

# **Failure reason analysis of an arch bridge and reinforcement scheme with hybrid structure**

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## **Abstract**

Arch structure has been one of the most popular architectural sculptures due to its graceful sculpts and rational bearing mechanism. In order to deal with the thrust at the arch foot and the out-plane stability of arch structure which could result in the failure of the whole structure, a practical arch bridge, which failed work after accomplishment, was taken as example to develop the research. Through analysis of the origin structure by finite element program Midas under dead and live load, the reason for the failure of the present arch structure was pointed out. Considering the concept of 'hybrid', three hybrid structures with arch as a composition were advanced to reinforce the initial structure. Two of them are arch-truss hybrid structure with different dimension, and another one is cable-supported arch hybrid structure. The present reinforced structures were analyzed and their reinforced effects were attained respectively. Through comparison of the bearing characteristic of each structure, a relatively most suitable structure was proposed to be used in this project, which could make as full as possible use of the hybrid structure.

**Keywords:** arch structure, arch bridge, failure, hybrid structure, reinforcement scheme

## **1. Introduction**

Arch structure, with rainbow-shaped appearance and attractive visual impression, could meet architect's pursuit of wonderful sculpture, to some degree. It has been one of the most popular architectural sculptures in buildings all the time, such as temple and church with arch structure in ancient Rome, stone arch bridge in ancient China and lots of modern arch buildings, etc. <sup>[1-3]</sup>

In addition to the architectural profile, the other cause for the widely application of arch structure is its rational mechanical characteristic. It is well known that with the arch axis being a thrust line, which could be derived from catenary, the arch only bears axial

compression force under uniform distributed load, which can utilize the material performance to the greatest extent. However, when an arch structure is designed, two issues should be paid more attention. The first one is how to deal with the thrust at arch foot<sup>[1, 4-6]</sup>, the other one is the lateral stability. If the two issues are not treated properly, problem could occur and the structure may be unsafe and unavailable.

In this paper, an arch steel bridge, in which the abutment was pushed away from its initial location and the arch buckled out of plane after the concrete deck was installed, was taken as an example and studied. Through analysis of the initial structure under static load, the failure reason of this bridge was investigated. Furthermore, the concept of ‘hybrid’ was introduced to reinforce this bridge. A few hybrid structures were advanced, analyzed and compared, and then the hybrid structure scheme suitable to this project was determined.

## 2. Failure reason of the initial structure

### 2.1. Overview of the project

#### 2.1.1. Structure constitution

The bridge which was taken as an example locates at Huanhu Road in Yantian District of Shenzhen. It is a single-spanned upper-supporting arch bridge with two concrete-filled steel tube (abbreviated as CFST) arch dumbbell-ties as its main bearing member. The clear span of the arch rib is 70m, and the whole length of the bridge is 76.5m. The deck is made of reinforced concrete continuous slab which was supported on the post connected to the arch rib, as shown in fig1. The other dimensions of the bridge, such as the distance of the two arch ribs, the diameter of the CFST arch, the arrangement of the bracing between the arch ribs etc, were also signified in Fig 1.

#### 2.1.2. Failure state

During the construction process of the bridge, the CFST arch rib and the post were installed accomplished normally and nothing especial happened. However, when the erection of reinforced concrete deck was accomplished, two unexpected thing occurred. The first one is that the abutment was pushed away for a distance and partial into pieces, as shown in Fig 2. Large horizontal movement at the arch foot and vertical deflection at mid of arch emerge. Even a ‘S’ shape was produced out of the arch plane, which mean the arch lose its stability in the direction crossing to the arch plane.

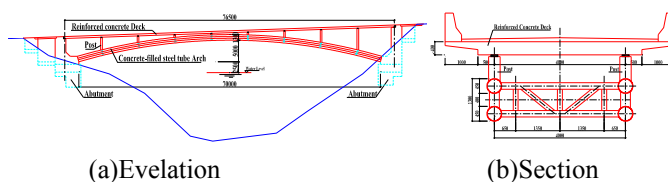


Fig 1 Elevation and section of the bridge



Fig 2 Failure of the bridge

From the description mentioned above, we can preliminarily come to that the damage of the bridge is a result of inappropriate treatment of arch foot and abutment, and improper design of out-of-plane bracing of the arc rib. In the following, we will verify it through research on the structure behavior of the original arch bridge structure system.

## 2.2. Structural behavior of the structure

Here, with finite element program Midas, the model of the origin structure was established and analysis of the structure under static load was developed.

### 2.1.1. Establishment of FEM model

With FEM software Midas, by simulating the arch rib and post as beam element, the deck as plate element, the bracing connecting the two ribs as truss element, an entire finite element model was built with actual size, as shown in Fig 3. The constrained node and their bound state are also shown in Fig 3. Among them the arch foot was completely constrained and two points at each end of the deck was constrained along vertical direction.

