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Seismic performance and collapse prevention of concrete-filled thin-walled steel tubular arches

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ABSTRACT

The primary objective of this paper is to investigate the seismic behaviour of concrete-filled steel tubular (CFST) arches using incremental dynamic analysis (IDA). A nonlinear elastic–plastic finite element model is developed using OpenSees software and is verified with a shaking table test. Single-record IDA studies indicate that a CFST arch undergoes global dynamic instability when subjected to ground motions of increasing intensity levels. During this process, either dynamic elastic buckling or dynamic elastic–plastic buckling may occur. Dynamic strength, which is defined as the capacity for preventing global dynamic instabilities of CFST arches, is determined with a series of multi-record IDA calculations. A lower bound equation that takes into account the effect of slenderness ratio, axial compression ratio, and included angle is proposed for the prediction of the dynamic strength of CFST arches.

1. Introduction

Arches with a CFST section, which consists of a thin-walled steel tube and a concrete core are widely used in bridge construction [1,2]. Compared with reinforced concrete arches, CFST arches can span longer distances without adding significant amounts of weight. The thin-walled steel tube also serves as a template in-situ, which greatly simplifies the concrete casting procedures. Compared with steel arches, CFST arches use less steel while still exhibiting satisfactory levels of stability and stiffness [3–6]. The origin of the CFST arch bridge can be traced back to 1937, when one was used to cross the Neva River in Russia with a span of 101 m. At the time it was not a popular bridge style because of the construction difficulties that occurred during concrete pouring. In the 1990s, an improvement in concrete pumping technology led to a CFST arch revival in bridge construction. Today, China serves as one of the largest markets for CFST arch bridges, with more than 300 CFST arch bridges and 40 bridges over 200 m constructed in the last 20 years [7]. Fig. 1 presents typical CFST arch bridges built in China in recent years.

China is an earthquake-prone country, with an average of 145 earthquakes each year. Over the last century, there has been at least one 7.0 magnitude or higher earthquake each year. In the southwestern province of Sichuan, an 8.0-magnitude earthquake struck Wenchuan in 2008. That disaster killed 69,197 people, injured 374,176, and led to 18,222 missing. In 2013, a 7.0-magnitude earthquake hit Ya'an (also in Sichuan Province), leaving over 190 dead and 12,000 injured. A lot of CFST arch bridges are constructed or are scheduled to be constructed in regions with high seismic risks, and thus the seismic design of CFST arch bridges should be given appropriate consideration. However, current codes or specifications for CFST arch bridges, such as DBJ/T 13-136 [8], only identify the design methods for the static behaviours of CFST arch bridges. Moreover, the general seismic design codes, such as JTG/T B02-01 [9] for highway bridges, and GB50111 [10] for railway bridges, do not include seismic design provisions for CFST arch bridges.

Most of previous studies on CFST arches focused on static behaviours for example, in-plane instabilities [2,11], long-term behaviours [12–15], and construction technologies [16]. Few researchers have investigated the seismic performance and responses of CFST arches. Wu [17] performed a nonlinear seismic analysis on the Second Saikai Bridge (230 m, Japan), in which the nonlinear seismic characteristics and seismic safety of the bridge were examined. The results suggested that the combined out-of-plane and longitudinal excitations should be considered during a seismic study on CFST arches. Zhang [18] presented a theoretical analysis on CFST arch bridges under tridirectional spatial seismic motions using the pseudo-excitation method. During his seismic analysis, a structural health monitoring technique was used. Zong [19] presented an analytical and experimental dynamic analysis of a CFST half-through arch bridge with a span of 90 m. A three-dimensional FE model was developed and an analytical modal analysis was carried out to obtain natural frequencies and mode

