An updating model for CFST arch ribs based on the improved ant colony algorithm

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Since the concrete filled steel tube (CFST) arch bridges are developing rapidly, it is essential to update the model of CFST arch rib in the condition assessment system of CFST arch bridges as the CFST arch ribs are the main components of these bridges. In order to study the model updating method for CFST arch ribs, the improved ant colony algorithm was introduced which was combined with the finite element method. The finite element model of experimental model of CFST arch rib was updated by the improved ant colony algorithm. The results showed that the updated parameters were calculated accurately and dynamic responses of the updated model were close to the experimental model.

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1. Introduction

Since the 1990s, the CFST (concrete filled steel tube) arch bridges have been developing fast in China. As time goes on, the diseases of ribs appear. The most outstanding disease is the separation between steel tube and concrete. According to the phenomena of separation, there are many test methods for this, such as ultrasonic detection, core drilling and slapping method. In order to make the calculation model of the arch rib close to practice, the method of model updating based on improved ant colony algorithm is studied, in which the disease of separation will be treated in the model with vibration parameters such as frequencies and mode shapes. What’s more, the test of CFST arch rib is carried out in laboratory.

According to the types of information, the model updating method can be classified into the updating method of modal parameters and the updating method of the static-load response; According to the modified object, they can be classified as matrix updating method and design parameter updating method; According to arithmetic, they can be classified as direct updating algorithm and iterative updating algorithm (Y.B. Yang,and Y.J. Chen 2009). S.W. Doebling had modified the model of a pre-stress bridge by the first order optimization algorithm, whose method belongs to local optimization algorithm (S. W. Doebling, F. M. Hemez, L. D. Peterson, and C. Farhat 1997). In 2001, Suykens JAK put forward coupled local minimizer algorithm which is efficient for overall searching (Suykens JAK, Vandewalle J, and De Moor B 2001). In 2008, the coupled local minimizers algorithm was compared with other local optimization algorithms by Pelin Gundes Bakir, the result showed the coupled local minimizers algorithm is comparatively more efficient (Pelin Gundes Bakir, Edwin Reynders, and Guido De Roeck 2008). Yang liu proposed adaptive coupled local minimizers algorithm where the initial population was generated with chaotic search method firstly, and then the gradient of population was calculated with the method of variable step size, so that adaptive coupled local minimizers algorithm had overcome the defects of common local optimization algorithms(Y. Liu, and Z. D. Duan 2008).

In recent years, the evolutionary algorithms have been applied in model updating. XIE K.Z. built a finite element spatial model of a concrete-filled steel tube basket handle anrch bridge and detected its damage by the modal curvature difference method of spatial curve (XIE K. Z. 2009). Qingguo Fei came up with a method for model updating based on the neural network, in which model updating was transformed into forward analysis so that the method was avoided iterative solution and complex nonlinear optimization problem of back analysis(Q. G. Fei; L. M. Zhang 2004). Guirong Yan had presented a model updating method based on improved genetic algorithm(G. R. Yan, Z. D. Duan, J. P 2007). A model updating method combined with genetic algorithm and particle swarm optimization was proposed by Xianren Kong, in which it searched the global by genetic algorithm firstly, and then the locality by particle swarm optimization. This method was more efficient than the method of single algorithm (T. H. Wu 2009). A. H. Wu updated the models of a five-story frame structure and Hu-men bridge by suggesting a new method that combined particle swarm algorithm with artificial immune algorithm. In 2010, Yulin Qin put forward a search algorithm combined chaos particle algorithm with quantum particle algorithm, which prompted the standard of searching quality (Y. Q. WANG, N. Yao, T. S. Zhang, and Y. J. Shi 2010). Yuanqing Wang brought forth a multi-stage updating model method based on traditional optimization theory, in which parameters were classified by sensitivity with three-step parametric technology. So the method was more efficient and precise than the one-step updating method (Beck, J .L.,Katafygiotis, L. S 1998). Inspired by the previous research, the model updating for arch ribs of CFST arch bridges is proposed in this paper based on improved ant colony algorithm.

