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COLLAPSE ANALYSIS OF A LONG-SPAN REINFORCED CONCRETE CONTINUOUS BRIDGE UNDER THE EXTREME EARTHQUAKES

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Abstract

Long-span bridge structures tend to fail under the extreme earthquakes, and nonlinearity should be considered in simulating this kind of event. It is difficult to simulate seismic-induced bridge collapse numerically with finite element analysis though, because the large degrees of freedom of the bridge model will result in unacceptable computational costs. Therefore, a simplified finite element model of the reinforced concrete continuous bridge is necessary to consider the nonlinearities of the bridge with high computational efficiency. In addition, the bearing capacities of fixed bearings are normally assumed to be infinite, and their influences on seismic damage of the bridge are neglected. In a real bridge, the bearing capacities of fixed bearings are designed to restrain the lateral displacements of girders, which will affect the response of the overall bridge structure. In this paper, a simplified finite element model was established for a typical three-span reinforced concrete continuous bridge. The simplified finite element model is verified to be effective by comparing the numerical results with the experimental results on mechanical behavior of the reinforced concrete pier and girder, and by comparing dynamic property of the bridge obtained using the simplified finite element model and a detailed finite element model. The collapse process of the reinforced concrete continuous bridge with different bearing capacities under the extreme earthquakes are simulated, and the collapse modes are analyzed. The numerical results indicated that the bearing capacity had an important influence on the collapse modes of the bridge.

Keywords: long-span continuous bridge, collapse analysis, simplified finite element model, fixed bearing, extreme earthquake

1. Introduction

From past records, reinforced concrete continuous bridges often suffer serious damage and even collapse under the extreme earthquakes. For example, Fig. 1a shows the flexural failure of a bridge pier under the Hyogo-Ken Nanbu earthquake [1]. The concrete cover was damaged and the steel reinforcements yielded. If the RC pier has insufficient ductility, shear failure of the pier would occur. Fig. 1b shows the flexural failure and the shear failure of the city viaduct piers under the Kobe earthquake [2], which led to the bridge collapse. In some cases, dislocation failure would occur due to the weak bearings between the girder and the piers. Figs. 1c and 1d show the dislocation failure under the Chile [3] and Taiwan [4] earthquakes. These failure would induce traffic interruption and delay of the rescue effort, which would in turn result in casualties and economic losses. Therefore, it is important to study the collapse mechanism and collapse modes of reinforced concrete continuous bridges, in order to establish a design theory on collapse prevention of bridges under the extreme earthquakes.

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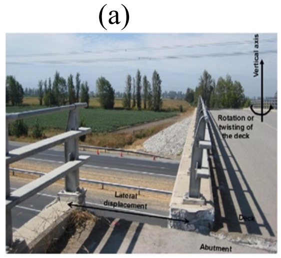
(b)



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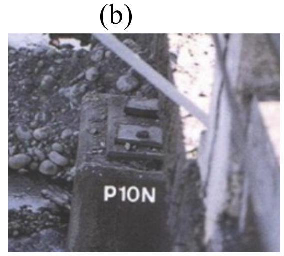


(d)

Fig. 1 – Bridge failures: (a and b) pier failure, and (c and d) dislocation failure

Seismic-induced bridge collapse can be analyzed through experimental methods, but it is quite costly and puts a high requirement on experimental technology. On the other hand, it is effective to study the collapse mechanism of bridges by numerical simulation methods [5], which include discrete element method [6] and finite element method [7]. It is normally imprecise to model the plastic behavior of a bridge due to seismic excitations by the discrete element method (DEM), while the finite element method (FEM) can handle this problem more precisely and has been adopted in simulation of structural collapse. Szyniszewski et al. [8] provided a simplified methodology for an energy-based progressive collapse assessment of multi-story buildings, and analyzed the progressive collapse of steel-framed buildings based on finite element method. Alashker et al. [9] established a simplified model of a steel building, in which the steel-concrete composite floors were attached to columns through shear tabs, and investigated key parameters influencing the robustness of generic composite floors subjected to the removal of a center column. Lu et al. [10] developed a FEM-based numerical model encompassing fiber-beam element, multilayer shell element, and elemental deactivation technique to predict the collapse process of high-rise buildings subjected to extreme earthquake. These studies demonstrated that a simplified finite element model is necessary for the collapse analysis of structures. However, limited research is available on simplified finite element model for the collapse analysis of reinforced concrete continuous bridges. Meanwhile, under the extreme earthquakes the bridge structure is likely to enter the strong nonlinear stage and the members suffer serious damage. Therefore, it is important to ensure precision to simulate the collapse behavior of the bridge.

