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Progressive collapse mechanism of continuous girder bridges under barge collision

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ABSTRACT

For important bridges, it is highly required that catastrophic failure of the entire structure be prevented. One of the most famous paradigms in China is the collapse of the Jiujiang Bridge under barge collision. In order to reveal the collapse mechanism and verify the modeling method of impact problems, this paper attempts to simulate the collapse of the Jiujiang Bridge with the program, LS-DYNA. Both the barge and the entire structure were modeled, in which the elasto-plastic damage cap model and the elastic plastic kinematic model were used for concrete and steel respectively. The interaction between concrete and steel were discussed and an ALE formulation was used for it. Additionally, the prestressed steel and gravity were also simulated. The simulation reproduced the collapse scene which is consistent with the real collapse process of the Jiujiang Bridge. It proves that the modeling method is reasonable and thus can provide instructions for other impact simulations.

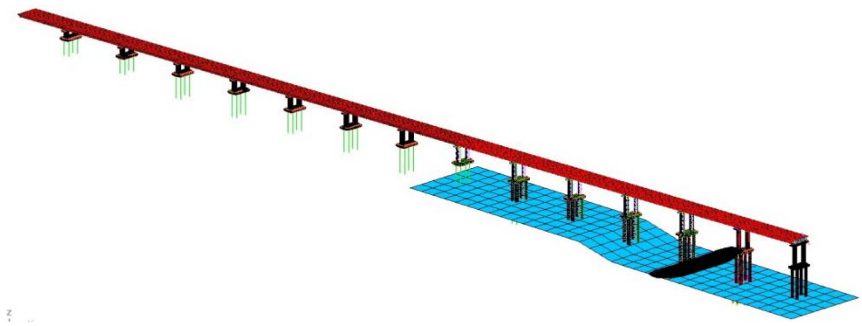

Figure.1 Finite element model of the Jiujiang Bridge under barge collision

1. INTRODUCTION

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Collapse process of bridges under vessel collisions is so complex that more and more researchers attempt to use numerical simulation methods in ship-bridge collision studies. In some simulations (Zili Wang and Yongning Gu, 2001; Jiancheng Liu and Yongning Gu, 2002; Gary R. Consolazio, 2005) the strain rates effect was involved for the steel of ships, however, the concrete was taken as an elastic material. A nonlinear material model with strain rate effects (HJC model) was employed in vessel-bridge collision simulations (Cheng Chen, 2006). Besides the HJC model, the elasto-plastic damage cap model was employed in the progressive collapse simulation for the continuous girder bridge (Hua Jiang, 2010; Kai Zhao, 2012).

The paper attempts to reveal the collapse mechanism of the Jiujiang Bridge under vessel collision. To ensure reliable computation results, a high-fidelity FE model, which includes the dynamic material model, interaction between steel and concrete, gravity, prestress and interaction between the soil and pile, was developed.

2. Review the causes of the Jiujiang Bridge collapse

The Jiujiang Bridge is a single pylon cable-stayed bridge which spans the Xijiang River. The south approach bridge is a continuous girder bridge with the span arrangement of 15×50m+40m. On June 15, 2007, a 3000DWT freighter with a cargo of sand struck the pier 23, causing pier 23 to pier 25 and approximately 200 meters of the girder to collapse. The span arrangement is shown in Figure2.

