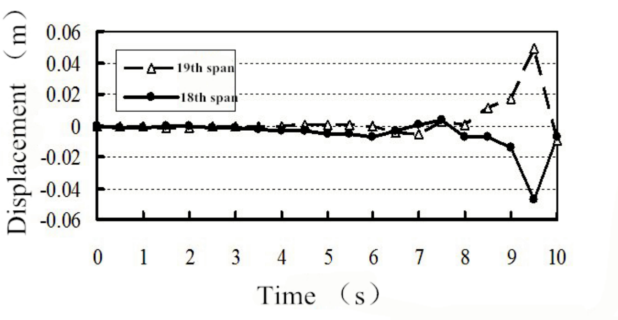


Fig. 18 – Displacement of girders at bracket expansion

(3) Lack of bent cap for most bridge piers.

Because most bridge pier have no bent cap and vertical earthquake action amplifies bend-torsion coupling effect of curved bridge, the connection part of collar beam and pier is easy to failure and can not work as a whole as shown in Fig.19. For example, the displacements of fixed pier top of the fifth and sixth continuous unit are shown in Fig.20. The results show that after peak acceleration of earthquake (t is about 12.25s) is reached, there will be a larger displacement difference between outside and inside of the 16th pier and the 19th pier respectively. It indicates that serious damage occurred in connection part of collar beam and pier, leading to greater relative horizontal displacement between the fifth and sixth continuous unit.

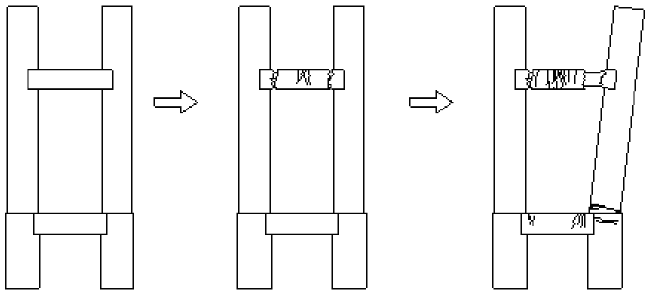
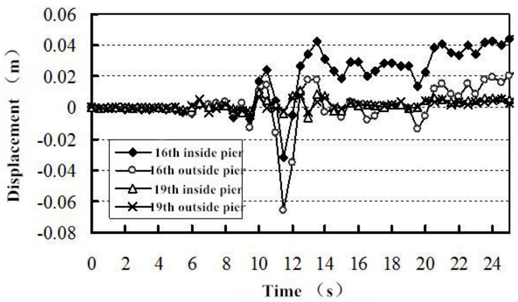
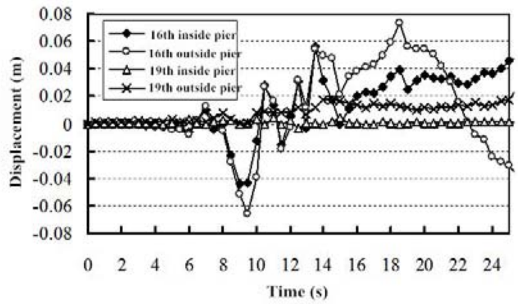


Fig. 19 – Seismic damage process of bridge pier without bent cap



(a) transverse direction



(b) longitudinal direction

Fig. 20 – Displacement of fixed pier top

(4) Inappropriate bearing arrangement.

Only one fixed bearing is set at outside of the 16th pier and longitudinal sliding bearing is set at inside of the 16th pier. Other piers are all installed with sliding bearings or laminated rubber bearings. Under the bi-directions horizontal earthquake action, in-plane rotation of girder around the fixed bearing occurred in curved segment, leading to longitudinal-transverse coupling displacement at expansion joint, as shown in Fig.21. The longitudinal-transverse coupling displacement results in extrusion and pounding of adjacent girders, leading to larger relative displacement and unseating eventually, which is consistent with the actual bracket damage as shown in Fig.17. In addition, horizontal seismic action of superstructure of the fifth continuous unit was totally bear by the 16th pier due to fixed bearing arrangement, leading to the pier destroyed rapidly.

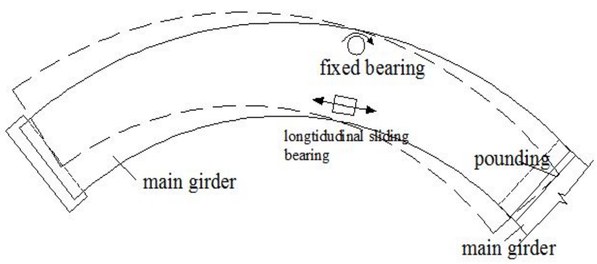


Fig. 21 –In-plane rotation of curved girder around the fixed bearing

(5) Girder-girder and girder-pier pounding effects.

The pounding effect between the 14th girder and the 13th girder, and the pounding effect between the 18th girder and 19th girder affect unseating obviously. Furthermore, the pounding effect between girder and pier aggravats the collapse failure. For example, the numerical simulation results of pounding effect between the 18th span and 17th pier is shown in Fig.22. It is indicated that the falling girder hit against the pier, leading to further damages and final collapse of the pier.

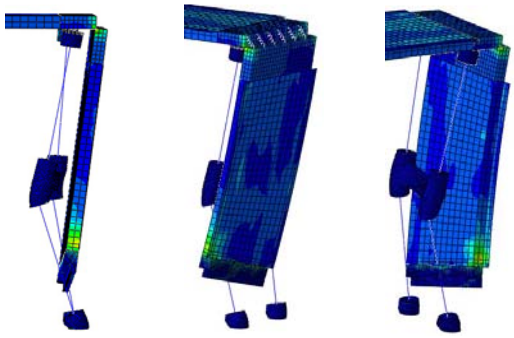


Fig. 22 – Pounding between girder and pier

5 Conclusions

As an engineering example of Baihua Bridge collapsed in Wenchuan earthquake, a multi-scale microstructure model of the curved girder segment of Baihua bridge is established by the finite element software ABAQUS. The numerical simulation of seismic damage and progressive collapse process of bridge are performed and the actual seismic damages of structure are factually reproduced. According to the numerical simulation results and field seismic hazard investigation, the failure cause and mechanism of seismic damages and progressive collapse of Baihua bridge during Wenchuan earthquake are revealed. Several conclusions can be obtained as follows.

(1) By establishing the multi-scale finite elements of pier and girder of Baihua Bridge and using the treatment scheme with force equilibrium condition, both the global and local mechanism properties and response behaviors of bridge structure can be obtained, and the actual seismic damage and collapse process can be simulated accurately with limited computation resource condition.

(2) The numerical results show that one side of the girder of the fifth continuous span dropped first from the bracket expansion joint due to excessive movement, and the falling girder hit against the pier. This leads to further damages and final collapse of the pier, then overall progressive collapse of the fifth continuous span.

(3) The complex and excessively strong near-fault earthquake effects in Baihua Bridge site is the most important reason for unseating of superstructure and destruction of pier.

(4) The dynamic properties difference between the fifth and sixth continuous unit, lack of bent cap for most bridge piers, bend-torsion coupling effect of curved girder bridge, unreasonable bearing arrangement and pounding effects are the main factors leading to the overall progressive collapse of the fifth continuous span of Baihua Bridge.

6. Acknowledgement

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