2. Improved ant colony algorithm

The Ant Colony Algorithm, a method for optimization, is developed from the research of the ant colony behavior of looking for food and relied on the probability of searching algorithm. It is a new method that can effectively solves the most majority of global optimization problems. It is a new method that can effectively solves the most majority of global optimization problems.

2.1 Model of multi-parameter ant colony algorithm

For the multi-parameter ant colony algorithm, there are n parameters, where searching range of the ith parameter is (ximin, ximax), so the searching range is divided into N equal areas. Then, optimization problem of n parameters is regarded as the problem of n×N searching path points, as shown in Fig. 1. The searching matrix is a pheromone matrix of n×N, in which each path point has its pheromone.

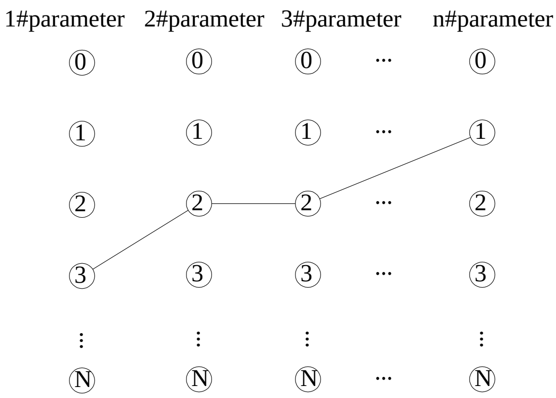


Fig. 1. Description of Ant Colony Algorithm.

2.2 Steps of ant colony algorithm

τ_{ij} is attracting strength in the *i*th step and *j*th node, P_{ij} is selection probability in the *i*th step and the *j*th node and f is objective function. The specific steps of ant colony algorithm are as follows:

Step 1: There are m ants and n updating parameters $(X_1, X_2, X_3, \cdots, X_n)$;

Step 2: The value range of *n* updating parameters is determined by the problem, the range is $(x_{i\min}, x_{i\max})$;

Step 3: Each updating parameter is divided into *N* equal areas in range, so each division is $h_i = (x_{i\max} - x_{i\min}) / N$;

Step 4: Based on initial date, $\tau_{ij} = c_{ij}$, which forms initial pheromone matrix;

Step 5: The selection probability P_{ij} of each path point of the *ith* parameter is calculated.

$$P_{ij} = \tau_{ij} / \sum_{j=1}^{N} \tau_{ij} \tag{1}$$

Step 6: The selected path point of the *k*th ant on the *i*th parameter is determined by turnplate selection method.

On the basis of probability calculation in step 5, the cumulative probability from the first path point to the *j*th path point is calculated.

$$F_{ij} = p_{i1} + p_{i2} + p_{i3} + \cdots + p_{ij} \ (j = 1, 2, 3, \cdots N) \tag{2}$$

If $F_{i(j-1)} < r \le F_{ij}$, where $r \in [0,1]$, the *j*th path point will be selected.

Turnplate selection method is a common method that allows each node to have the opportunity to be selected according to the size of the pheromone.

Step 7: The turnplate selection from the first parameter to the *n*th parameter is selected successively by the *k*th ant and the path point passed by ants in each parameter. Finally, the total path of the *k*th ant is determined, that is a set of updated parameter values $(x_1, x_2, x_3, \cdots, x_n)$;

Step 8: The corresponding objective function value (f_k) is calculated based on updated parameter values $(x_1, x_2, x_3, \cdots, x_n)$ of the *k*th ant.