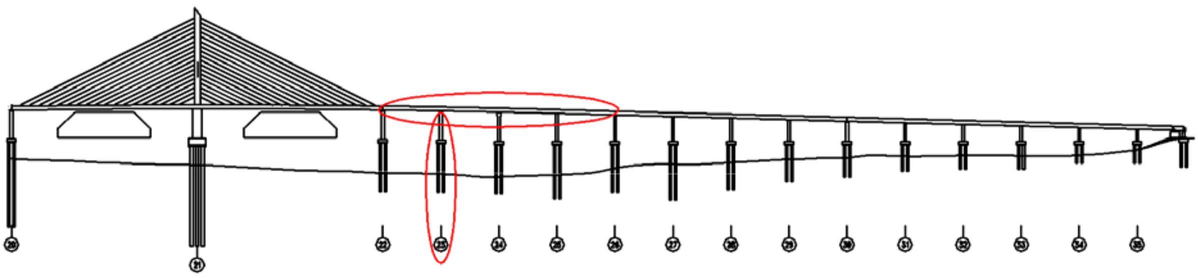


Figure2 Span arrangement of the Jiujiang bridge

Figure3 Collapse scene of the Jiujiang Bridge

3. High-fidelity FE barge and bridge models

3.1 Barge model

Modeling the barge is one of the key points in the collision simulation. In general, the impact speed of vessels is relatively slow and thus the crush deformation is focused in a local area, whereas the other parts far away from the impacted region almost don't deform and they just provide mass and stiffness. Therefore, the bow should be modeled with a high resolution mesh and the rear vessel body can be modeled roughly with rigid bodies.

In the study DWT of the barge is 2000 tons and all of the components in this model were modeled using shell elements. A high resolution mesh was modeled for the bow section and the other parts of the barge were modeled by equivalent mass. For the steel in the bow section, a bilinear stress-strain relationship was adopted (*MAT _PLASTIC_KINEMATIC) and the strain rate effect was also considered by using Cowper-Symonds formulation (Cowper, G.R and Symonds, P.S.,1957). Parameter values of the stress-strain relationship are shown in Table1.

Table 1 Material parameters of the barge

Material model	RO (Kg/m^3)	E (MPa)	PR	SIGY (MPa)	ETAN (MPa)	BETA	SRC (s^{-1})	SRP	FS
*MAT_PLASTIC _KINEMATIC	7890	2.1×10^5	0.3	238	21	0	40.4	5.0	0.35
*MAT_RIGID	7890	2.1×10^5	0.3	Null	Null	Null	Null	Null	Null
*MAT_RIGID	7890	2.1×10^5	0.3	Null	Null	Null	Null	Null	Null

Note: RO=Mass density; E=Young's modulus; PR=Poisson's ratio; SIGY=Yield stress; ETAN=Tangent modulus; BETA=Hardening parameter; SRC=Strain rate parameter for Cowper-Symonds strain rate model; SRP= Strain rate parameter for Cowper-Symonds strain rate model; FS=Failure strain for eroding elements.

The barge model is shown in Figure 4.

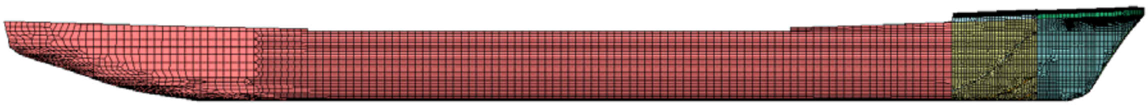


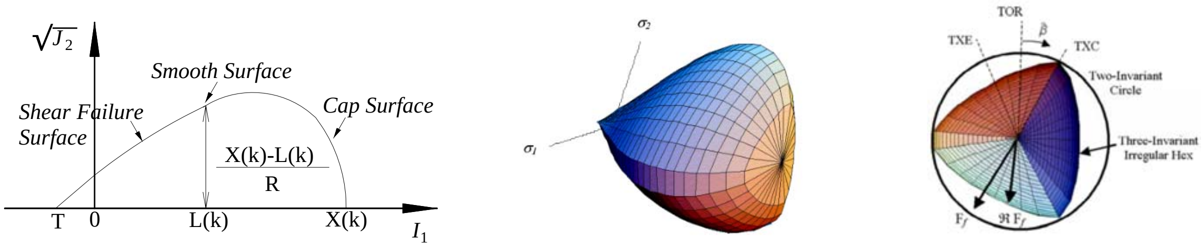
Figure4 Finite element model of the barge

3.2 Bridge model

The concrete and steel bars were modeled with hexahedral elements and truss elements respectively. In order to ensure the computational accuracy, element size of these important zones of the impacted pier 23, such as the impacted zone, the top and bottom of pier columns and piles, was 0.15m and 0.30m in other zones. In addition, the mesh size of the girder in these collapsed spans was 1.0m. For the other piers and girders, the mesh size was 0.5m and 4.0m respectively.

