Temperature Stress Study on the Arch Bridge Strengthening based on Midascivil Solid Element

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Abstract. When using Midas/civil solid element modeling analysis arch bridge strengthening by enlarging section method, found system temperature change stress is too large, serious discrepancies with the actual project. The main reason is that: It is difficult to consider the effect of bonded rebar in the strengthening scheme by simulation analysis; Due to the different linear expansion coefficient, the new and old materials lead to the mutual restraint strain at the contact interface. At present, there is a large temperature stress in the structure of mixed masonry (pouring) of many different materials in the Chinese engineering field when the structure is simulated by the solid element, which need further research and solution in the future.

1. Introduction
In recent years, with the rapid development of China's economy, the number of national cars has increased at high speed, which leads to a rapid increase in traffic volume. Therefore, with the influence of the external environment and the load level increases, the early construction of masonry arch bridge has been unable to meet the current traffic demand, resulting in insufficient bearing capacity[1], damage occurred, pits, spalling and cracking and other adverse conditions in advance, is in urgent need of bridge strengthening.

At present, Midas/civil as the finite element analysis, design and calculation software are commonly used in the strengthening project of arch bridge in China. In the design and calculation of the old arch bridge strengthening with the enlarging section method, the domestic engineering circles often use the beam element to simulate the arch bridge structure[2]. In the study of arch bridge mechanics in the domestic academia, the arch structure is often simplified as a space bar system by beam element[3]. However, the beam element model is based on the assumption of the flat section deformation in the elementary mechanics and is only suitable for the structure with larger slenderness ratio. For the arch structure in three-dimensional pressure state with smaller slenderness ratio, based on the finite element theory, the Midas/civil solid element modeling analysis can reflect the stress characteristics more[3].

However, when the solid element is used to analyze the old arch bridge strengthened by the enlarging section method, an unreasonable situation appears in the analysis result: the temperature stress at the most unfavorable position is too large, which is far beyond the allowable range of engineering experience. At present, the domestic and foreign academic circles have less research on the solid element modeling and analysis of the strengthening of the old arch bridge with the enlarging
section method, and the problem of the higher temperature stress is rarely raised. This paper presents a practical bridge engineering as an example to study the large temperature stress in the analysis of the Midas/civil solid element model[4] and to find the source and elimination method of the stress, and provide reference for other similar engineering structures with large temperature stress in the results of modeling and analysis of solid elements.

2. Project overview
The arch bridge to be reinforced in the example of this paper is called Changwu Bridge, built in 1998. The superstructure of this bridge is solid slab rib stone arch, the infrastructure is solid stone pier, bridge size: length 88.5m, width 5.1m, clear span 3*26m, the main arch vector 1/6, perennial flooding depth of about 1-2 m, concrete bridge deck, steel reinforced concrete column railing, as shown in Figure 1.

Based on the results of engineering test, the main arch ring, the spandrel structure, the abutment and the vertical wall of the arch bridge are all damaged in varying degrees, and the cracks in the serious parts of the bridge exceed the limit value[5], and these structures need to be strengthened.

3. Strengthening design and Midas/civil modeling
3.1. Build the Midas/civil software model of bridge strengthening
Build the Midas/civil solid element software model of bridge strengthening to simulate the shape and size of the bridge completely. The overall bridge model is shown in Figure 2.
3.2. Model calculation results
Analyse the overall bridge solid element software model, get the action effect of various loads on bridge. According to the action effect, General Specifications for Design of Highway Bridges and Culverts[6] and Code for Design of Highway Masonry Bridges and Culverts[7], the stress-strain of the most unfavorable position of the bridge is obtained. The stress-strain represents the ultimate bearing capacity of the bridge and the serviceability limit deformation are shown in Table 1.

| Load combination | Item                             | Pressure stress (mPa) | Shear stress (mPa) | Tensile stress (mPa) | Deformation x (mm) | Deformation y (mm) | Deformation z (mm) |
|------------------|----------------------------------|-----------------------|--------------------|----------------------|---------------------|---------------------|---------------------|
| 1a               | Old bridge structure             | 0.9                   | 0.04               | 0.03                 | 2                   | 1.5                 | -6                  |
|                  | Strengthening structure          | 4.0                   | 0.11               | 0.09                 | 2                   | 1.4                 | -6                  |
| 2b               | Old bridge structure             | 0.75                  | 0.022              | 0.02                 | 1.7                 | 1.1                 | -4.5                |
|                  | Strengthening structure          | 2.9                   | 0.07               | 0.066                | 1.8                 | 0.9                 | -4.5                |

*the most unfavorable combination of the ultimate limit states.
**the most unfavorable combination in the serviceability limit states.

According to the above stress and strain data, the stress of the structure is lower than the strength of the strengthening and old arch ring. The maximum deformation of the structure is lower than allowable value of the serviceability limit. This strengthening plan is feasible.

4. Temperature stress

4.1. Discover problem
Although the results of the Midas model can meet the requirements of the strengthening design, it is found that the structural stress distribution is not reasonable after detailed observation.

Under the ultimate limit states, the stress produced by the dead load accounts for 20% to 25% of the total stress. The stress produced by the moving load accounts for 15% to 20% of the total stress. But the stress produced by the system temperature is up to 55% to 65% of the total stress, this is not in conformity with the actual project, and it indicates that there is a big problem in this calculation model.