For the collapse analysis of continuous bridges, the bearing capacities of fixed bearings need be considered because fixed bearings are prone to fail as the connections between the piers and the girders, which results in the change of seismic forces in the girders and the piers. It is found that strong fixed bearings can decrease the pounding responses of girders and increase the seismic forces in the piers [11]. On the contrary, once the weak fixed bearings fail, the inertia force of the girder to the pier will decrease and the pounding response of the girder will increase. Therefore, the bearing capacities of fixed bearings may lead to different collapse modes of continuous bridges.

In this study, a simplified finite element model was established for a typical three-span reinforced concrete continuous bridge. The simplified finite element model is verified to be effective by comparing the numerical results with the experimental results on mechanical behavior of the reinforced concrete pier and girder, and by comparing dynamic property of the bridge obtained using the simplified finite element model and a detailed finite element model. The collapse process of the reinforced concrete continuous bridge with different bearing capacities under the extreme earthquakes are simulated, and the collapse modes are analyzed.

2. Numerical model of bridge

2.1 Bridge detail

Fig. 2 shows the elevation view of a typical three-span (90 m+160 m+90 m) reinforced concrete continuous bridge. The compressive strengths of the concrete used for the pier and the girder are 40 MPa and 50 MPa respectively. The steel reinforcement has an elasticity modulus of 206 GPa and a yield strength of 335 MPa. Bidirectional fixed bearings are installed on pier #2, and transverse-only fixed bearings are installed on the rest of piers.

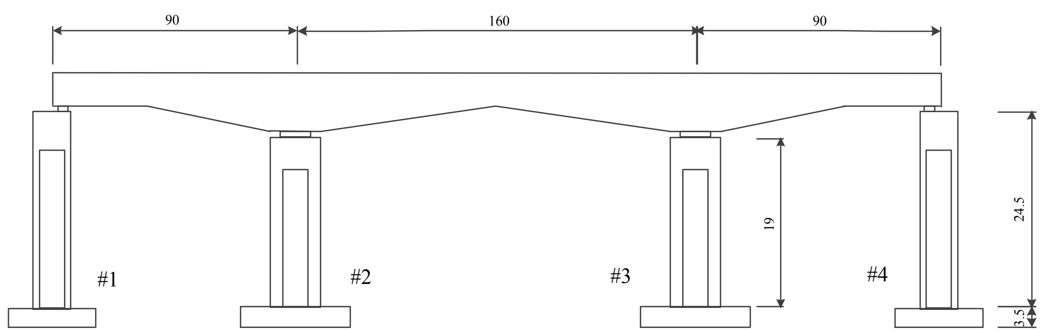


Fig. 2 – Bridge model (unit: m)

2.2 Simplified bridge model

The multilayer shell element is based on the principles of composite material mechanics, which is capable of simulating coupled in-plane/out-of-plane bending, in-plane shear, and coupled bending-shear behavior of reinforced concrete shear walls [12]. This type of element is composed of a number of layers with different thicknesses and different material properties [13]. The hollow pier can be decomposed into four walls as the four sides of the pier, and the multilayer shell element is used to model the four walls of the pier using the finite element software LS-DYNA, as shown in Fig. 3. The hollow box girder of the bridge is also modeled in this way, and the reinforced concrete continuous bridge is established as shown in Fig. 4. To verify the simplified modeling method, a cyclic loading test of reinforced concrete hollow pier and a monotonic loading test of a reinforced concrete box girder are simulated, and the dynamic properties of the bridge are obtained by the simplified finite element model and a refined finite element model respectively.

