Time-dependent reliability analysis for out-plane stability of CFST arches

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Abstract. Concrete filled steel tubular (CFST) arches have been widely used in bridge structures for the advantages of material properties and construction technologies. However, studies for out-plane stability with the consideration of uncertainties due to the concrete creep have been limited. In this paper, the limit state function (LSF) for out-plane creep stability of CFST arches is established. The statistical information of creep coefficient of concrete is obtained based on the Monte Carlo Simulation (MCS) method. Based on the models of out-plane creep stability, the time-dependent reliability method and the finite element reliability method (FERM) are combined to investigate the reliability deterioration for the out-plane stability of CFST arch ribs. The results show that the reliability indices for out-plane creep stability decreases sharply with time; the deterioration of time-dependent reliability is significant in the first 200 days; the effects of steel ratios on the time-dependent reliability index is remarkable.

1. Introduction
Incomplete statistics show that more than 400 CFST arch bridges have been constructed in the world. Although the first CFST arch bridge was built in 1990 in China, it developed very fast in the past two decades [1]. Therefore, investigations on theory and experiment for this type of bridge have attracted some attentions from researchers.

For the characteristics of high strength and large span, the main arch ribs are commonly quite slender, the instability becomes the key problem. Although considerable contributions on time-independent stability of CFST arches have been devoted, studies of time-dependent stability with and without considering uncertainties due to the concrete creep have been limited.

Madsen and Bazant presented a simple probabilistic model. The model allows calculation of simple statistics for shrinkage and creep effects for structural elements. The analysis is performed by a matrix method which gives essentially exact results if the time discretization is close enough [2]. Bazant and Liu investigated the uncertainty in the prediction of the effects of creep and shrinkage in structures. A method of taking into account the uncertainty due to the error of the principle of superposition is also presented. It is concluded that the distribution of creep effects is approximately normal if the creep parameters are normally distributed [3]. Li and Melchers performed the analysis of uncertain creep and shrinkage effects. There kinds of load, a sustained load of uncertain magnitude, a stationary Gaussian loading process, and a Poisson loading process are involved in the study. Numerical example shows that the method is of good accuracy and efficiency [4].
Although the influences of uncertainties on stability of CFST arches have been performed by Jiang et al., researches on the time-dependent reliability for stability of CFST arches are limited, especially for the out-plane stability [5]. In view of the above questions, the reliability deterioration for the out-plane creep stability of CFST arches are investigated. Based on the combination of general FE softwares and reliability toolbox, reliability indices for different time intervals can be obtained.

2. LSF for out-plane creep stability
A limit state of a structure is a condition or design performance requirement, which the structure must satisfy to fulfil its structural function. The boundary between desired and undesired performance of a structure is generally defined as

\[ Z = R - S \]  

where \( Z \) is the limit state function; \( R \) is the structural resistance and \( S \) is the load effects.

If the time-dependent effects are considered, the resistance model can be described as \( R(t) \). Then equation (1) can be rewritten as

\[ Z(t) = R(t) - S \]  

where \( R(t) \) is the deteriorated resistance function related to time \( t \).

3. Deteriorated model for out-stability
For different constraints of circle arches, the elastic in-plane creep bearing capacity can be approximately obtained by the analytical method. While for parabolic arches, the out-plane creep bearing capacity can only be obtained by mathematical methods.

A parabolic arch subjected to both vertical and lateral loads may have lateral deformations, as shown in Fig.1. If the concrete creep is considered, the total lateral deformation can be expressed as:

\[ z = z_0 + z_c \]  

where \( z \) is the total deformation; \( z_0 \) is the time-independent deformation; \( z_c \) is the lateral creep deformation.

![Figure 1. Lateral deformation of parabolic arches](image)

To obtain the deteriorated model for out-plane creep stability of CFST arches, the time-dependent deformation is recognized as an initial geometric imperfection. By introducing the imperfection in the finite element (FE) model, the out-plane creep strength could be obtained. In the FE analysis, the ideal elastic-plastic constitutive relationship is used for steel, and an improved equivalent stress-stain law of Han’s (Han, 2004), presented by Liu (Liu, 2005) is used for concrete [6, 7]. Both material nonlinearity and geometric nonlinearity are considered in the analysis. The creep-induced deformation is calculated by the age-adjusted effective modulus method (AEMM).