### 2.1.2. Structural behavior

Static analysis was carried out on bridge subjected to dead load and living vehicle load and some typical results were attained.

The reaction under dead load at one end of the arch was shown in Fig.4. It could be found that the reaction at one foot is considerably big probably due to small rise-to span ration, about 9120kN along the longitudinal direction under dead load and 11400kN under combination of dead and live load, which may lead to the damage of the abutment.

The maximum deflection under the combination of dead load and living load is about 0.121m exceeding serviceability limit states, which is due to an inferior vertical rigidity.

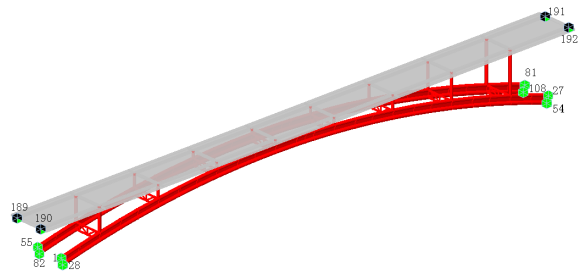


Fig 3 Finite element model of the bridge

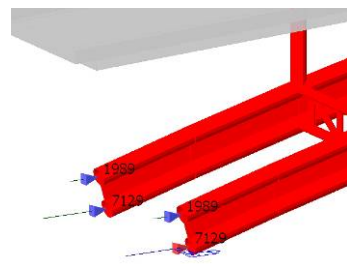


Fig 4 Reaction under dead load

By modal analysis, the front ten order vibration mode was got, and the first two mode shape was shown in Fig 5 as well as period. The first order vibration period is 1.311s and is relatively large. The first and the second order mode are both lateral vibration of the bridge, which means that the bridge is weak in lateral direction and is apt to lose its stability.

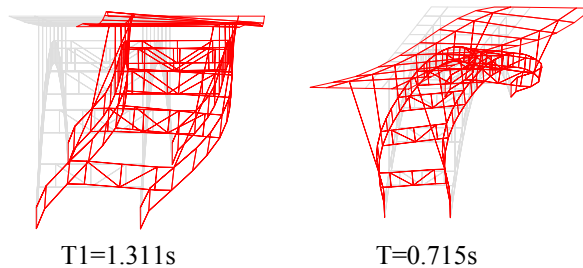


Fig 5 The first and second vibration mode

From the above discussion, we know that great thrust to the abutment, exceeding-limit deflection at middle and insufficient lateral stiffness results in the failure of the bridge. The following reformations were recommended in order to solve above mentioned problem.

### 3. Reinforcement of the structure

Before the reinforced structure was proposed, the following questions should be considered: how to deal with the large thrust and how to improve the vertical and lateral stiffness.

Generally, there are many ways to handle the thrust transferred to the support in the structure. In paper [6] eight methods to deal with the bearing thrust in large-span latticed shell or arch structure were advanced and discussed, among which, adding anti-push structure, falling to the ground and reducing column distance or increasing column section are ways that don't change the bearing mechanism, but improve the anti-push capacity of the supporting structure. Other ways, such as arranging tie bar, adding transverse diaphragms, improving column flexibility, laying longitudinal beam or truss and altering the curvature, can reduce or eliminate the thrust to supporting structure by enhancing the load-bearing or load-transferring principle.

When it come to the presented arch bridge, although the abutment can be reconstructed and reinforced, the latter ways are inclined to be adopted. According to the method mentioned before, concept of 'hybrid' was introduced and several hybrid structures were proposed to strengthen the bridge. When the hybrid structures were put forward, either reducing the thrust or improving the stiffness was considered primarily.

#### 3.1. Concept of 'hybrid'

According to the reference the author investigated, the relatively earlier proposal of hybrid structure in civiling engineering field was in the book named <Structure Systems><sup>[4]</sup> written by Heino Engel. In this book, structure systmes were classified by the load-bearing mechanism. Hybrid strcutre is a system consisting of two or more structures with different load-bearing way. The components in hybrid structure could make up the shortcoming of each other and work together more effectively.

### 3.2. Strengthened structure schemes

On the basis of the arch structure, other structure or member whose load-transferring mechanism is different and complementary with arch structure was introduced to improve and strengthen the structure as follows.

#### 3.2.1 Hybrid structure consisting of arch and truss

In this part, a hybrid structure consisting of arch and truss was described. Through changing force flow direction, truss structures can transmit the load to the supporting structure and generally produce little horizontal reaction under vertical load. By arranging truss element between the poles, a hybrid structure consisting of arch and truss came into being, as shown in fig 6(a).

Since the height at mid span is very small, no brace was laid and a solid-web was used. To improve the effect of truss, the thickness at mid span was heightened, and another reinforcement structure was forced, as shown in fig 6(b).