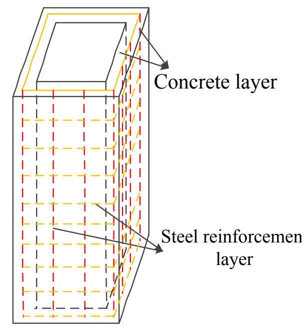


Fig. 3 – Multilayer shell element.

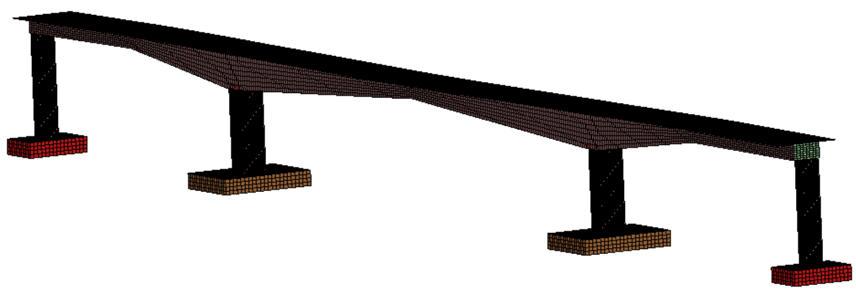


Fig. 4 – Simplified finite element model of the bridge.

2.2.1 Model verification for the hollow pier

Cyclic loading test of a reinforced concrete hollow pier is simulated to validate the proposed simplified modeling method. The detailed dimension is shown in Fig. 5. The strength of the concrete is 30 MPa, and yield strength of steel reinforcements is 385 MPa. The steel reinforcement ratio and volume-stirrup ratio are 1.4% and 3.5% respectively [14]. The axial compression ratio of the pier is 0.1

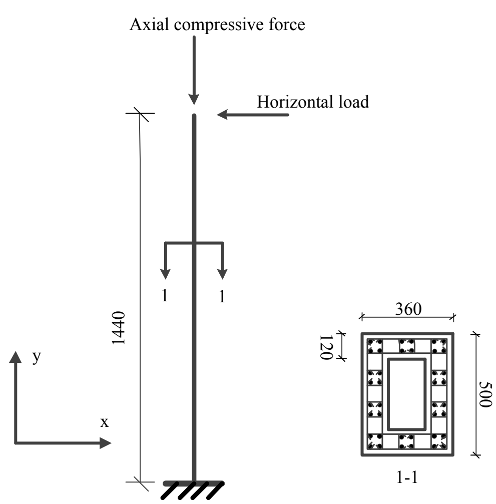


Fig. 5 – Specimen dimension (unit: mm)

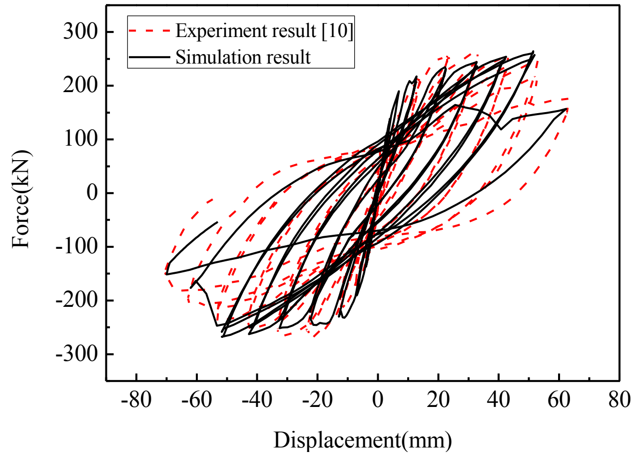


Fig. 6 – Comparison between numerical simulation result and experimental result for a hollow pier

Fig. 6 shows the comparison between the hysteretic curves from the numerical simulation and the cyclic loading test of the hollow RC pier, in which it is clear that the curves match well and strength degradation, stiffness degradation, and pinching effect can be accurately simulated by the simplified model. Even for the final stage of the hysteretic response when deterioration of the pier becomes evident, the discrepancies between the simulation results and the experimental results are still within an acceptable range in engineering practice.

