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A Preliminary Study on the Application of Computer Simulation in the Progressive Collapse of Bridges

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Abstract

Bridges are important lifeline projects, so the collapse accidents of bridge will cause significant casualties and properties losses. Computer simulation has a bright future to discover the reasons of bridge accidents. Taking the progressive collapse accidents of stone arch bridges which suffered greatest in recent years for an example, this paper establishes a finite element (FE) model of the stone arch bridge with the general-purpose finite element program-MSC.MARC. The process of the collapse is simulated with the contact algorithm and the deactivation of elements, and the possible reasons of the collapse are analyzed. Furthermore, the importance of different components of the stone arch bridge is indexed with the conception of the generalized structural stiffness, so as to identify the most critical regions of the stone arch bridge. The predicted critical regions are verified to be correct and reasonable via limit analysis, which provides references for the design, construction and maintenance of arch bridges.

Keywords: Stone arch bridge, Progressive collapse, Computer simulation, Deactivation element, Critical region.

1 Introduction

Being one of the conventional bridge types, arch bridge has long history and beautiful shape. It is widely distributed in the world and plays an important role in bridge engineering. Even though the materials and technologies of bridges have developed greatly in recent years, arch bridge is still very competitive for small and medium-span bridges.

However, the collapse accidents of arch bridges repeatedly happened (Cheng M.X., 2008). In recent 14 years, there were more than 5 import collapse accidents of arch bridges in China which caused more than 100 casualties. These accidents aroused the concern and thinking of bridge engineers. It is very important to correctly reproduce the process of bridges accidents, to analyze the possible reasons of collapse and to determine the most critical regions for the bridge safety, which could provide favourable references for the bridge design, construction and collapses prevention.

Based on a typical stone arch bridge accident, this paper simulates the entire process of the progressive collapses with the general purpose finite element (FE) program MSC.Marc. The possible reasons that result in the progressive collapses of the arch bridge are analyzed. Then, based on the conception of the generalized structural stiffness, the importance indices of different components of the arch stone bridge are evaluated and the critical regions are obtained. Finally, the identified critical regions are verified via the limit (pushdown) analysis.

2 FE model of the stone arch bridge

2.1 Bridge parameters

The background of this research is a 3-span stone arch bridge with a total length of 233.55m and each span of 58.5m. The heights of the two piers are 25.61m and 27.00m respectively. And the height-length ratio of each arch is 1/5 and the thickness of the main arch is 1.2m.

The material strengths of different components are listed in Table 1, which are based on the Chinese Code for Design of Highway Masonry Bridges and Culverts (JTG D61-2005).

Table 1. The material parameters of different components (unit: MPa)

Material properties	Main arch	Transverse wall	Spandrel arch	Pier	Foundation	Filler	Pavement
Young’s modulus	13,293	7,300	7,300	11,256	25,500	7,300	30,000
Yielding strength	10.13	5.25	6.30	8.58	13.40	1.12	20.10
Cracking strength	0.32	0.13	0.13	0.28	1.54	0.11	2.01

2.2 FE model and elemental failure criterion

Because the dimensions of the structural elements of the stone arch bridge are much larger than the size of the stone blocks, no matter what kind of analytical method (FE method or other numerical methods such as discrete element method, rigid body spring element method, DDA, etc.) is adopted, it is neither possible nor necessary to simulate the stone blocks one by one. Hence, this paper built the FE model of the stone arch bridge with the general purpose finite element program MSC.Marc. In order to improve the computational accuracy, quadrilateral planar elements are used and fine-mesh elements are adopted in the complicated joints.

The stones in the arch bridge are modelled as elasto-plastic-fracture material in the FE analysis (Bazant and Planas, 1997; Jiang J.J et al., 2005). The yielding and cracking strengths are listed in Table 1. Besides, when the materials reach a certain level of damage, they will be completely failed. Therefore, “birth-death element” technology is used to remove the failed elements. Total strain is used as the elemental failure criterion, that is, when the maximum tensile or compressive strains of elements exceed the threshold value, a subroutine named “UACTIVE” is used to remove the element from the FE model (MSC.Marc Documentation, Volume D).

