Collapse Causes Analysis and Numerical Simulation for a Rigid Frame Multiple Arch Bridge

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Abstract. Following the collapse accident of Baihe Bridge, the author built a plane model of the whole bridge firstly and analyzed the carrying capacity of the structure for a 170-tons lorry load. Then the author built a spatial finite element model which can accurately simulate the bridge collapse course. The collapse course was simulated and the accident scene was reproduced. Spatial analysis showed rotational stiffness of the pier bottom had a large influence on the collapse from of the superstructures. The conclusion was that the 170 tons lorry load and multiple arch bridge design were the important factors leading to collapse.

1. Introduction
Baihe Bridge in Huairou District, Beijing was a reinforced concrete rigid-frame arch bridge, which had four spans and the single spans were 50 meters each. The rise to span ratio was 1/10 and the width of the bridge deck was 11.5 meters. The substructures considered of solid piers and foundations of socketed piles. Fig.1 is the diagram of the span arrangements of Baihe Bridge.

Baihe Bridge was built in 1988 and it has been operating for twenty years. In July 2011, when a 170 tons lorry which was severely overloaded moved to the first span of Baihe Bridge, the whole four spans collapsed successively. Fig.2 is the photo of the collapsed Baihe Bridge.
2. Analysis software and calculation contents

Bridge structure calculation software GQJS was used to build a plane finite element model of Baihe Bridge, allowing to analyze structural forces and load effects in a 170 tons lorry load. A general space finite element software was used to build a spatial finite element model in which geometric nonlinearity, material nonlinearity and contact nonlinear were considered\(^1\). In this part, the collapse process of Baihe Bridge was simulated and different rotational stiffness as a parameter influencing the collapse form was analyzed.

In the plane finite element model some factors such as the dead load, the heavy lorry load, construction phases, concrete shrinkage and creep were considered. The plane model included 161 solid elements and 150 series of reinforcement models. Wheel loads were arranged as the real situation in the first span. Fig.3 is the plane model of Baihe Bridge.

![Fig 3. Plane Model of Baihe Bridge](image)

The compression bearing capacity indicated that the major arch legs of the first span could not meet the design criteria of the 170 tons load. For example, the axial compressive strength in the right arch spring of the first span was 12.648MN, less than the axial load effect of 14.076MN. Other sections of the first span met design criteria but had a low degree of safety in compression and flexural capacity. From this we could already conclude that the main stress components had insufficient strength of the 170 tons load.

3. Numerical simulation of collapse process

3.1 Spatial finite element model

Using an adequate computer program a spatial simulation model was built in which geometric nonlinearity, material nonlinearity and contact nonlinearity were considered. The bridge deck, piers and block set walls were modelled as stratified shell elements, and the arch ribs were modelled as beam elements. Fig.4 is the spatial model of Baihe Bridge.

![Fig 4. Analytical Model](image)

3.2 Analysis cases

Two typical values of the rotational stiffness of the pier bottom were considered to simulate different constraint conditions according to some documentations\(^2\)\(^3\), as showed in table 1.
3.3 Analysis results

3.3.1 Analysis results in the case A. The whole four spans collapsed in the case A. Fig.5 lists dynamic printscreens of collapse process. Firstly, when the lorry transited to the center of the first span, the horizontal beams and arch ribs of the first span showed large plastic deformation and collapsed immediately, as indicated in a and b. Arch spring of the second span nearby the first span happened large deformation and collapsed immediately, as indicated in c and d. And then the third span and the forth span happened chain reaction and finally the four spans all collapsed, as indicated in e and f.

| Analysis case | Rotational stiffness of pier’s bottom $(\times 10^{11} \text{ Nmm/rad})$ |
|---------------|---------------------------------------------------|
| Case A        | 3.24                                              |
| Case B        | 4.86                                              |

![Collapse Process in the Case A](image-url)
3.3.2 Analysis results in the case B. If the rotational stiffness of the pier bottom equals 4.86×10¹¹ Nmm/rad, progressive collapse ended in the second span. If the rotational stiffness was larger, the second span would not collapse. As indicated in Fig.6, first the arch spring of the first span showed plastic deformation, and with gradually increasing deformation, the first span collapsed, as indicated in a,b,c. Immediately the arch spring of the second span showed large plastic deformation, and started to collapse, as indicated in d,e,f. Further the second span collapsed and the arch ribs of the third span damaged to a certain extent. However due to the large enough rotational stiffness, the piers could bear the unbalanced horizontal force and further collapse ended.

3.4 Influence of rotational stiffness on collapse forms
Fig.7,8 showed the displacement time history curve of the pier top in the case A and B. Displacement in the direction of the lower span takes positive values while negative value is taken to the opposite direction. The maximum horizontal displacement of the pier top is -230mm in the case A, while it equal -160mm in the case B.
Fig. 7. Displacement Time History Curve of the Top of Piers in the Case A

Fig. 8. Displacement Time History Curve of the Top of Piers in the Case B

Fig. 7 shows the horizontal displacement value of the top of pier1 which is positive at the beginning, subsequently there is a sharp shift towards negative value. As negative displacement increases to a certain value, the second span collapsed. When the horizontal displacement value of pier2 increased to a certain value, the third span collapsed, and so on, the chain reaction finally leading overall collapse. Fig. 8 shows negative displacement of pier1 appearing a platform in the case B and later increasing lowly with time, finally the pier can’t resist horizontal thrust from the second span and the second span collapsed. Because the rotational stiffness of pier2 is large enough to resist the horizontal thrust of the third span, progressive collapse ended.

3.5 Collapse cause analysis
The immediate cause of the bridge collapse was the overloaded lorry, because the 170 tons load was far beyond the design load. Different rotational stiffness of the pier bottom had a large influence on the collapse form. Baihe Bridge was designed as a multiple arch bridge and the piers were not designed for single direction thrusted piers. Because the rotational stiffness was insufficient, progressive collapse occurred in all four spans.

4. Conclusions
Many rigid-frame multiple arch bridges were built in the 1980s in China because of aesthetic value and for saving material. After thirty years operation this kind of bridges was insufficient to meet the existing design loads. Moreover, multiple arch design also implies a lot of questions. Baihe Bridge was a typical case. Through this paper engineers can understand this kind of bridge more clearly.
Aimed to this kind of bridge, we suggest to limit traffic load or strengthen and even dismantle this bridge type.

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