The elasto-plastic damage cap model (*MAT_Schwer_Murray_Cap_Model) was adopted for the concrete. The elasto-plastic damage cap model, known as the

Continuous Surface Cap Model (Schwer, L. E., Murray, Y. D., 2002), was obtained through the modification of the elasto-plastic cap model (Schwer, L. E., Murray, Y. D.,1994). Its failure shapes on the meridian plane, the Haigh-Westerggard space and the deviatoric plane are shown in Figure.5.



(a) Meridian plane (b) Haigh-Westerggard space (c)Deviatoric plane
Figure.5 Failure surface of the elasto-plastic damage cap model

The elastic plastic kinematic hardening model was employed for the steel bar (*MAT _PLASTIC_KINEMATIC) in which strain rate effects were also taken into account.

An ALE formulation (*CONSTRAINED_LAGRANGE_IN_SOLID) was used to simulate the interaction between the concrete and steel bars.

The gravity also played an important role in the collapse process and therefore the gravity of the structure was simulated (*LOAD_BODY_Z).

From the hydrology and navigation data, the ship's speed was around 2.6m/s~3.8m/s, a typical speed of 3m/s was adopted in the study. In addition, the impact point was applied at the file cap of Pier 23 and a head-on collision model was finally developed in the paper, as shown in Figure 6.

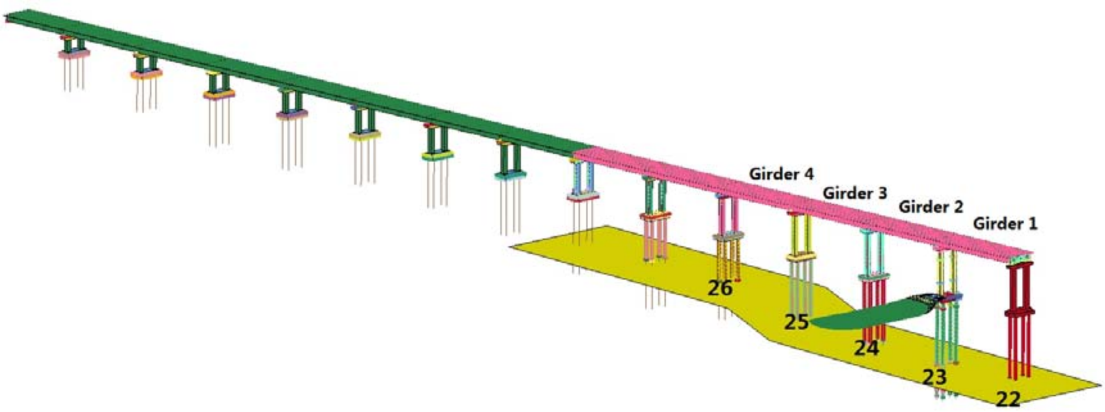
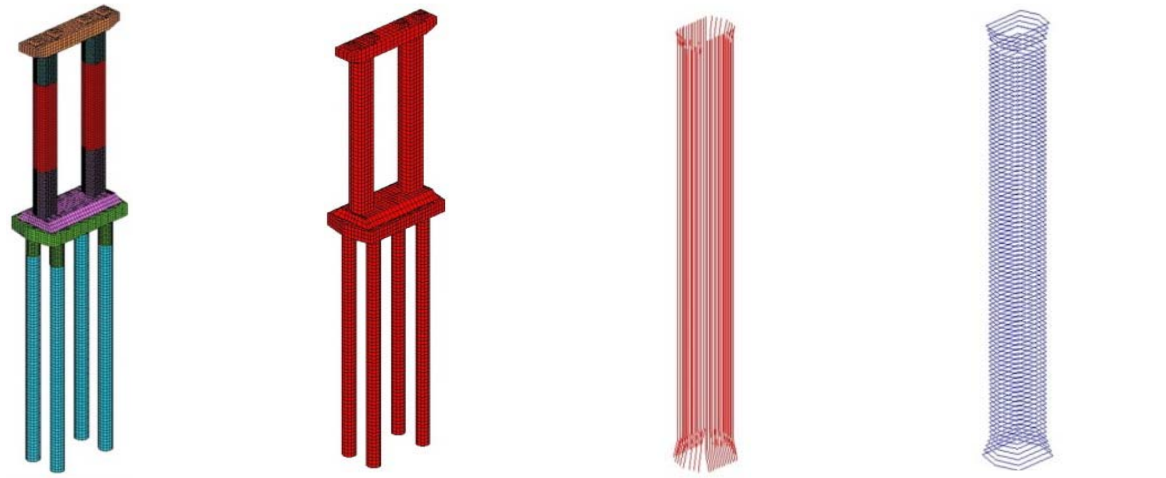
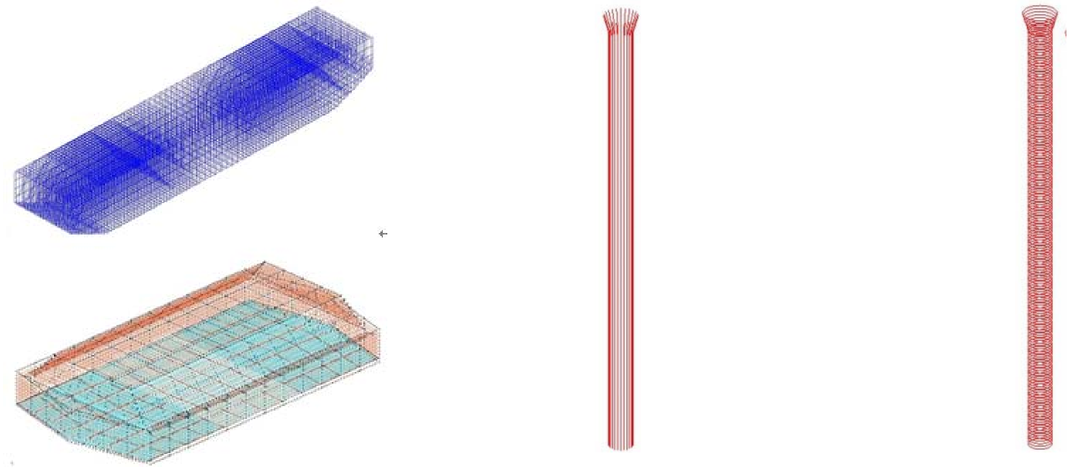


