Engineering Structures 98 (2015) 118–127

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

An experimental study on out-of-plane inelastic buckling strength of fixed steel arches

Yan-Lin Guo [a], Si-Yuan Zhao [a,*], Yong-Lin Pi [b], Mark Andrew Bradford [b], Chao Dou [a]

[a] Department of Civil Engineering, Tsinghua University, Beijing, China
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, UNSW Australia, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 12 January 2015
Revised 16 April 2015
Accepted 16 April 2015

Keywords:
Fixed arch
Out-of-plane buckling strength
Experimental investigation
Numerical modeling analysis

ABSTRACT

This paper presents an experimental study on the out-of-plane inelastic buckling strength of fixed circular steel arches under symmetric and non-symmetric loading. A test loading arrangement that allows for lateral deflections to develop freely under vertical loading is described. A finite element (FE) model consisting of the tested steel arch and the loading system is established for carrying out supplementary numerical investigation on the inelastic out-of-plane buckling strength of the fixed steel arches. The FE numerical model is validated by the experimental results. From the experimental results and supplementary FE investigation, it is found that the out-of-plane inelastic buckling strength of fixed steel arches is influenced significantly by the magnitude and distribution of initial out-of-plane geometric imperfections, as well as the out-of-plane elastic buckling modes and the in-plane loading patterns. It is also found that the out-of-plane buckling strength of a fixed steel arch under non-symmetric loading is lower than that under symmetric loading. Based on the experimental and FE results, a lower bound interaction equation is developed for predicting the out-of-plane inelastic buckling strength in the design of fixed circular steel arches against their out-of-plane failure.

1. Introduction

Fixed steel arches have been widely used in buildings and bridges. Under in-plane loading, a fixed steel arch may fail in an out-of-plane inelastic buckling if it does not have adequate lateral bracings. Studies on elastic and inelastic out-of-plane buckling strength of steel arches have focused mainly on laterally pin-ended arches [1–13]. Because the distributions of the internal actions and out-of-plane elastic buckling loads of fixed steel arches are different from those of pin-ended steel arches [14–16], it is expected that their out-of-plane inelastic buckling strengths differ from those of pin-ended steel arches [17–19].

Although a number of analytical and numerical studies of the out-of-plane elastic and inelastic buckling of pin-ended arches have been published in the literature [1–13], there are very limited investigations on the out-of-plane elastic and inelastic buckling strength of fixed steel arches. Pi and Bradford [14], Bradford and Pi [15] investigated the out-of-plane elastic buckling of fixed circular arches. Pi and Bradford [16] also studied the effects of pre-buckling deformations on the out-of-plane elastic buckling of fixed arches. Dou et al. [17] showed the significant influences of the buckling mode shapes on the accurate derivation of the out-of-plane elastic buckling load of fixed arches, and Kang and Bert [18] applied the differential quadrature method to compute the eigenvalue for elastic flexural–torsional buckling of arches with different boundary conditions. Besides, Pi and Bradford [19] studied the out-of-plane strength of fixed steel I-section arches numerically. These analytical and numerical results need to be validated against the experimental results of steel arches. As a consequence, the present paper focuses on the experimental investigations of the out-of-plane elastic and inelastic buckling of fixed steel arches.

While several experimental studies of the out-of-plane elastic buckling of arches have been conducted [20–23], only three experimental investigations of the out-of-plane inelastic strength of fixed steel arches have been reported [24–27]. Sakimoto et al. [24] conducted tests on three freestanding and nine braced circular or parabolic steel arches having a box section and a constant rise-to-span ratio of $f/L = 0.2$ under combined vertical tilting and horizontal lateral loading. Sakata and Sakimoto [25] investigated experimentally the out-of-plane inelastic buckling of steel I-section arches under eight concentrated gravity loads or tilting loads. Recently, La Poutre et al. [26] carried out an experimental study of the out-of-plane inelastic buckling of circular steel I-section arches. Fifteen arches having a constant length and included angles varying from 90° to 180° were tested under a centrally concentrated

---

* Corresponding author. Tel.: +86 13439150461; fax: +86 010 62796859.
E-mail address: zhaosy005@163.com (S.-Y. Zhao).

http://dx.doi.org/10.1016/j.engstruct.2015.04.029
0141-0296/© 2015 Elsevier Ltd. All rights reserved.

load. Dou et al. [27] carried out tests on the inelastic buckling and strength of steel I-section circular arches. All of the arches used in these experimental studies [24–27] were in-plane pin-ended and out-of-plane fixed. In the Ref. [26,27], to prevent the torsion restraining effect of the loading device on the arch rib during out-of-plane deformations, a hydrostatic bearing was used at the loading point on the arch crown, resulting in a tilting load through a tension rod, while in the Refs. [24,25] both gravity and tilting loads were applied.

It is known that the out-of-plane inelastic buckling strength of a steel arch is significantly influenced by the distribution and magnitude of its initial out-of-plane geometric imperfections [19]. Unfortunately, these were not thoroughly investigated [24–26]. In addition, the in-plane boundary conditions and load cases have significant influences on the out-of-plane inelastic buckling strength of fixed arches. Hence, further experimental investigations of the out-of-plane inelastic buckling strength of fully fixed steel arches and the effects of initial out-of-plane geometric imperfections on the strength provide significant contributions to the pertinent literature.