The piers are constructed on the natural foundation which is located on slightly weathered rocks. When the horizontal loads on the piers exceed the allowable value, the pier may horizontally slide or overture to collapse. This movement cannot be simulated with the conventional fixed boundary condition. Thus, in order to precisely simulate the interaction between the foundation and the pier, Mohr-Coulomb friction contacts (MSC.Marc Documentation, Volume A), which is provided by MSC.Marc, is used to simulate interface between the pier and the foundation.

3 Simulation of the progressive collapse

3.1 Load cases

Considering the possible collapse reasons in the real accidents, the following two load cases are simulated respectively.

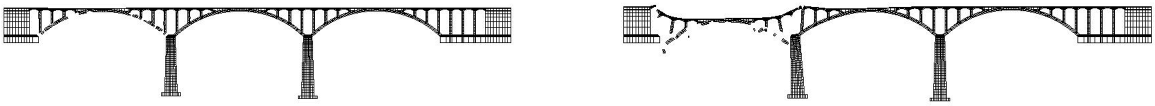
Load Case 1: Collapse due to insufficient material strength (poor construction quality) of the first main arch. Based on the material strength in Table 1, the tensile and compressive strength of the first main arch are reduced by 40%, while the young's modulus, Poisson ratio and density are kept unchanged.

Load Case 2: Collapse due to horizontal slide in the foundation of the left abutment. The left abutment is moved to left side step by step to simulate the slide in the foundation. And the maximal horizontal slide is set to be 100mm.

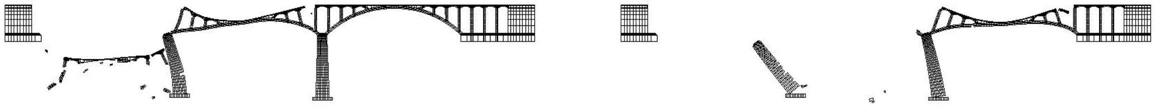
3.2 Simulation results

Because the actual bridge collapsed without any traffic load, in the FE simulation, only dead load is considered while the live load is neglected. The two load cases and their corresponding FE analysis results are shown in Figure 1 and Figure 2.

Load Case 1: Collapse due to insufficient material strength of the first main arch



(a) The beginning of the collapse (b) The collapse of the first span

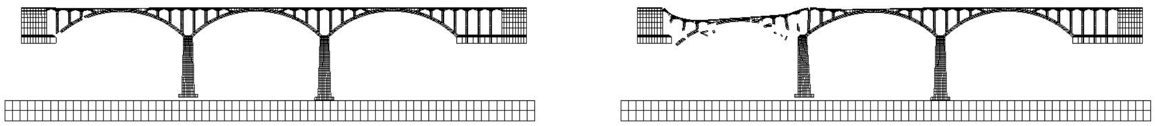


(c) The collapse of the second span (d) The collapse of the third span

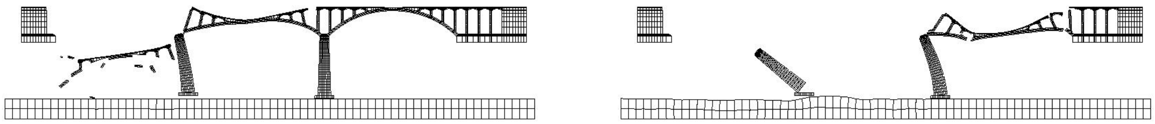
Figure 1. The simulated collapse process of Load Case 1

Figure 1 shows a typical process of the progressive collapse of the stone arch bridge. And this process clearly indicates that because of the insufficient strength of the first span, the first arch crushes to collapse firstly under the gravity load. The initial damages are uniformly distributed inside the first arch. Consequently, the collapse of the first span triggers a large unbalanced horizontal load at the top of the first pier (the numbers of piers are listed in Figure 1). This unbalanced horizontal load results in a large horizontal displacement at the top of the first pier, which significantly changes the original arch axis of the second span. This deformation induces huge additional bending moments in the second arch. When the flexural stresses exceed the flexural resistance of the stone arch, the second span fails. Similar process takes place in the third span till the collapse of the entire bridge.

