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Out-of-plane creep buckling analysis on slender concrete-filled steel tubular arches

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ABSTRACT

Concrete-filled steel tubes (CFST) are becoming a popular structural solution for arch bridges because of their high compressive strength and efficiency in construction. For long span CFST arch bridges, the time-dependent behaviour of the core concrete may affect the stability of CFST arches. Despite this, only limited research has been carried out to date on their creep buckling behaviour. In this context, this study aims to investigate the influence of the prebuckling deformation induced by time effects on the out-of-plane stability of single parabolic CFST arches with fixed ends and subjected to uniformly distributed loads applied along the span by means of the finite element method using ABAQUS. The time-dependent behaviour of the concrete has been described using the Eurocode 2 model and implemented in the analysis using the integral type creep law. The nonlinear material property and the confinement effects under ultimate condition have also been taken into account and implemented in ABAQUS with UMAT subroutines. The accuracy of the proposed analysis method has been validated against the experimental results of an out-of-plane buckling test of a 1:10 scaled CFST arch reported in the literature. An extensive parametric study has been then carried out and it has been found that the ultimate capacity of the arches can be decreased by up to 18% due to the prebuckling deformation induced by time effects. Finally, designing equations are proposed based on the finite element analysis results to predict the ultimate loads of CFST arches accounting for time effects.

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1. Introduction

The use of concrete-filled steel tubular (CFST) arches is gaining popularity for bridge applications because of the enhanced load carrying capacity and ease of construction provided by the composite solution. Current trend is to increase the span length of the arches and to remove the wind braces between adjacent arches for architectural purposes (Fig. 1). This is highlighted by the fact that, at present, among the 300 CFST arch bridges, 86 bridges have spans over 150 m and 26 bridges are supported by arches without wind braces [1]. For the majority of CFST arches that do not possess wind braces, the ratio between their arch length (S) and their radius of gyration about the vertical axis (k_y) ranges between 150 and 300. The possible implications associated with this high out-of-plane slenderness need to be accurately evaluated from a structural viewpoint.

Extensive work has been performed to date in investigating the static behaviour of CFST arches, e.g. [2–5], their seismic response, e.g. [6–8], their dynamic performance, e.g. [9,10] and their long-term service deformations, e.g. [11–14]. For long span CFST arches, the creep and shrinkage of the core concrete can increase the instantaneous arch deflections by about 20%–30% and produce increases in instantaneous steel tube stresses in the range of 30%–50% [11–14]. These increased variations may trigger possible instability problems in slender CFST arches if not accurately accounted for. Ma et al. highlighted that creep effects might also considerably influence the dynamic behaviour of CFST arch bridges [15–18].

Creep buckling problems associated with CFST members can be conveniently grouped into two main categories [19]. In the first group, the instability is induced by the increased deformations exhibited by the composite member under high sustained loads, typical of the situations with large dead-to-live load ratios, and, in these cases, the occurrence of the instability is usually expressed in terms of the critical time before buckling takes place. For this kind of problem, the material of the member may undergo nonlinear creep due to the high levels of sustained loading. The second creep buckling category is related to situations with small dead-to-live load ratios and the failure of the member occurs due to the application of an instantaneous overload, for example induced by a large live load. In this context, the creep law of the concrete is taken as linear, and creep and shrinkage tend to increase the displaced

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Fig. 1. Example of CFST arch bridges without wind braces.

shape of the member as well as the stress level in steel tube prior to the application of the live load.

A number of researchers have numerically investigated the first kind of creep buckling problem and developed suitable theoretical models considering CFST circular arches with pinned and fixed ends to investigate their in-plane creep buckling due to sustained loading (e.g. [20–24]). No research has been published to date (to the knowledge of the authors) on CFST arch bridges to investigate how the possible increase in the time-dependent deformations influences the stability of CFST arches subjected to instantaneous overload. This situation is particularly critical for long-span CFST arch bridges for which the dominant load case consists of the out-of-plane instability under earthquake load combinations because of their low width to span ratio [25,26].