2.2.2 Model verification for the box girder

Monotonic loading test of a reinforced concrete box girder is simulated to validate the proposed simplified modeling method. The detailed dimension is shown in Fig. 7. The concrete strength is 30 MPa, and the yield strength of steel reinforcements is 300 MPa [15]. Fig. 8 shows the comparison between the numerical simulation results and the experimental results for the box girder. The figure shows that the numerical simulation performs fairly well to capture the yielding and hardening characteristics of the box girder.

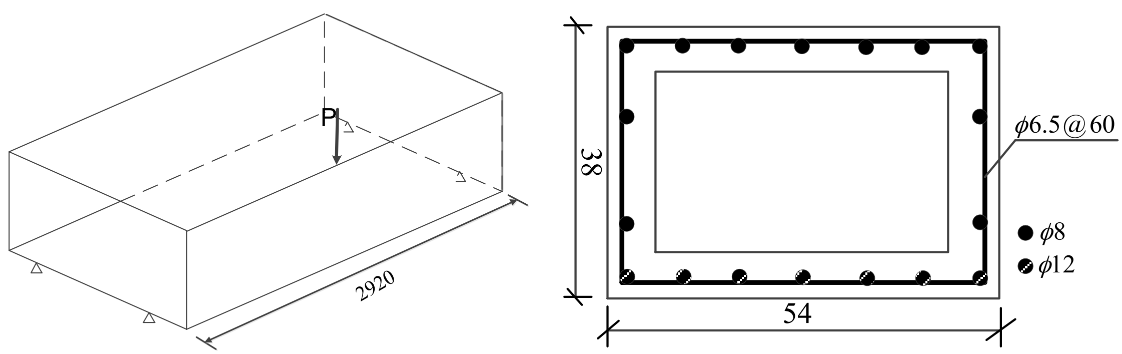


Fig. 7 – Specimen dimension (unit: mm)

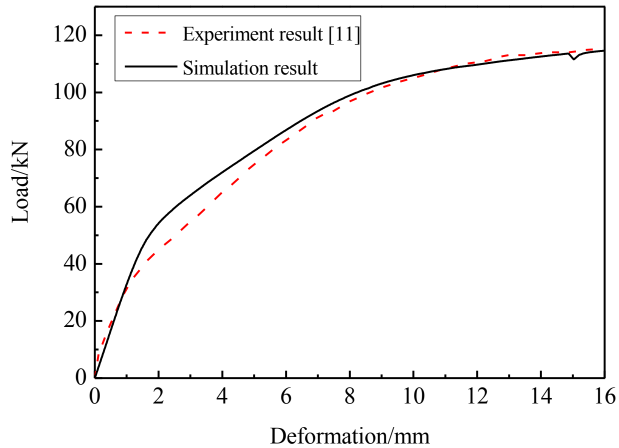


Fig. 8 – Comparison between numerical simulation result and experimental result for a box girder.

2.2.3 Dynamic property of the bridge

Refined finite element model is considered to be a reliable model to analyze the seismic-induced failure of a bridge [16, 17]. A refined model is constructed for the continuous bridge, in which solid elements are employed to model the concrete and Belytschko beam elements are employed to model the steel reinforcements. Perfect bonding is assumed between the steel reinforcement and the concrete. Dynamic properties of a structure can reflect the overall dynamic performance of the structure, and the dynamic properties of the continuous bridge using the simplified model and the refined model are obtained and compared with each other in Table 1. As shown in Table 1, the first three natural frequencies as well as vibration modes of the bridge from the two models are close, therefore the simplified model is effective.