Figure 6 Finite element model of the collision



(a) Pier 23 (b) Other piers (c) Longitudinal steel of piers (d) Transverse steel of piers



(e) Steel in pier caps and pile caps (f) Longitudinal steel of the piles (g) Transverse steel of the piles

Figure7 Detailed modeling of bridge members

4. Analysis of the mechanism of the whole bridge collapse

Generally speaking, the collapse can be divided into 2 phases. One is the failure of Pier 23 and the other phase is the progressive collapse of the adjacent spans.

4.1 Collapse of pier 23

As a matter of convenience, the impacted column of pier 23 was referred as column A and the opposite column was called column B. Accordingly, piles at the barge side were referred as pile A and piles at the other side were called pile B, as shown in Figure8.

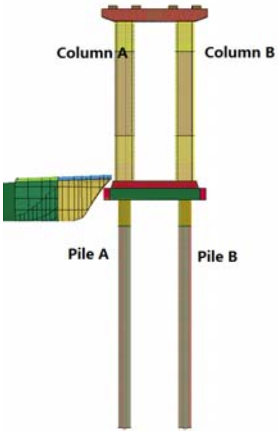
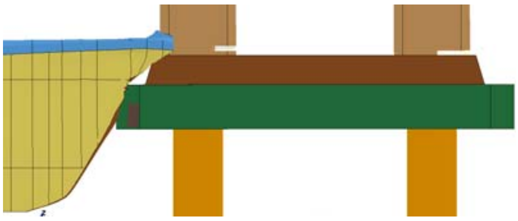
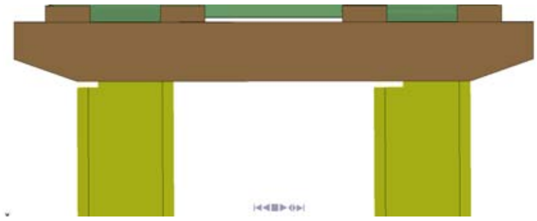