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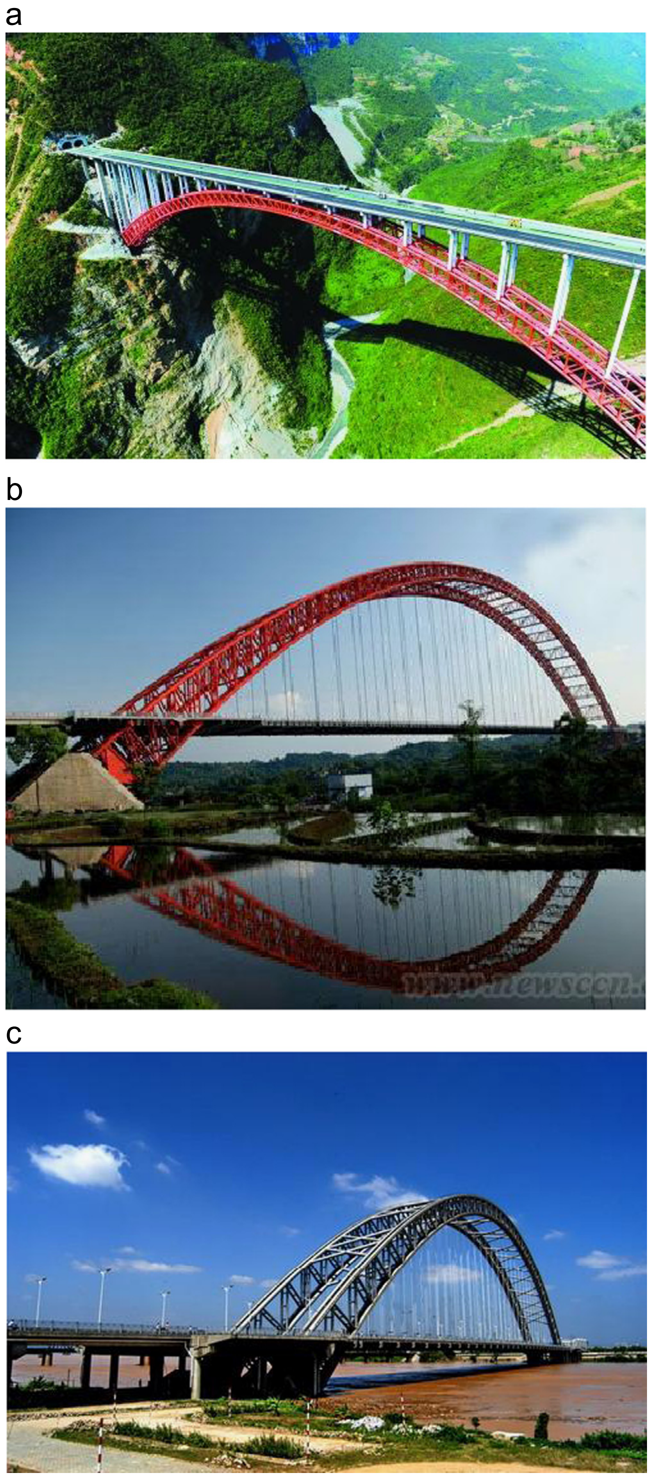

Fig. 1. Typical CFST arch bridges. (a) Zhijing River bridge (430m, 2009), (b) bosideng Bridge (530m, 2013) and (c) yong River Bridge (338m, 2004).

shapes. Wen [20] analyzed the influence of different damping coefficients on the dynamic response of a CFST arch bridge. The results showed the effects of different values and different types of damping coefficients on dynamic responses to be quite remarkable. Taken together, these findings reveal an analytical studies trend of concentrating on seismic assessments while ignoring the development of general design guidance.

In routine design, a bridge must meet different performance objectives under seismic loads. These objectives include being able to withstand frequent earthquakes without damages; to remain repairable, despite sustaining some damage during a moderate earthquake; and remaining stable and safe for rare but powerful earthquakes. Given these objectives, an evaluation of a bridge's structural integrity should include subjecting the bridge to different ground motion levels. This evaluation method would be superior to the popular method of only testing a bridge against a single level of intensity. In this study, we present a method for carrying out this more rigorous testing method: the incremental dynamic analysis (IDA). The IDA is a parametric analysis method that involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, which then produces one (or more) curve (s) of response parameterized versus the intensity level [21–26]. Through IDA analysis, it is feasible to assess the seismic behaviour of CFST arches from the elastic–plastic stage up until collapse.

This study investigates the seismic behaviour of CFST arches based on the IDA method. A finite element model is developed with OpenSees using a shaking table test as verification. The failure mechanism and failure modes of CFST arches that are subjected to severe earthquake attacks are investigated. The dynamic strengths for a set of ground motions and various parameters are obtained and summarized, and a lower bound design equation is proposed for the prediction of the dynamic strength of CFST arches.

2. Finite element model

An open source object-oriented nonlinear structural analysis software, open system for earthquake engineering simulation (OpenSees), is used for the nonlinear elastic and elastic–plastic seismic analyses of CFST arches. The OpenSees program was developed at the University of California, Berkeley, primarily for earthquake simulations. It also contains static analysis features with both load and displacement control schemes.

2.1. Basic assumptions and element type

The basic assumptions adopted in this investigation are: (1) the composite cross-section remains plane and perpendicular to the arch axis during deformation; (2) the arches are slender (i.e. the dimensions of the cross-section are much smaller than the length of the arch) and thus the shear deformation is not included in the analysis; (3) the steel tube is assumed to be bonded fully with the concrete core during deformation. The last assumption is consistent with the full bonding requirement of the specifications for CFST arch bridges [8,27], which specify that the pouring of the concrete core must be strictly controlled to ensure that the concrete fully bonds with the steel tube. During construction, self-compacting concrete is poured into the steel tubes to ensure that the concrete flows properly while also maintaining its required level of density [28]. In addition, after the concrete has been cast, an ultrasonic examination should be conducted to ascertain the gaps between the concrete and steel tube. If gaps exist, drilling and additional concrete castings are required. This assumption is also supported by test results [29], where the maximum interface shear stress was found to be lower than the lower bond strength and no debonding was observed at the end of the tests.

OpenSees' Nonlinear beam-column element satisfies the three basic assumptions above, and is used to simulate the steel–concrete composite arches. The integration along the element is based on the Gauss–Lobatto quadrature rule (two integration points at the element ends) [30]. The fiber section, which is discretized into smaller regions for which the material stress–strain response is