Table 1 – Comparison of dynamic properties between simplified and detailed method

Model / Modes	**Simplified method**		**Detailed method**	
	Frequency（Hz）	**Vibration Mode**	**Frequency**（Hz）	**Vibration Mode**
1	0.55	Longitudinal vibration	0.55	Longitudinal vibration
2	0.88	Transverse vibration	0.86	Transverse vibration
3	0.98	Vertical vibration	0.92	Vertical vibration

3. Numerical results

To study the influence of bearing capacity on the collapse modes of the bridge, the horizontal bearing capacity is designed as 10%, 20%, and 30% of the vertical bearing capacity of the fixed bearing for weak, medium, and strong bearings, respectively. In order to simulate bridge failure, the El-Centro ground motion [18] is adopted, and the peak ground acceleration is scaled up to 1.2 g, according to the extreme earthquake in Chinese code [19]. Seismic failure analysis is conducted in the longitudinal and transverse directions of the bridge.

Fig. 9 shows the collapse modes of the bridge with different bearing capacities under the extreme earthquake. Fig. 9a shows the piers suffer no damage with weak bearings, but the girder has large displacement at the right end as shown in the dotted circle, which may cause the risk of unseating. Fig. 9b shows that with medium bearings, pier #2 and pier #1 fail, and the bridge collapses. Fig. 9c shows that with strong bearings, the middle span girder collapses, pier #2 and pier #3 fail, and the rest of the piers suffer no damage.

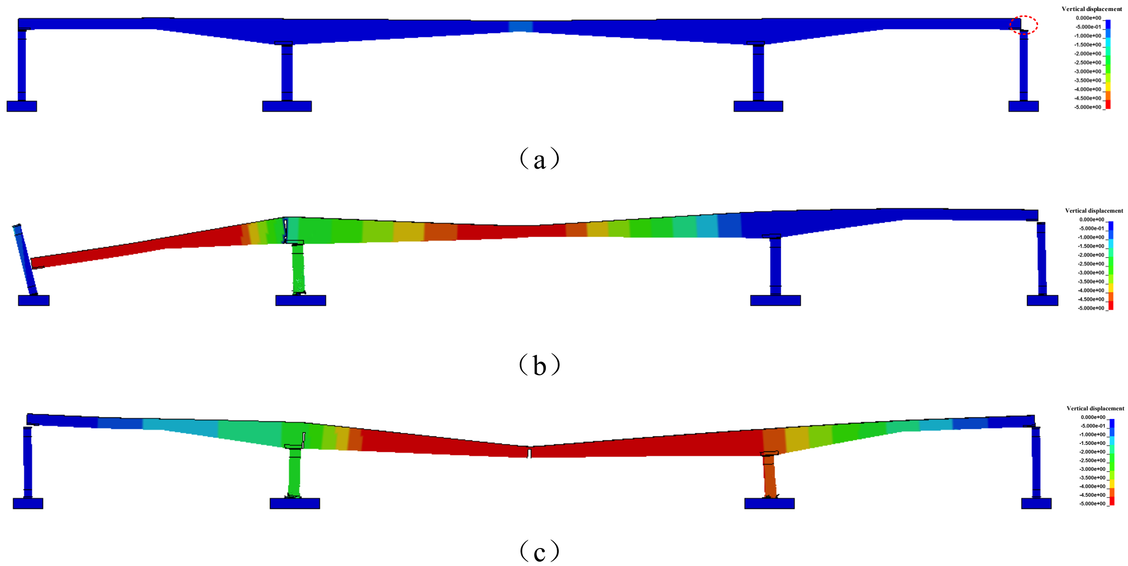
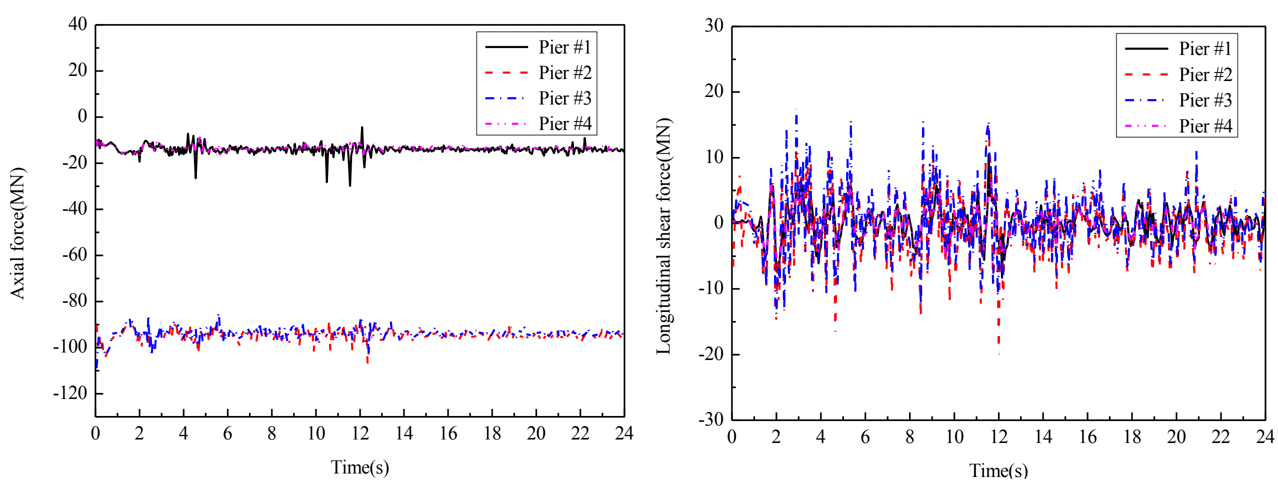