Figure 8 Notations for pier 23 members

From the collision simulation, it was found that Pier 23 is short of the capacity to resist the impact force. At 0.4s, tension cracks developed at the column bottom and pile top, as shown in Figure9.



(a) Pier column bottom



(b) Pier column top

Figure 9 t=0.4s

As the transverse displacement of the pile cap increased, the damage of the column bottom and pile top became heavier at 0.5s and tension cracks formed at the pile top, as shown in Figure10.

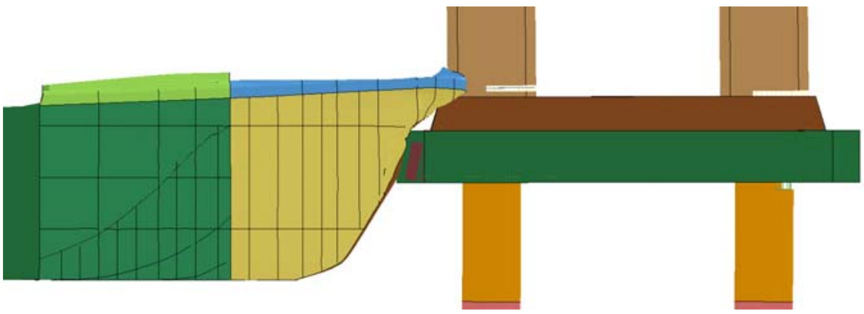


Figure 10 t=0.5s

As the pile cap deformed increasingly, concrete of the column bottom failed totally. Consequently, the connection of piles and piers to the pile cap was linked by steel bars only and the vertical capacity of the pier decreased evidently. Therefore, the pile cap deformed rapidly due to the gravity of the superstructure, as shown in Figure 11.

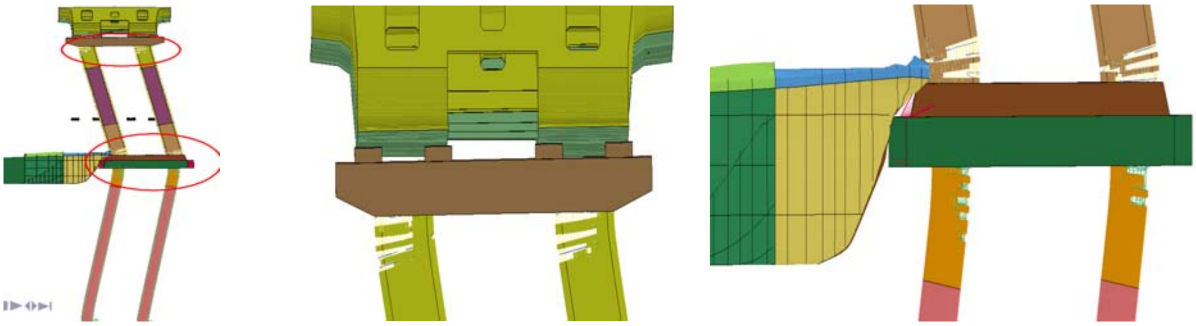
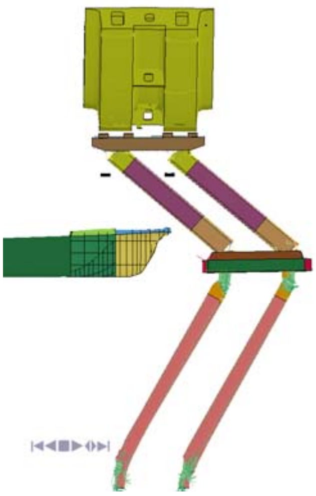
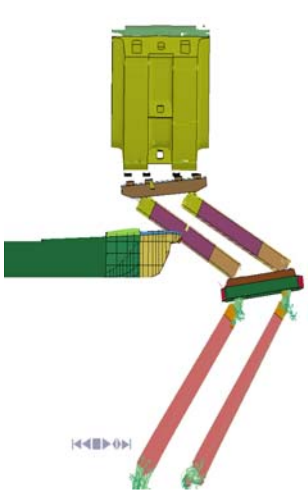