Step 9: According to update pheromone of f_k in path passed by the *k*th ant, a new pheromone matrix is formed and the updating equation is as follows:

$$\tau_{ij}^{new} = \rho \tau_{ij}^{old} + Q / f_k \tag{3}$$

where Q is a positive constant, and $\rho \in [0, 1]$ is an evaporation coefficient of pheromone from 0.5 to 1.0. τ_{ij}^{old} is the old pheromone, τ_{ij}^{new} is the new pheromone;

Step 10: Repeat the step 5～9, until all m ants pass the searching;

Step 11: The biggest path point (x_i') of pheromone τ_{ij} in each parameter is found, and the most optimal values $(x_1', x_2', x_3', \cdots, x_n')$ of major cycle is solution;

Step 12: Reduce the value of positive parameter

$$x_{i\max} = x_i' + ah_i \quad x_{i\min} = x_i' - ah_i \tag{4}$$

Where a is a positive integer;

Step 13: Go back to step 3, if $\max(h_1, h_2, h_3, \cdots, h_n) < \varepsilon$, where ε is an arbitrary small real number, then calculation is over, otherwise follow step 5～13 again.

2.3 Update algorithm

2.3.1 Mutation operation

The individual parameter of the updating parameters is selected according to the random probability and its value is multiplied by a mutation operator P_i. Then the objective function value of mutation operation is calculated, if the value of objective function is less than the value of no mutation, the pheromone of mutation operation will be distributed again. The concrete steps are as follows:

(1) Solutions without mutation are $(x_1, x_2, x_3, \cdots, x_i, \cdots, x_j, \quad \cdots, x_n)$, two parameters x_i and x_j are selected according to random probability.

(2) The mutation operators P_i and P_j are produced randomly, then:

$$x_i' = x_i \times P_i \quad x_j' = x_j \times P_j \tag{5}$$

(3) The new solutions

$$(x_1, x_2, x_3, \cdots, x_i', \cdots, x_j', \cdots, x_n) \tag{6}$$

2.3.2 Crossover operation

Some parameters' values are exchanged between two groups of solutions, which are selected randomly, and then the values of objective function are calculated after crossover. If the crossed objective function value is less than before, the crossed solution will be kept and pheromone will be distributed again. The steps are as follows:

(1) Two positions i and j are selected of un-crossed solutions according to random probability.

$$X_1 = (x_{11}, x_{12}, \cdots, x_{1i}, \cdots, x_{1j}, \cdots, x_{1n})$$
$$X_2 = (x_{21}, x_{22}, \cdots, x_{2i}, \cdots, x_{2j}, \cdots, x_{2n}) \tag{7}$$

(2) The values of position i and j are exchanged in two groups of solution: $x_{1i} \leftrightarrow x_{2j}$, $x_{1j} \leftrightarrow x_{2i}$;

(3) The new solutions:

$$X_1' = (x_{11}, x_{12}, \cdots, x_{2j}, \cdots, x_{2i}, \cdots, x_{1n})$$
$$X_2' = (x_{21}, x_{22}, \cdots, x_{1j}, \cdots, x_{1i}, \cdots, x_{2n}) \tag{8}$$

3. Model updating for arch rib of CFST

3.1 Objective function

The objective function is constructed with the first two order natural frequencies and the first curvature mode shape difference, as follows:

$$f(x) = \sum_{i=1}^{8} index_{i,j} + \sum_{j=1}^{2} \left| f_{aj} - f_{uj} \right| \tag{9}$$

$$index_{i,j} = \left| K_{i,j}^{a} - K_{i,j}^{u} \right| \tag{10}$$

Where f_{aj} is calculated value of natural frequency and f_{uj} is measured value of natural frequency, $K_{i,j}{}^{a}$ is calculated value of curvature mode and $K_{i,j}{}^{u}$ is measured value curvature mode, j is the order.