Fig. 9 – Collapse modes of the bridge with different bearing capacities: (a) weak bearings, (b) medium bearings, and (c) strong bearings

Fig. 10 shows the time history curves of the internal forces on the piers with weak bearings under the extreme earthquake. Fig. 10a shows that the axial forces on all piers have no sudden decrease and the piers suffer no damage. As shown in Fig. 10b, the longitudinal shear force on pier #2 is the largest before 1s, then it is close to the longitudinal shear force on pier #3 because the longitudinal fixed bearing on pier #2 fails under the extreme earthquake, and then the fixed bearing turns into a sliding bearing after 1s.



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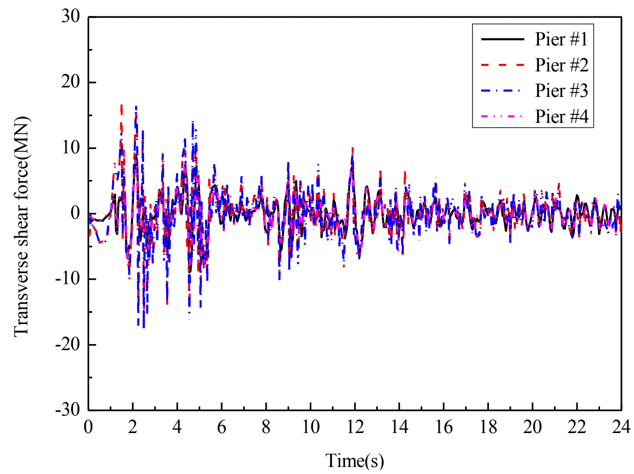
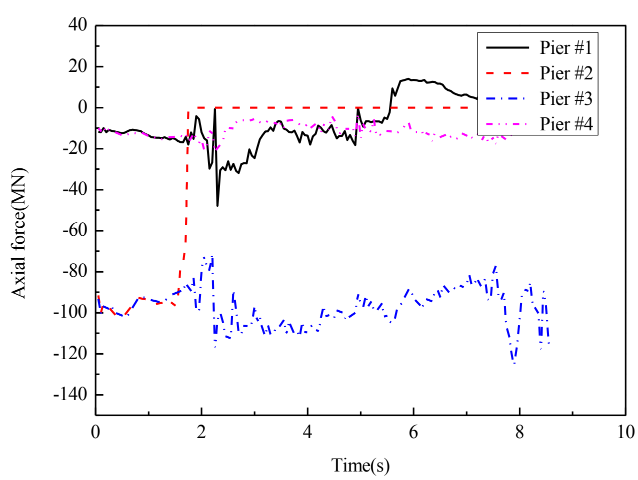


(c)

Fig. 10 – Time history curves of internal forces on piers with weak bearings: (a) axial force, (b) longitudinal shear force, and (c) transverse shear force

