Reliability analysis of round-ended concrete-filled steel tube tower

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Abstract. Based on reliability theory and reliability analysis module of ANSYS, round-ended CFST tower reliability of Houhu Bridge is systematically studied by Monte Carlo method and response surface method. Research shows the integration of finite element theory and reliability theory can be applied to complex structural reliability analysis.

1. Introduction
Round-ended cross section is a special section with two arcs at both ends and a rectangle in the middle. Wuhan Houhu bridge is the first cable-stayed bridge with circular end CFST structure. We have studied the mechanical performance of round-ended double-legged towers by numerical simulation and on-site monitoring technology[1-4]. Relying on engineering application of Wuhan Houhu Bridge, the paper analyzes the reliability of the structure by ANSYS. The Monte Carlo method and response surface method are used to analyze the reliability of the round-ended CFST tower of Wuhan Houhu Bridge. The section of CFST tower is shown in Figure 1.

2. Implementation of reliability analysis in ANSYS
ANSYS has a probabilistic design system (PDS) solver for probabilistic analysis. PDS provides two reliability calculation methods, Monte Carlo method and response surface method. PDS can work out the acceptable failure probability of structure according to acceptable maximum deformation and maximum stress, identify the parameter that has the greatest influence on the failure probability, and calculate the sensitivity of output results to input parameters.
3. Reliability analysis of round-ended CFST tower

3.1. Modeling

3.1.1. Material parameters
CFST tower is subjected to eccentric compression load, the values of the following parameters are set according to the actual size effect and dispersion, namely test value 60MPa, comprehensive strength fck 38.5MPa, tensile strength ft 2.64MPa. Steel is considered to be an ideal isotropic elastoplastic material with yield strength 235MPa.

3.1.2. Calculation Model
The concrete is simulated with Solid 65. The steel tube is simulated with Shell181, and the thickness of the shell element is 0.02 m. It is assumed that the concrete and steel are well bonded with a reinforcement ratio of 0.02. The geometric dimensions of the model are the same as engineering structure. The bottom of the round-end CFST tower is considered to be the consolidation while the top of the main tower to be the free end. With no account of the slippage between steel tubes and the concrete, so as to build a finite element model in a co-node connecting method.

3.2. Model verification
During the construction monitoring, 26 embedded vibrating wire strain gauges are distributed inside the concrete in the middle of the tower at elevation of +34.905 and 6 embedded vibrating wire strain gauges on the outer surface of the steel tubes. In order to verify the accuracy of the model, analysis was made between the finite element simulation results and the measurements from strain gauges embedded in the structure. The specific positions of the strain gauges are shown in Figure 2.

![Figure 2. The specific positions of the strain gauge (H=+34.905m)](image)

- Vertical strain gauges
- Longitudinal strain gauges
- Transverse strain gauges

According to the numerical simulation results, the stress changes of the core concrete under 14 working condition of calculation are shown in Figure 3. The selection of each node’s in the figure corresponds to the measurement point position in the stress monitoring test.

The comparison show stress curves, under axial compression and eccentric compression conditions, the measured stress data has a change trend well aligned with the calculated data. Hence, it is verified that the built model can be used to reliability analysis of CFST tower.
3.3. Statistical parameters
In the reliability analysis, the following factors need to be considered, namely material properties, geometric parameters, uncertainty in the calculation model, and load variability.

3.3.1. Material property parameters
Table 1. The statistical parameters of material properties [5]

| Random parameters | Distribution patterns     | Average Value coefficient | Variation coefficient | SI  |
|-------------------|---------------------------|---------------------------|-----------------------|-----|
| $f_y$             | Normal distribution       | 1.080                     | 0.080                 | MPa |
| $f_{ck}$          | Normal distribution       | 1.35                      | 0.135                 | MPa |
| $E_c$             | Log-normal distribution   | 1.32                      | 0.135                 | MPa |

3.3.2. Geometric parameters
The geometric parameters of structure refer to the test data can be determined by parameter estimation and hypothesis testing. The statistical parameters of concrete-filled steel tubes are shown in Table 2.

Table 2. The statistical parameters of dimension [6]

| Random parameters | Distribution patterns     | Average Value coefficient | Variation coefficient | SI  |
|-------------------|---------------------------|---------------------------|-----------------------|-----|
| Steel dimension   | Normal distribution       | 1.00                      | 0.05                  | mm  |

3.3.3. Load parameters
Shi Xianzhen [7] made use of the measured cable force samples of Monte Carlo method, inferred the distribution type of the measured cable force of a long-span concrete cable-stayed bridge. The regular measurements of the bridge cable force during the operation period showed that the cable force caused
by live load from vehicles holds a very small proportion. A load is applied in this research that is determined according to the cable force value designed in [4]. The load parameter indexes are set, as shown in Table 3.