Curvature equation is as follows:

$$K_{ij} = \left| w'' \right| / (1 + w'^2)^{3/2} \tag{11}$$

where the derivation of curve equation is solved by the central difference method.

$$w' = (\phi_{i,j} - \phi_{i-1,j}) / 2l_i \tag{12}$$

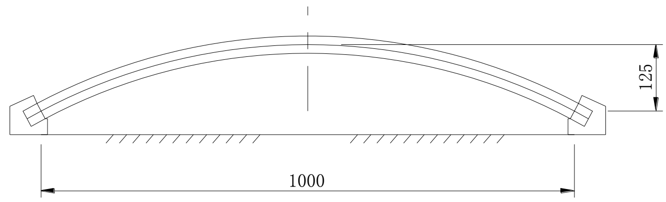
$$w'' = (\phi_{i-1,j} + \phi_{i+1,j} - 2\phi_{i,j}) / (l_{i-1} l_i) \tag{13}$$

where $\varphi_{i,j}$ is the vibration quantity of the ith node in the jth order, l_i is the length.

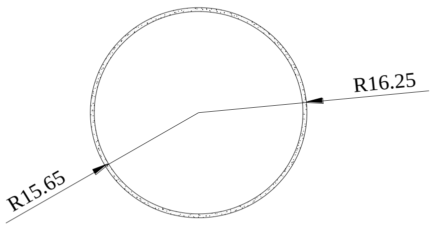
4. Example

4.1 General situation

Arch rib's section in the model is a single circle tube, the section's outer diameter is 325 mm, inner diameter is 313 mm , the thickness of the steel tube is 6 mm, Designed span length of the arch rib is 10m with a rise of 1.25 m, the ratio of the rise to the span length is 1/8. The test model is shown in Fig. 4.1, The steel is Q235C, Elastic modulus is $2.06 \times 10^5 MPa$. Tube concrete is C50, the strength of concrete after 28 days is 56.3*MPa*, and the elastic modulus of the concrete which is filled in the steel tube after 28 days is $3.90 \times 10^4 MPa$.



(a) Elevation(cm)



(b) Section(cm)

Fig. 4.1. The experimental model of arch rib.

4.2 Dynamic characteristic test

4.2.1 Test section

The arch rib model is divided into 8 regions, as shown in Fig. 4.2. The sections of arch rib 1/8, 1/4, 3/8, 5/8, 3/4, 1/2, and 7/8 are selected as test sections.

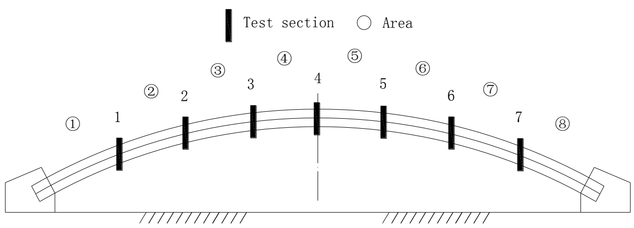


Fig. 4.2. Test sections arrangement of the arch rib.

4.2.2 Measuring-point arrangement

A vertical acceleration sensor and a lateral acceleration sensor in each test section are fixed, as shown in Fig. 4.3.

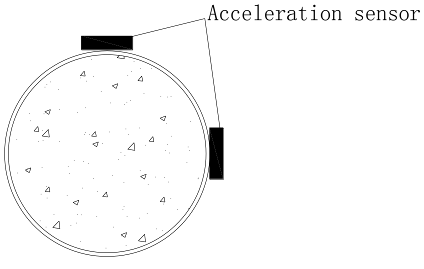


Fig. 4.3. Measuring-point arrangement.

4.2.3 Test results

Natural frequencies of the test are shown in Table 4.1.

Table 4.1. Measured natural frequencies /Hz.

Order	1	2	3	4	5
frequency	11.24	31.29	31.78	44.00	61.11
Order	6	7	8	9	10
frequency	69.91	107.56	109.51	132.00	158.40

4.3 Test for local Cavity of CFST Arch Rib

As the test model is not large, the cavity situation of the concrete in the steel tube can be defined roughly with the percussion method. The arch rib was divided into 8 regions, the cavity situations are measured from four positions in each area, and then the cavity heights are calculated and the Average figure is taken, the results are demonstrated in Table 4.2.