Fig. 11 shows the time history curves of the internal forces on the piers with medium bearings under the extreme earthquake. Fig. 11a shows that the axial force on pier #2 suddenly decreases at approximately 1.8s resulting in the failure of pier #2, and then the axial forces on pier #1 and pier #3 increase. This is because that pier #1 and pier #3 share the weight of the girder after pier #2 fails. Pier #1 is in tension after approximately 5.8s, because the girder generates deformations and pier #1 suffers horizontal force which causes the pier in eccentric tension as shown in Figs. 9b and 11b. Fig. 11b shows that the longitudinal shear force on pier #2 is the largest before 2s, and then the force suddenly decreases because the pier fails. Therefore, the collapse mode of the bridge would be that first the longitudinal fixed pier fails, then the internal forces are redistributed resulting in the increased forces on adjacent piers, and finally the girder fails, leading to the collapse of the bridge.



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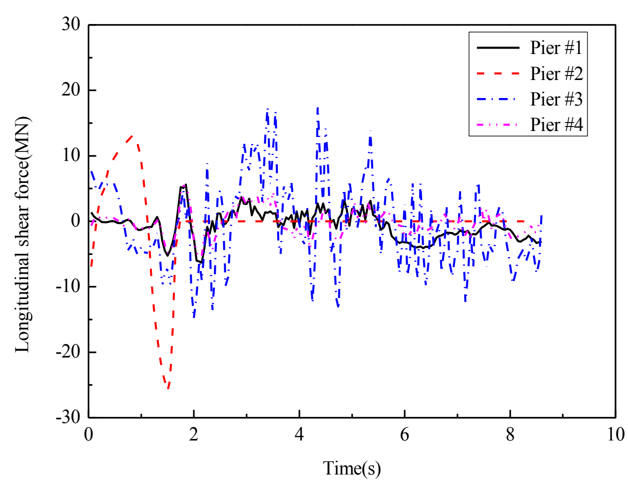

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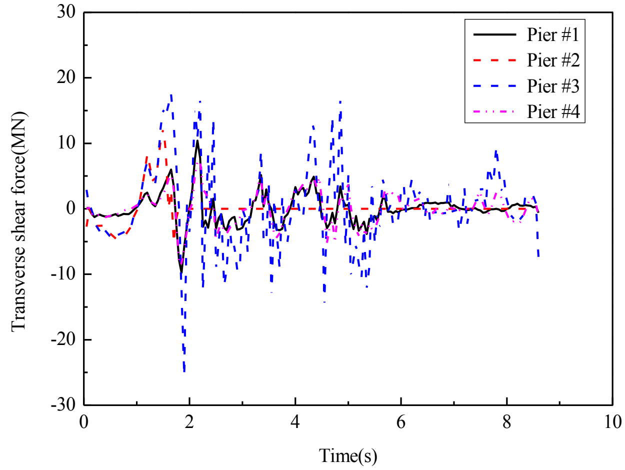
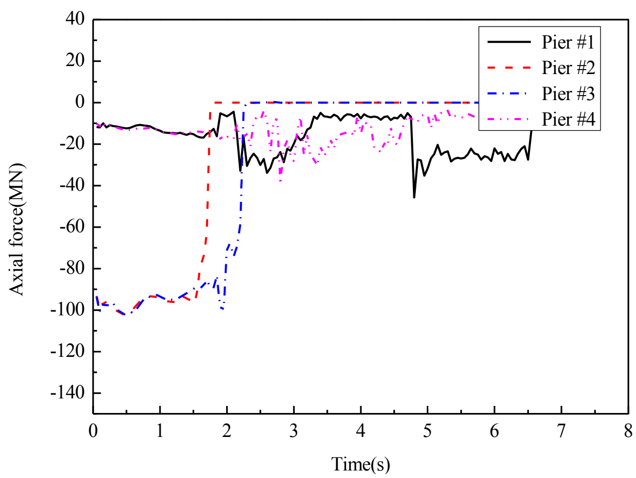


(c)