Figure 11 t=4.0s

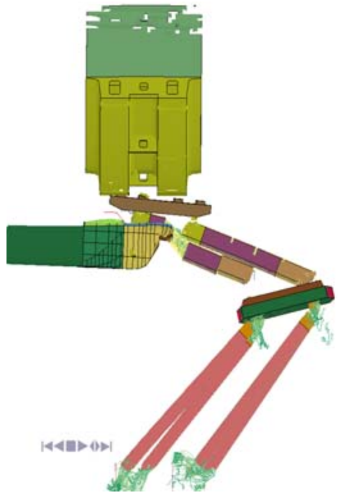
The concrete of pile top failed totally at 0.69s and the piles lost the capacity to resist the gravity of the superstructure. As a result, the columns and girder fell and the barge was pounded by the falling columns at 7.6s. Subsequently, the barge was pushed into the river by the falling columns and girders, as shown in Figure 12.



(a) t=6.9s



(b) t=7.6s



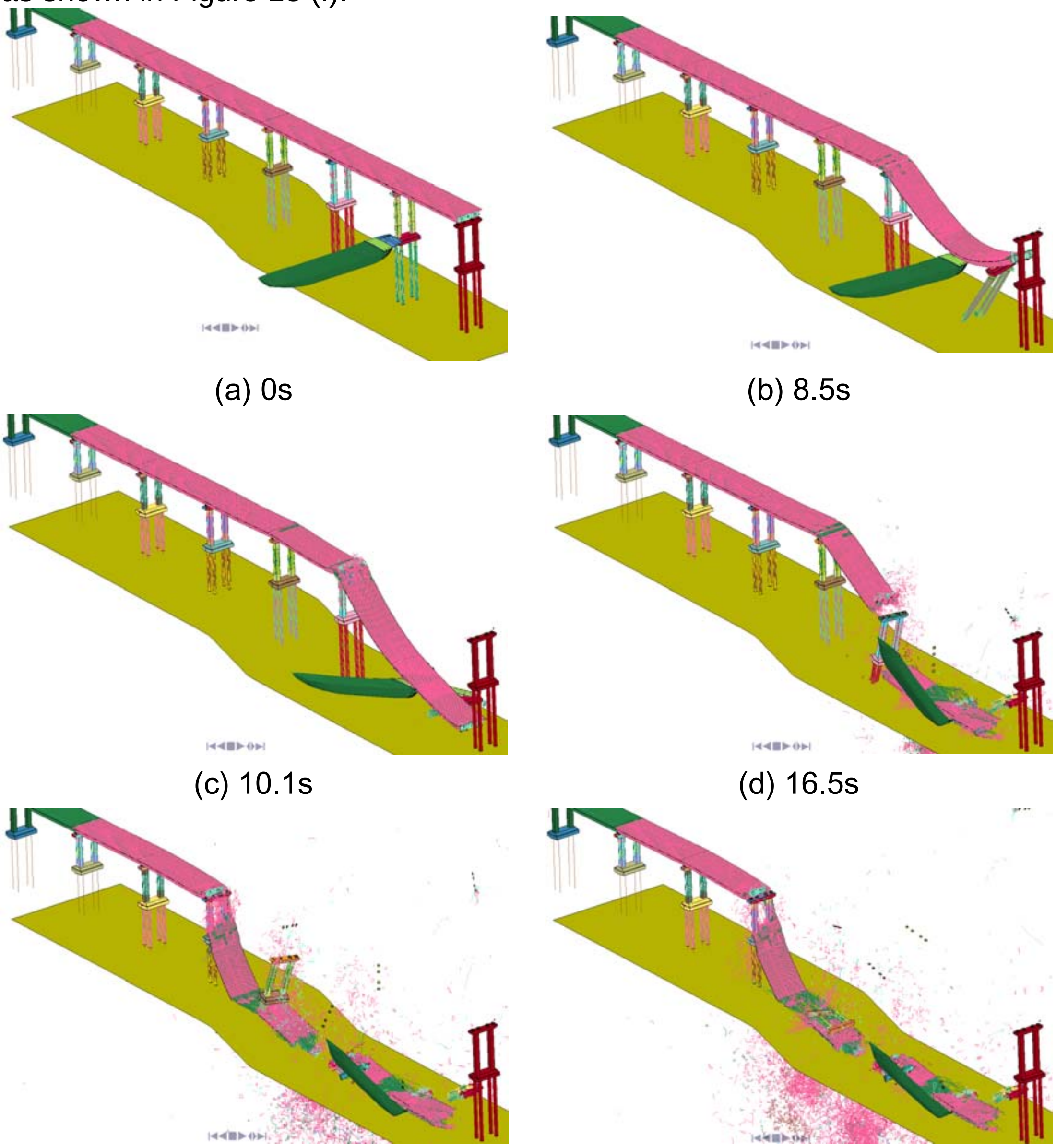
(c) t=8.3s

(d) t=10.2s

Figure 12 The collapse of pier 23

4.2 Progressive collapse of adjacent spans

Figure 13 illustrates the complete collapse process from the simulation. When Pier 23 collapsed after 0.69s, girder 1 and girder 2 fell into the river subsequently, as shown in Figure 13(b). Then girder 1 and girder 2 broke when girder 1 struck the river bed. Afterward, the suspended girder 2 rotated around the top of pier 24 until it struck pier 24, as shown in Figure 13(c). Next pier 24 also collapsed by the hit of girder 2 and led to the falling of girder 3 (Figure 13(d)). Then pier 25 collapsed as the same manner of pier 24. Consequently, girder 4 fell without the support of pier 25 and rotated around the top of pier 26 (Figure 13(e)). Finally, girder 4 didn't strike pier 26 because the higher river bed between pier 25 and 26 prevented girder 4 from rotating after striking the river bed, as shown in Figure 13 (f).