4.4 Model modification

The finite element calculation model was constructed by ANSYS, as shown in Fig. 4.4. Both the steel tube and the concrete which were filled in steel tube use beam188 element. The whole arch rib model was divided into 8 regions, and the concrete cavity heights in each area were taken as updating parameters. The finite element model of arch rib had 32 elements. The physical parameters of steel tube: $E_s = 2.06\times10^{11} Pa$, $\rho = 7850 kg/m^3$, $\gamma = 0.3$; the physical parameters of concrete : $E_c = 3.45\times10^{10} Pa$, $\rho = 2550 kg/m^3$, $\gamma = 0.2$.

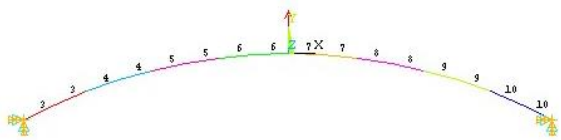


Fig. 4.4. The finite element model of arch rib.

4.5 Model updating

(1) Initial values of updating parameters

The concrete cavity heights in each area were taken as updated parameters, so the initial condition was that there is no concrete cavity in the model.

$$h^{(0)} = (0,0,0,0,0,0,0,0) \tag{14}$$

(2) Objective function

The objective function was constructed by natural frequencies of the first two orders and the first-order curvature mode, it had 8 areas, so there were 8 points' curvature mode values.

(3) Optimization algorithm

According to the objective function values and the initial values of updated parameters, the program based on improved ant colony algorithm was represented by APDL of ANSYS. The allowing error is: $\tau = 1\times10^{-8}$. When $\left|f(X^{(k+1)}) - f(X^{(k)})\right| \le \tau$, the computation was convergence. At this time, the values of parameters were most close to the measured values, and values of the updated parameters were the optimal solution.

After updating the finite element model based on improved ant colony algorithm, updated values of 8 parameters were shown in Table 4.2.

Table 4.2. Separation height values /mm.

Area	1	2	3	4	5	6	7	8
Updated	1	52	49	38	38	49	52	1
Test	0	43	46	51	50	44	43	0
Absolute error	1	9	3	13	12	5	9	1

Among the updated parameters of each area, the updated absolute errors of vault exceed 1cm, while the errors were less than 1cm in the other areas, so the separation heights of arch rib were reflected.

After updating the finite element model, the natural frequencies of calculation were shown in Table 4.3

Table 4.3. Natural frequencies of the updated model /Hz.

Order	1	2	3	4	5
Calculated value	11.24	31.29	31.76	45.26	62.54
Test value	11.24	31.29	31.78	44.00	61.11
Error（%）	0	0	0.06	2.86	2.34
Order	6	7	8	9	10
Calculated value	71.64	105.89	109.28	132.84	163.07
Test value	69.91	107.56	109.51	132.00	158.40
Error（%）	2.47	1.55	0.21	0.64	2.95

After updating the finite element model, errors of the top 10 natural frequencies were less than 5% between the calculated values and the measured values, and the result could meet the requirements of the test.

5. Conclusions

Through studying the model updating method of CSFT (concrete-filled steel tube) arch rib based on improved ant colony algorithm, some conclusions has been drawn.

1. Improved ant colony algorithm could accurately identify the separation heights between steel tube and core concrete, and the model can be updated.

2. The updated separation heights of each area were less than 1cm except for the vault area, so it could reflect the separation situation of arch rib.

3. The updated finite element model can accurately reflect the dynamic response of the structure. The errors relating to natural frequency of the updated model were less than 5%,and the result that ant colony algorithm combined with the finite element method brings meet the requirements of the test.

4. The updated model reflects the practical condition, therefore it can be applied in the health monitoring systems of CSFT arch bridges.

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