Table 3. The statistical Load parameters[8]

| Random parameters                                      | Distribution patterns | Average Value coefficient | Variation coefficient | SI   |
|--------------------------------------------------------|-----------------------|---------------------------|-----------------------|------|
| cable force caused by dead load                        | Normal distribution   | 1.06                      | 0.07                  | KN   |
| cable force caused by live load                        | Wei bull's distribution|                          |                       |      |

3.4. Implementation of Monte Carlo method in ANSYS

The static analysis shows concrete fails prior to steel tubes. Tests indicate that the improvement of the bearing capacity of round-ended concrete is limited. Therefore, the strength control conditions of concrete-filled towers are adopted to make the tensile and compressive stresses of the concrete section lower than the design strength.

The first principal stress of each node, after extraction as the tensile stress, the maximum value is assigned to the variable max1. Then, the third principal stress of each node, the minimum value is assigned to the variable min3. The definition of the distribution parameters of each random variable is shown in Table 4. The output variables are defined as dets1=ftk-max1 and dets3=ack-ack(-min3)=fck+min3. The graphs of the probability density function and distribution function of each random input parameter are drawn, as shown in Figure 4–Figure 7.

Table 4. The definition of the distribution parameters of random variable

| Random variables/MPa | Reference values | Distribution patterns | Variation coefficient | Average Value | standard deviations |
|----------------------|------------------|-----------------------|-----------------------|---------------|---------------------|
| Compressive Strength (Fck) | 32.4          | Normal                | 0.135                 | 32.4          | 4.374               |
| Tensile strength(Ft)  | 2.64             | Normal                | 0.135                 | 2.64          | 0.3564              |
| Elastic modulus(Ex1)  | 38000           | Log-normal            | 0.135                 | 38000         | 5130                |
| Thickness of steel tube/mm | 20             | Normal                | 0.05                  | 20            | 0.4                 |

Figure 4. Distribution function graph of Fck

Figure 5. Distribution function graph of Ft
200 times of Monte Carlo calculations are made for the random variables with Latin hypercube sampling. The change curves of the variables sample averages during the 200 times of sampling are drawn, as shown in Figure 8–Figure 11. The sample average of each random variable gradually approaches horizontal, manifested as average convergence. Therefore, it is believed that 200 times of sampling has basically satisfied the needs of Monte Carlo calculation.

The histograms of the random variables values randomly taken during the 200 times of sampling are drawn, as shown in Figure 12–Figure 15. The histograms of the random input and output variables are fairly closer to their probability function curves, characterized by satisfactory smoothness and no large gaps.
Through the 200 times of Monte Carlo calculations of this model, the obtained structural reliability that satisfies the requirement for tensile strength (dets1 > 0) is 98.69% and the confidence interval of reliability is [96.47%, 99.70%] on the condition of a 95% confidence level; the structural reliability that satisfies the requirement for compressive strength (dets3 > 0) is 98.89%, and the confidence interval of reliability is [97.53%, 99.64%] on the condition of a 95% confidence level.

3.5. Implementation of response surface method in ANSYS
The Bespoken matrix method is used to determine the response surface sample size. The response surface is fitted according to the sampling calculation results. The quadratic approximation with cross terms is used to fit the regression model. In addition, the isolated or uncorrelated terms are automatically filtered out using the forward stepwise regression method. When the fitting accuracy is 95%, the fitting surfaces of the output variables dets1 and dets3 with ft and fck as the input variables are obtained, as shown in Figure 16.
Figure 16. The fitting surface

(a) dest1  (b) dest3

Figure 17. Random sample values of output variables

(a) dest1  (b) dest3

Figure 18. The histogram of the output variables

(a) dest1  (b) dest3
In order to further improve the calculation accuracy, the number of simulations is set to be 10,000 times. The random sample values of the output variables dets1 and dets3 are shown in Figure 17, and Figure 18 is their histogram. The sampling results are very convergent, and both dets1 and dets3 basically obey normal distribution.

4. Conclusion
This paper conducted the nonlinear finite element analysis of CFST towers and explored the reliability of round-ended CFST towers using the finite element reliability analysis module.

(1) The Monte Carlo method is adopted to calculate reliability. With stress as the output control index, it is calculated that the structural reliability satisfies the requirement of tensile strength and compressive strength.

(2) The response surface method is adopted, and it is calculated that dets1>0, that is, the structural reliability satisfies the requirement of tensile strength and compressive strength.

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