Load Cass 2: Collapse due to horizontal slide in the foundation of the left abutment.



(a) The beginning of the collapse (b) The collapse of the first span



(c) The collapse of the second span (d) The collapse of the third span

Figure 2. The simulated collapse process of Load Case 2

The collapse process in Figure 2 indicates that after a large horizontal slide happens in the foundation of the left abutment, the arch axis of the first span is changed and significant additional bending moment is induced in the first main arch, which results in the collapse of the first span. And the initial damage happens in the skewback near to the left abutment where the additional bending moment is the largest. Meanwhile, the collapse of the first span triggered a large unbalanced horizontal load at the top of the first pier, followed by the corresponding horizontal displacement, which changed the shape of the second span. Similarly, the second span collapses and the collapse process propagates to the entire bridge.

The main difference between Load Case 1 and Load Case 2 is the positions of the initial damage. In Load Case 1, the initial damage occurs at the weakest position in the first main arch, while in Load Case 2, the initial damage occurs at the skewback of the first main arch. Besides, in Load Case 2, significant horizontal displacement in the foundation of abutment should be observed at the site of bridge collapse. These differences will help to identify the reason of the collapse.

4 Critical regions of the stone arch bridge

In order to avoid the collapse accidents of arch bridge, it's necessary to deeply understand the mechanism of the arch bridges and to pay more attention to the critical regions of the arch bridges to improve the global safety margin. Generally, bridge structure is an organic mechanical system which is made of a series of components. Each component of the structure has a different degree of importance subjected to the external loads. Even in the same component, different parts also have different importance for the safety of the whole structure. Therefore, in order to ensure the global safety of the bridge, the critical components and critical regions of the bridge should have more safety margins. Hence, importance indices of the components should be evaluated firstly to determine the critical regions of stone arch bridge.

4.1 Importance indices of the components

The importance indices of the structural components not only depend on the mechanical properties of the structural system itself, but also depend on the characters of the external loads. Besides, they are influenced by the targets of the structural performance. A literatures study shows that the existing methods to evaluate the importance indices can be divided into two categories (Agarwal et al., 2001; Nafday, 2008; Lin, 2009; Liu and Liu, 2005): load-independent evaluation methods or load-dependent evaluation methods. The former methods mainly focus on the self-properties of the structural system and evaluate the importance indices of structure members from the perspective of topology or the stiffness distribution of the structural system. The latter methods consider not only the structural attributions (stiffness, strength, topology, etc.) but also the load properties (loads distribution, magnitude, load path, etc.) on the structures.

A generalized structural stiffness-based importance index I, which is proposed by Lin (2009), is adopted in this work. Both external load properties and stiffness properties are considered in the proposed generalized structural stiffness. Therefore, the importance indices of the structural components can be measured by the change of the generalized structural stiffness after a component is damaged. The simplified expression is shown as follows:

$$I = 1 - K_f / K_0 = 1 - U_0 / U_f \tag{1}$$

in which, K_0 and K_f are the generalized structural stiffness of the structure before and after one component is damaged, U_0 and U_f are the total strain energies of the perfect structure and the damaged structure respectively.

The importance indices presented by Lin are based on one-dimensional beam elements, but the FE model of the stone arch bridge in this paper is a continuum element model. The importance indices of structural components from Eq. (1) will be influenced by the element sizes. For example, a region which actually should have high importance indices may obtain a lower value from Eq. (1) if this region is meshed with very small elements. In contrast, the importance indices in unimportant regions may be amplified due to a large element size. Therefore, in order to eliminate the influence of elements size on the importance indices, Eq. (1) is modified to Eq. (2), in which the importance indices in Eq. (1) is divided by the corresponding elemental volume V.

$$\Gamma = (1 - U_0 / U_f) / V \tag{2}$$

4.2 *Critical region analysis*

The following procedures are proposed to evaluate the importance indices of structural components of the stone arch bridge:

(1) Build up the FE model of the stone arch bridge by FE program (MSC.Marc, etc.). And assign the corresponding material and geometric properties to different elements;

(2) Calculate the total strain energy of the original structure under gravity load via linear elastic computation.