Fig. 11 – Time history curves of internal forces on piers with medium bearings: (a) axial force, (b) longitudinal shear force, and (c) transverse shear force

Fig. 12 shows the internal force time history curve of piers with strong bearings under the extreme earthquake. Fig. 12a shows that under the extreme earthquake, the axial force of pier #2 suddenly decreases at approximately 1.8s resulting in the pier #2 fails, the axial forces of pier #1 and pier #3 increase, and then pier #3 suddenly decrease at approximately 2.1s. This is because that pier #1 and pier #3 share the weight of the girder on the pier #2 resulting from the pier #2 fails, and then the pier #3 fails. As shown in Figs. 12b and 12c, after pier #2 failing, the transverse shear force of pier #3 increases and then decreases suddenly. It indicates that the larger transverse shear force leads to pier #3 failing because of strong transverse bearings on the pier. Therefore, this kind of collapse mode of the bridge can be summarized that the longitudinal fixed pier fails, the structural internal forces are redistributed resulting in the increased forces to the adjacent piers, the transverse force causes transverse fixed pier (#3) failing, and then the bridge collapses.



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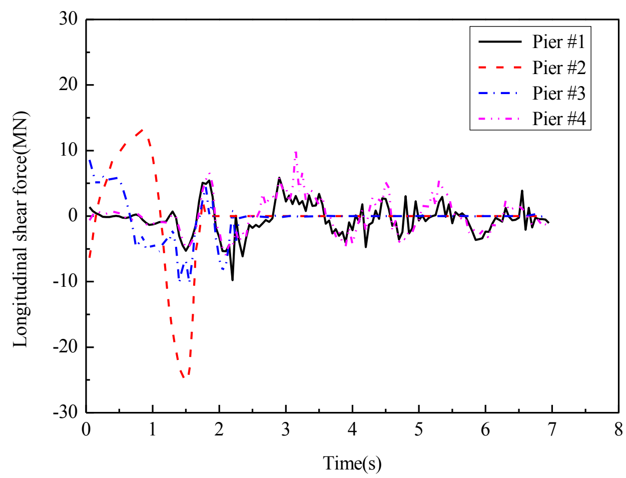

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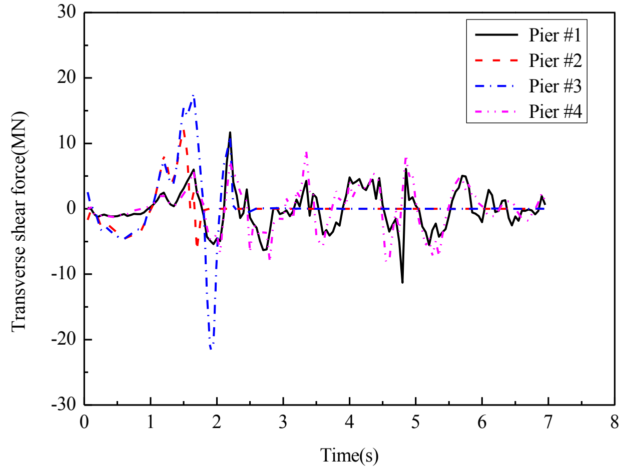

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Fig. 12 – Time history curves of internal forces on piers with strong bearings: (a) axial force, (b) longitudinal shear force, and (c) transverse shear force

4. Conclusions

A simplified modeling method is proposed to simulate the collapse process of a typical three-span reinforced concrete continuous bridge under the extreme earthquake. The simplified finite element model is verified to be effective by comparing the numerical results of the reinforced concrete pier and girder with the experimental results, and comparing the dynamic properties of the bridge using the simplified model with those using the refined model. The collapse processes of the reinforced concrete continuous bridge with different bearing capacities under the extreme earthquake are simulated and analyzed. The numerical results indicate that the weak bearings are easily to fail under the extreme earthquake, which protects the piers from damage, but it may result in large girder displacement; use of the medium bearings can cause the fixed pier to fail under the longitudinal earthquake; use of the strong bearings can cause not only the fixed pier to fail under the longitudinal earthquake, but also the adjacent pier to fail under the transverse earthquake.

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