4. Probability modelling

4.1. Creep coefficient
The statistical information of basic random variables for creep coefficient is shown in Table 1.
Table 1. Statistics of basic random variables for creep coefficient [2]

| Random variable | Distribution type | Coefficient of variation |
|-----------------|-------------------|--------------------------|
| c               | Normal            | 0.10                     |
| w/c             | Normal            | 0.10                     |
| a/c             | Normal            | 0.10                     |
| Calculation mode | Normal            | 0.23                     |

Notes: c is cement content, w/c is the water-cement ratio, a/c is the aggregate-cement ratio.

The statistical information of creep coefficient for different models can be obtained using the MCS method. The results are shown in Table 2.

Table 2. Statistical information of creep coefficient for different models

| Statistical parameter | CEB-FIP model | Eurocode model | B3 model |
|-----------------------|---------------|----------------|----------|
| Mean value            | 0.823         | 0.824          | 0.819    |
| Standard deviation    | 0.194         | 0.195          | 0.199    |
| Coefficient of variation (COV) | 0.236       | 0.237          | 0.242    |

Let the B3 model for example, the COV curve with time t is shown in Fig.2.

Figure 2. COV of creep coefficient for different time intervals

The results show that: the COV of creep coefficient varies sharply in the first 100 days. 200 days later the COV keeps constant approximately.

The distribution type of creep coefficient is confirmed by the K-S test method. The results are shown in Table 3.

Table 3. Results of K-S tests

| Distribution type | Normal | Lognormal | Exponential | Gamma | Poisson | Rayleigh |
|-------------------|--------|-----------|-------------|-------|---------|----------|
| H                 | 0      | 1         | 1           | 1     | 1       | 1        |

Notes: H is the test result, H=1 means reject the original hypothesis and H=0 means accept the original hypothesis.
The K-S test shows that the creep coefficient merely obeys the normal distribution hypothesis which agrees well with the CEB-FIP mode.

4.2. Statistical parameters

The statistics of the basic random variables (RVs) are listed in Table 4.

Table 4. Statistics of basic RVs

| RV       | Distribution type | Coefficient of variation |
|----------|-------------------|--------------------------|
| $f_{cu}$/MPa | Lognormal         | 0.13                     |
| $f_y$/MPa  | Lognormal         | 0.083                    |
| $E_c$/MPa  | Lognormal         | 0.10                     |
| $E_s$/MPa  | Lognormal         | 0.06                     |
| $D$/mm     | Normal            | 0.0135                   |
| $t_s$/mm   | Normal            | 0.035                    |
| $\phi$     | Normal            | 0.24                     |

Notes: $f_{cu}$ is the concrete compressive cube strength, $f_y$ is the yield strength of the steel tube, $E_c$ is the elastic modulus of concrete, $E_s$ is the elastic modulus of steel, $D$ is the outer diameter of the steel tube, $t_s$ is the wall thickness of the steel tube and $\phi$ is the creep coefficient [8, 9].

5. Procedure of time-dependent FERM

The procedure of FERM based on ABAQUS, ANSYS and MATLAB is illustrated in Fig.3.
6. Case study

6.1. Model parameters
A CFST model arch shown in Fig.4 is selected as an illustrative example. The span of the arch is 7.5m, and the rise-to-span ratio is 1/5. The outer diameter of the cross-section is 121mm and the wall-thickness is 4.5mm. The elastic modulus of concrete is 206GPa, and the elastic modulus of steel is 37.84GPa. The concrete loading age is assumed to be 28d. The creep coefficient is calculated according to the CEB-FIP model.

![Figure 4. A CFST arch subjected to uniformly distributed vertical load and single lateral load](image)

6.2. Results of reliability analysis
Let the concrete loading age to be 28 days. The deterioration of reliability index with time \( t \) is shown in Fig.5.

![Figure 5. Deterioration of reliability index with time](image)

The results show that the reliability index decreases sharply with time \( t \). The value varies from 7.5 to 7.1 in 1000 days.

Let time \( t \) to be 1000 days, the effects of steel ratios on the reliability index are shown in Fig.6.
The results show that the effects of steel ratios on the reliability index are significant and the values ranges from 5.2 to 7.5.

7. Conclusions
The LSF for out-plane creep stability of CFST arches is established in this study. The stastical information of creep coefficient of concrete is obtained based on the MCS method. Based on the models of out-plane creep stability, the time-dependent reliability method and the FERM are combined to investigate the reliability deteriotion for the out-plane stability of CFST arch ribs.

The results show that: reliability indices for out-plane creep stability decreases sharply with time; the deteriotion of time-dependent reliability is significant from \( t=0 \) to \( t=200 \) days; the effects of steel ratios on the time-dependent reliability index is remarkable.

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