Fig. 6 Hybrid structure of arch and truss

#### 3.2.1 Hybrid structure consisting of arch and cable

It is well known that cable structure generated pull at supporting point, contrary to the arch structure which creates push, and many structures was stiffened by cable.<sup>[5,7]</sup> Based on this idea and in view of decreasing supporting horizontal reaction, a hybrid structure of arch and cable was put forward to reduce horizontal reaction and reinforce the origin structure, as shown in fig 7. When the cable was arranged, the clearance height demand was considered.

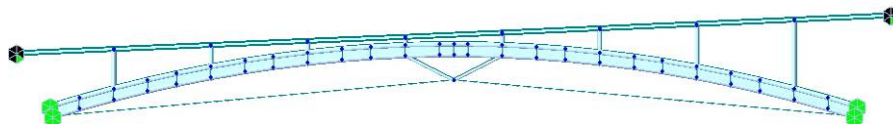


Fig. 7 Hybrid structure of arch and cable

## 4. Analysis and Comparison of the strengthened structure

Under dead load and live load, the three structure systems proposed in section 3 were analyzed and compared on horizontal reaction, deflection at mid, stress in CFST arch and the fundamental vibration period. The reaction, deflection and fundamental period was listed in table 1 and the stress was shown in fig 8. To be convenient, the three structures marked as structure A, structure B, and structure C respectively, according to the order of their being advanced.

From table 1, it can be seen that Structure A and B could effectively reduce the thrust by about 7% and 14% respectively under dead load, by 13% and 19% under the combination of dead load and live load compared to the origin structure. They also could decrease the maximum deflection and fundamental period significantly which means improvement of stiffness. Structure C could lessen the horizontal reaction to the greatest extent among the three structures but contribute little to the reduction of deflection and improvement of stiffness due to the arrangement limited to space under the bridge.

Table 1 Comparison of reaction, deflection and period

Structure system	horizontal Reaction(kN)		deflection at mid(mm)		fundamental period(s)
	dead load	combination	dead load	combination	
origin structure	9120	11400	84.6	105.6	1.311
Structure A	8470	9960	55.2	63.6	0.696
Structure B	7870	9240	43.0	49.2	0.71
Structure C	7450	9700	83.5	136	1.314

Fig 8(a) shows the compounding stress consisting of axial and bending stress under the combination of dead and live load, and fig 8 (b), the bending stress only. Structure B and C can both reduce the stress level in the arch member as well as the bending stress, and the later more, which means the performance of truss structure works. However, in reducing of the stress in arch member, the arch-cable structure makes little effect, which is owing to the limited layout of the cable.

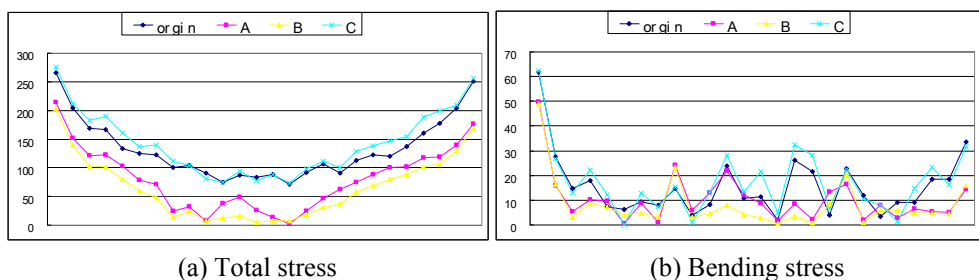


Fig 8 Stress in the CFST arch

As a summary of the above analysis and comparison, the two truss structures can both improve the structure feature, including reducing the arch foot thrust, deflection and stress level and raising the structure stiffness. And the cable-supported structure could contribute to decrease of supporting thrust only. To obtain as better as possible reinforced effect, the advantage of the truss structure and the cable-supported structure were supposed to be used and a cable-supported arch-truss structure was recommended to be adopted.

## 5. Conclusion

Arch structure was favored by architect due to its attractive appearance and could be found in many structures from ancient to modern. In the design of arch structure, two issues are met. One is the big arch foot thrust and the other is the stability. In the present paper, an arch bridge failed to work after its accomplishment was taken as an example to discuss and the following conclusions were obtained.

- (1) Due to small rise-to span ratio, the origin structure produce great thrust to the abutment under the combination of dead and live load. And the big deflection value at mid span exceeds the allowable states. The origin structure has a weak lateral and vertical stiffness.
- (2) The idea of 'hybrid' could be introduced to form hybrid structures to strength the origin structure. The three present structures could benefit the structure to a certain degree.
- (3) The truss structures were efficiently influential in reducing the thrust at arch foot and stress in arch member and improving the stiffness of the strucutre. The cable-supported structure only perform well in decreasing the thrust.
- (4) A hybrid strucutre consisting of cable and arch-truss was supposed to be adotped to reinforcement of the present arch bridge.

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