4.2. The reason for the higher temperature stress
After repeated modification and debugging of the model, and communicating with other experienced designers and construction engineers, the reason why the temperature stress is too large is basically determined as follows:

4.2.1. The difference of coefficient of linear expansion
The arch bridge is strengthened by enlarging section method, and pour a layer of C30 concrete on the old bridge's main arch ring. The coefficient of linear expansion of the main arch ring material of the old arch bridge is 8×10^-6, and the coefficient of linear expansion of the C30 concrete is 1×10^-5. The two kinds of materials with different coefficients of linear expansion are tightly integrated on the old and new interfaces on the strengthening position. When the structure is heated or cooled, the deformation produced by different materials is different, but they are mutually restricted, it generates the stress mutation caused by inhomogeneous deformation on the strengthening interface. As shown in Figure 3.
4.2.2. The difference of calculation principle
Because the calculation model is difficult to consider the effect of bonded rebars in practical engineering, the temperature strain on the contact interface in the calculation model is entirely supported by the old arch ring and the C30 concrete poured. The calculation theory according to the Midas/civil model as follows:

Set the system temperature variable to be $\Delta C$, the coefficient of linear expansion of the C30 concrete is $\alpha_1$, modulus of elasticity is $E_1$, the coefficient of linear expansion of the old arch ring material is $\alpha_2$, modulus of elasticity is $E_2$, the microelement length of the two materials is $dx$. When the two materials exist alone, their deformation in the same direction like equation (1):

$$\Delta_1 = \Delta_C \cdot \alpha_1 \cdot dx \quad \Delta_2 = \Delta_C \cdot \alpha_2 \cdot dx$$

When the new and old material contact interface of the strengthened bridge, the C30 concrete is closely connected with the old arch ring material. The deformation of the two materials is limited to each other, which causes the same deformation of the two materials. Set the deformation of two materials on the strengthening interface is $\Delta$, and the constraint deformation of the C30 concrete and the old arch ring material is $\Delta_1^\prime = \Delta_1 - \Delta, \Delta_2^\prime = \Delta - \Delta_2$. This constraint deformation is the difference between the original deformation of the new and old arch ring material and the actual deformation caused by the restriction of the strengthening interface. The constraint deformation amount is transformed into the internal stress of the new and old materials on the strengthened interface. The values are equal and the direction is opposite. The formula for converting the constraint deformation into internal stress like equation (2):

$$\frac{\Delta_1^\prime}{dx} E_1 = \frac{\Delta_2^\prime}{dx} E_2$$

By replacing $\Delta_1^\prime = \Delta_1 - \Delta, \Delta_2^\prime = \Delta - \Delta_2$, into equation (2), it can be obtained

$$\Delta = \frac{\Delta_1 E_1 + \Delta_2 E_2}{E_1 + E_2}$$

At this point, the stress caused by the difference of temperature deformation between the new and the old materials on the contact interface like equation (3):
\[
\sigma_c = \frac{(\Delta_1 - \Delta) \cdot E_1}{dx} = \frac{(\Delta - \Delta_2) \cdot E_2}{dx} = \frac{E_1 \cdot E_2 \cdot \Delta \cdot (\alpha_1 - \alpha_2)}{E_1 + E_2}
\]  

(3)

It is known from the equation (3) that the temperature stress is proportional to the difference of the coefficient of linear expansion of the two materials on the contact interface, and is inversely proportional to the sum of the modulus of elasticity of the two materials.

Replace the two material parameters of strengthening interface into equation (3), and assuming that the temperature difference is 10°C, then it can be found that the contact interface stress is about 5.87MPa.

For the Midas model of Changwu bridge, it is a whole model. There may be other way of stress transfer, so the actual temperature stress calculated is not so large. But it still accounts for 55% to 65% of the calculated results, which is consistent with the equations derivation in this section, which indicates that the conventional Midas/civil solid element model does have the problem of large temperature stress.

5. Summary
When considering the effect of temperature change, the Midas/civil solid element finite element model simulating strengthening old arch bridge with different material mixed masonry (pouring) obtain a problem of large temperature stress. The main reason for this problem is that the coefficient of linear expansion of different materials on the contact interface is different, resulting in the inconsistency of temperature and strain, resulting in larger restraint stress on the contact interface. The scope of this problem is very extensive. It exists not only in the Midas/civil solid element simulation analysis enlarging section method to strengthening the old bridge, but also exists in different degrees when using other finite element software to analyze the hybrid material masonry (pouring) structure.

However, a large number of engineering examples show that the influence of temperature change on different materials mixed masonry (pouring) structure is not so large. The existence of this problem makes great errors in theoretical simulation and practical engineering.

At present, most designers use the Midas/civil beam element modeling to carry out the mechanical analysis in the design of the strengthening of the old bridge with the enlarging section method. But according to the finite element theory, the model modeled by the solid element is more suitable for the mass masonry structure than by the beam element. In the future, with the further development of engineering technology and the stricter requirements of the industry, it will become a trend to use solid element modeling to analyze the mass structures of different materials mixed masonry, for example, the arch bridge is strengthened by enlarging section method. Therefore, it will become an unavoidable problem to simulate the large temperature stress of different materials on the contact interface.

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