This paper therefore presents an experimental study on the out-of-plane inelastic buckling strength of fixed circular steel arches. Symmetrical three-point loading and non-symmetrical two-point loading schemes are arranged in the experimental study. The influences of the initial out-of-plane geometric imperfections and the elastic buckling mode shapes on the out-of-plane inelastic buckling strength are investigated experimentally. Based on the test results, a FE numerical model for the out-of-plane inelastic strength of fixed steel arches is established for the supplementary numerical investigation. The experimental and numerical results are to be used to develop the design equation for the out-of-plane inelastic buckling strength of fixed circular steel arches.

2. Out-of-plane elastic buckling analysis

Because it is difficult to apply gravity point loads to a freestanding arch while it experiences out-of-plane deformations during testing (Fig. 1a) [26], the loads will be applied to the arch through vertical ties as shown in Fig. 1b. The ties are no longer vertical, but inclined during the out-of-plane deformations and so the direction of the applied load changes accordingly. Because of the influence of inclined ties, the out-of-plane elastic buckling behavior of the arch shown in Fig. 1b may be different to that of the freestanding arch shown in Fig. 1a. To facilitate the experimental investigation, it is important to determine whether the out-of-plane elastic buckling behavior of fixed arches under loads applied through vertical ties (Fig. 1b) is different from that of freestanding arches under gravity loads (Fig. 1a). For this, the commercial FE software ANSYS [28] was used to determine the respective out-of-plane elastic buckling loads and mode shapes. The arches were modeled by the Timoshenko beam element BEAM188, while the ties were assumed to be rigid and modeled by the two-node link element Link8 of ANSYS. The arches were assumed to have a doubly symmetric steel I-section with the dimensions listed in Table 1, in which h is the overall height of the I-section, b is the width of the flange, t_f is the flange thickness, and t_w is the web thickness. The rise-to-span ratios f/L of the arches were assumed to vary from 0.1 to 0.4 with a constant span of $L = 6$ m. An ideal bi-linear stress–strain curve was adopted for the steel, with Young's modulus $E = 206$ GPa and shear modulus $G = 81$ GPa.

The relationships between the out-of-plane elastic buckling loads F and the rise-to-span ratios f/L for freestanding arches and for arches with vertical ties are shown in Fig. 2a and b for symmetric three-point loading (o_1 and o_3 at the quarter points from both ends and o_2 at the crown) and non-symmetric two-point loading (o_3 at one quarter point and o_2 at the crown) respectively. It can be seen that the out-of-plane elastic buckling loads of arches with vertical ties are significantly higher than those of the counterpart freestanding arches. It can also be seen that under the symmetrical three-point loading, arches with vertical ties buckle in an out-of-plane anti-symmetric two-half-wave mode while the freestanding arches buckle in an out-of-plane symmetric one-half-wave mode. Under the non-symmetric two-point loading, the out-of-plane buckling shapes are non-symmetric both for arches with vertical ties and for freestanding arches. In addition, it can be seen from the Fig. 2a and b that the out-of-plane elastic buckling load F increases when the rise-to-span ratio of arch f/L increases from 0.1 to 0.2, but decreases when the rise-to-span ratio of arch f/L increases from 0.2 to 0.4, and that the buckling load has a peak value when f/L equal to 0.25 for symmetric three-point loading or when f/L equal to 0.2 for non-symmetric two-point loading. With knowledge of the out-of-plane elastic buckling behavior of steel arches under loading through the vertical ties, an experimental investigation of the out-of-plane inelastic buckling strength was carried out.

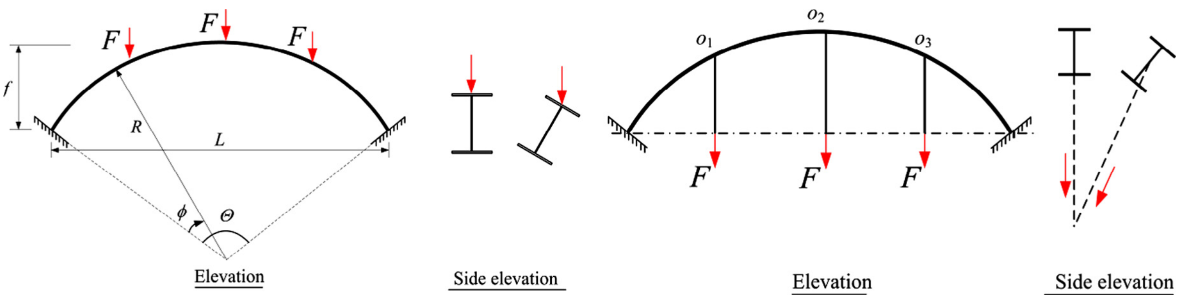
3. Experimental investigation of out-of-plane inelastic buckling

3.1. Specimens

Steel plate designated Q235B [29] was used for fabrication of the steel I-section arch specimens. The flanges were rolled to the curved shape from steel plates by a hot-rolling machine while

Table 1
Dimensions of models.

Dimensions of the cross-section (mm)				Span of arches (m)
h	b	t_f	t_w	
200	100	12	8	6



(a) Freestanding arches (b) Arches with vertical ties

Fig. 1. Fixed arches.