(a) 0s (b) 8.5s

(c) 10.1s (d) 16.5s

(e) 23s (f) 27s

Figure 13 Collapse process of the entire bridge

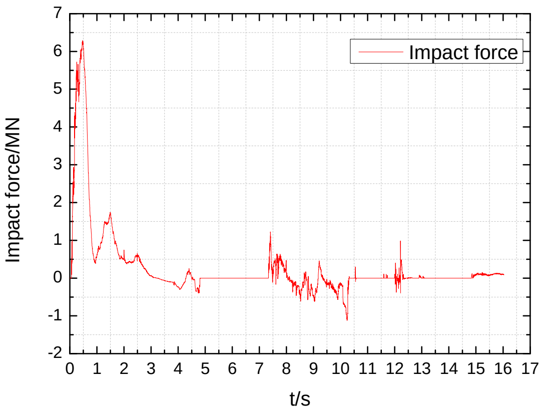


Figure 14 Impact force time history

Figure 14 illustrates the impact force time history of the barge. It shows that the impact force reached the peak value at 0.4s when the damage was slight. The impact force decreased rapidly because the damage became much heavier after 0.4s. After 4.0s, the barge and pile cap separated and impact force turned to zero. Afterwards, the barge was pounded into the river and the impact force was beyond concerns.

5. CONCLUSIONS

First, the collapse of pier 23 was induced by both the impact force and the gravity of the superstructure.

Second, progressive collapse happened after the failure of pier 23. For important bridges, it should be prevented in bridge design and thus engineers should pay much attention about such failure modes.

The simulation reproduced the collapse scene which shows a good agreement with the real collapse process. Therefore, the modeling method in the paper is reasonable and thus can provide instructions to other impact simulations.

6. Acknowledgement

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