(3) Remove elements one by one with the subroutine named "UACTIVE". Calculate the total strain energy of the damaged structure and the volume of the removed element;

(4) Calculate importance indices of all components with Eq. (2);

(5) Sort the importance indices of all elements in descending order. In this paper, the elements whose cumulative volume is in the first 10% of the total volume are defined as the critical regions of the stone arch bridge.

Following the above steps, the importance indices of all elements are obtained and sorted in descending order and the elements, whose cumulative volume is in the first 10% and last 10% of total volume, are obtained respectively. The elements, whose cumulative volume is in the first 10%, are mainly distributed at the following 5 regions: (1) the top of the piers; (2) the skewbacks of the main arches; (3) the upper and lower surfaces of the arch in 1/4 span near to the piers; (4) the skewbacks of spandrel arches; (5) the junctions between the transverse walls and the main arches. They are shown in Figure 3. Obviously, these regions are critical regions of the stone arch bridge and should be paid more attentions in the design, construction and maintenance. In contrast, the importance indices of elements in the middle of the spans and the fillers are the lowest. And they are shown in Figure 4.

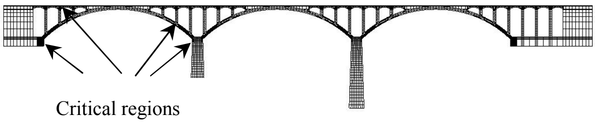


Figure 3. The distribution of critical regions

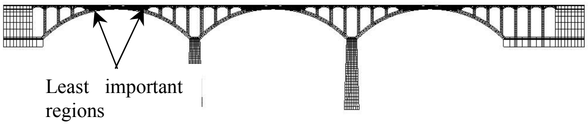


Figure 4. The distribution of least important regions

4.3 *Verification of indentified critical regions*

In order to verify the rationality of the critical regions obtained by above importance assessment method, the following four structures are analyzed via limit analysis (pushdown analysis).

(1) The original structure (Structure I);

(2) The structure whose material strengths in the critical regions are strengthened by 20% (Structure II);

(3) The structure whose material strengths in the least-critical regions are strengthened by 20% (Structure III);

(4) The structure whose material strengths in critical regions are reduced by 20% (Structure IV).

During the limit analysis (pushdown analysis), the gravity load on the bridge is increased proportionally until the structure collapses. The ultimate load capacities of different structures are shown in Table 2.

Table 2 obviously declares that the ultimate load capacity of the original structure is about 2.42 times of the self-weight load. After the materials in critical regions are strengthened, the ultimate load capacity of the Structure II increases significantly and is approximately 2.72 times of the self-weight load. When the strengths of the materials in critical regions are reduced, the ultimate load capacity decreases obviously to 1.70 times of the self-weight load. Hence, the ultimate load capacity of the structure is extremely sensitive to the strengths of the critical regions. In contrast, when the materials in least-critical regions are strengthened, the ultimate load capacity of the structure even reduces a little reversely. This phenomenon is due to the changing of failure modes after strengthening the materials in least-critical regions. In general, it is reasonable to strengthen critical regions and the effect of strengthening critical regions is much better than strengthening other regions. Therefore, the critical regions obtained by the proposed importance assessment method are reasonable.

Table 2. Ultimate load capacities for different structures

Structure Typical	I	II	III	IV
Ultimate load capacities/Weight	2.42	2.72	2.16	1.70

5 Conclusion

Based on the simulation of the progressive collapse of a typical stone arch bridge, this paper reproduces the collapse process and evaluates the importance indices of all structural elements. The critical regions of the stone arch bridge are obtained. The following conclusions are obtained:

(1) A rational element failure criterion is critical for a correct simulation of the collapse process of the stone arch bridge;

(2) The simulated collapse process will provide favourable references to investigate the collapse reasons;

(3) The critical regions of the stone arch bridge are obtained by evaluating the importance indices of all elements, which can be used to develop a rational design, construction, inspection and maintenance, so as to avoid the occurrence of the accidents of arch bridges.

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