In this context, the purpose of this paper is to numerically investigate how prebuckling deformations produced by creep and shrinkage influence the out-of-plane buckling of single parabolic CFST arches (Fig. 2). As the start of a serial investigation, circular cross-section is adopted in this investigation because this is the simplest cross-sectional shape and is the foundation to develop the whole designing theory for the out-of-plane stability of CFST arches with different cross-sectional shapes, e.g. rectangular shaped, dumbbell shaped, and lattice cross-sections. In this work, the arch ends are assumed to be fixed, which is representative of typical support arrangements of real CFST arch bridges. The loads applied to these arches are uniformly distributed along their span because this is one of the representative loading cases for arches and all the other kind of loads (e.g. the single concentrated force representing a heavy vehicle) are applied on the arches combining with the uniformly distributed loading in the real application. The sustained loading is applied with the value corresponding to the quasi-permanent loading combination (including the dead load and the quasi-permanent values of live loads, e.g. the lane traffic loads) in accordance with the Chinese code JTG D62-2004 [27]. In the following, the profile of the arch is expressed by the following parabolic equation:

$$y = h \cdot \left[1 - 4 \cdot \left(\frac{x}{l}\right)^2\right] \tag{1}$$

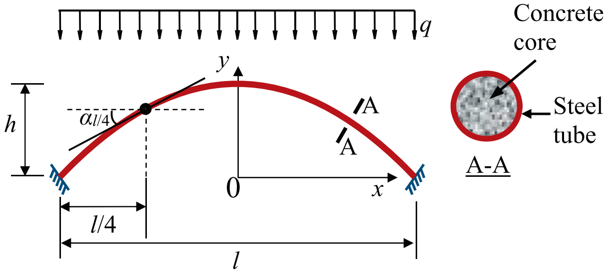


Fig. 2. Parabolic arch used in this analysis.

where *l* denotes the span length of the arch (m), *h* represents the rise of the arch, *x* and *y* depict the coordinates of the nodes defined with the Cartesian coordinates shown in Fig. 2.

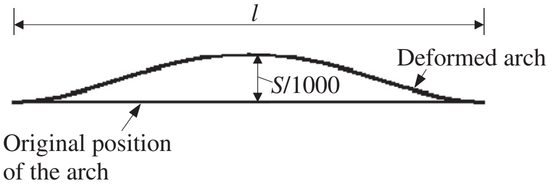
The numerical model is developed using ABAQUS [28] based on which a parametric study is performed to investigate the occurrence of out-of-plane creep buckling of CFST arches due to the application of the instantaneous overload. The creep and shrinkage of the core concrete are modelled using the Eurocode 2 [29] implemented using the integral-type creep law, while the material nonlinearities and the possible confinement effects for the core concrete under high stress level are modelled with constitutive equations proposed by Han [30]. These constitutive models are implemented within the ABAQUS numerical model using the user-defined UMAT subroutine. The analysis method is benchmarked against available experimental data from an out-of-plane buckling experiment of a CFST arch. Relying on the results of parametric study, a design equation is then derived based on regression techniques for possible use in routine design to enable engineers to predict the out-of-plane stability resistance of CFST arches accounting for time effects.

2. Finite element model

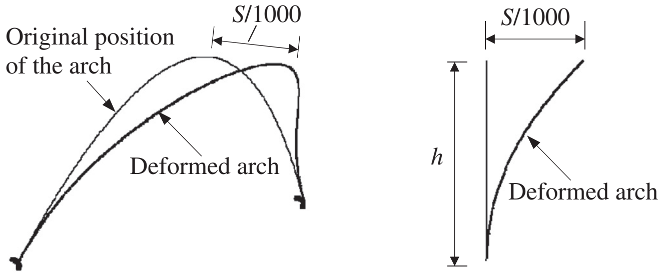
2.1. Finite element formulation

The finite element model is developed with ABAQUS [28], assuming that plane sections remain plane and that no slip or separation occurs between the steel tube and the concrete core in both long-term and buckling analyses. The concrete core and the steel tubes are modelled separately using Timoshenko beam elements (using element B31 in ABAQUS) and are specified using same discretisations in the finite element model. The full shear interaction is enforced by using the same group of nodes for the steel and concrete elements. The geometric imperfections are included in the finite element simulation as the critical buckling modes scaled to appropriate imperfection amplitudes of *S*/1000, with *S* being the arch length. Through initial ultimate capacity predictions of CFST arch arrangements based on imperfections produced with different combinations of buckling modes, it has been observed that the most critical case consists of the first eigenmode and the buckling mode adopted to represent the imperfections is shown in Fig. 3 for a representative CFST arch case.

A preliminary study is performed to specify the mesh refinement. This is performed following standard finite element practice where



(a) Top view



(b) Isometric view (c) Lateral view

Fig. 3. First buckling mode of the arch.

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