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Design rules for out-of-plane stability of roller bent steel arches with FEM

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ABSTRACT

This paper describes a numerical investigation into the out-of-plane buckling behavior of freestanding roller bent steel arches. As roller bent arches have structural imperfections which differ considerably from those of hot-rolled or welded sections, specific attention is paid to their inclusion in the numerical model. Sensitivity analyses are performed to assess the influence of the imperfections due to roller bending on the out-of-plane buckling response. The accuracy of the finite element model is checked by comparing the results with earlier performed experiments as presented in a related paper. The finite element model is able to replicate the structural behavior displayed by the experiments with good accuracy. A database is created with elastic–plastic buckling loads for a large number of freestanding roller bent arches. The numerical data is analyzed and presented in a so-called imperfection parameter diagram from which imperfection parameter curves are derived. The imperfection parameter curves are substituted into the European column curve formulation, leaving the original column curve formulation unaffected but extending its applicability to the out-of-plane buckling response of roller bent arches. The column curve with proposed imperfection parameter expressions can be used to check the out-of-plane buckling response of a roller bent steel arch with known non-dimensional slenderness.

1. Introduction

The application of roller bent steel has seen a steady increase in the construction industry over the past decades. Ease of manufacturing make roller bending a suitable method for achieving curved structures. Roller bent steel is often applied in circular arch structures where its primary function lies in carrying the acting loads to the abutments. The loads are resisted by means of a combination of compression and bending, making the member susceptible to buckling. When local buckling is not considered, arch instability can be subdivided into three different categories: snap-through buckling (Fig. 1(a)), in-plane buckling (Fig. 1(b)) and out-of-plane buckling (Fig. 1(c)). The latter occurs when an arch has no lateral bracing and is considered ‘freestanding’. This paper presents a study of the structural performance of freestanding circular roller bent steel arches by means of the finite element method, for which out-of-plane buckling is the governing failure mode. The performance of the finite element model is verified through comparison with experimental results as reported in a related paper, La Poutré et al. [1].

1.1. Previous studies on out-of-plane arch buckling

The earliest theoretical studies on out-of-plane arch buckling only considered elastic buckling where material non-linearities and imperfections were ignored. Valuable contributions were published by Timoshenko and Gere [2] and Vlasov [3] who provided formulae to approximate the elastic out-of-plane buckling load of freestanding arches. Further refinements to calculation procedures for approximating the elastic buckling load were proposed by Vacharajittiphan and Trahair [4], Yoo [5] and Rajasekaran and Padmanabhan [6].

The necessity to include material non-linearities and imperfections to obtain an accurate representation of out-of-plane buckling behavior of arches was recognized in Japan by the end of the 1970s. Research studies included experiments conducted on arches with square hollow sections by Sakimoto et al. [7] and welded I-sections by Sakata and Sakimoto [8] supplemented with finite element analyses by Komatsu and Sakimoto [9], Sakimoto and Komatsu [10] and Sakimoto and Komatsu [11]. These Japanese research studies culminated in design rules. For the calculation of the slenderness, the arch was treated as a straight column under uniform compression with identical cross-section, where the arch length corresponded with the column length. Column curves were proposed by Sakimoto et al. [12] and Sakimoto and Sakata [13] to allow a check of the out-of-plane arch stability. Their applicability was limited to arches with square hollow sections and rise-to-span ratios between 0.1 and 0.2.

As the Japanese design provisions treated the out-of-plane arch buckling case identically to that of a column, the rise-to-span ratio

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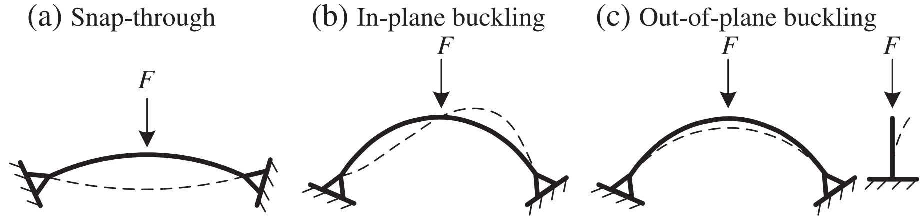

Fig. 1. Global instability phenomena for arches.

of the arch was considered to be of minor importance. However, earlier theoretical studies revealed that the rise-to-span ratio can have a significant effect on arch buckling. This was recognized by Papangelis and Trahair [14] who performed experiments on arch buckling. These experiments were used to validate an in-house finite element code developed by Pi and Trahair [15] from which design rules for arch buckling were developed and proposed. Pi and Trahair [16] stated that for pin-supported arches subjected to radial loading and simply-supported arches subjected to uniform bending, the Australian column curves were considered suitable for the design of arches failing by out-of-plane buckling. For out-of-plane fixed arches a similar approach was used; Pi and Bradford [17]. According to Pi and Trahair [16] and Pi and Bradford [17] the arch slenderness was defined as the square root of the ratio between the plastic capacity and out-of-plane elastic buckling load, taking implicitly into account the geometric properties of the arch. For arches subjected to vertical loading, interaction formulae were proposed to check the out-of-plane stability. These interaction formulae are analogous to those of a beam-column failing by elastic–plastic buckling. The interaction formulae were valid for out-of-plane simply supported arches, Pi and Trahair [18] and out-of-plane fixed arches, Pi and Bradford [17].

1.2. Scope and aims

It is clear that the out-of-plane buckling behavior of steel arches has received large attention, comprising analytical, numerical and experimental studies. However, investigations involving material non-linearities and imperfections were limited to either welded box-sections or wide-flange sections for which the influence of the roller bending process on the structural properties of the arch was not taken into account. Earlier experiments and finite element analyses by the authors have shown the influence of the roller bending process on the structural properties of wide flange sections. Using the existing design rules to check the out-of-plane buckling response of freestanding arches without taking into account the influence of the roller bending process can lead to either conservative or unconservative designs. The main goal of this paper is two-fold: providing numerical modeling techniques for roller bent steel members and suggesting design rules for out-of-plane buckling of arches with finite element analyses. The European column curve formulation as described in EN 1993-1-1 [19] (Eurocode3) will be adapted to include the out-of-plane buckling of arches. The results from 3 different finite element analysis types will be used to express the numerical data in the column curve diagram to arrive at a design rule. Arches can be subjected to a wide range of loading types. In general a distinction is made between symmetric and unsymmetric loads. The present finite element study is limited to the former one. Design rules are proposed for a total of four load cases as shown in Fig. 2. The arch geometry is shown in Fig. 2(a), where S is the arch length, R the radius, 2γ is the subtended angle, L is the span and f is the rise. Arches with two opposite end moments (Fig. 2(a)) and a radially distributed load (Fig. 2(b)) are rather academic load cases. These load cases serve for comparison with other load cases, as the internal forces are limited to uniform bending or uniform compression for an arch under two opposite end moments or a radially distributed load, respectively. Arches with a central point load (Fig. 2(c)) or uniformly distributed load (Fig. 2(d)) display a combination of internal bending moments and compressive forces. During the loading phase, the loads will undergo no directional change and are hence termed gravity loading. The present study is limited to circular I-section arches made from either steel grade S235 or steel grade S355 bent about their major axis through the roller bending process.

With the exception of arches subject to two opposite end moments, all arches are pin-supported, preventing outward spreading

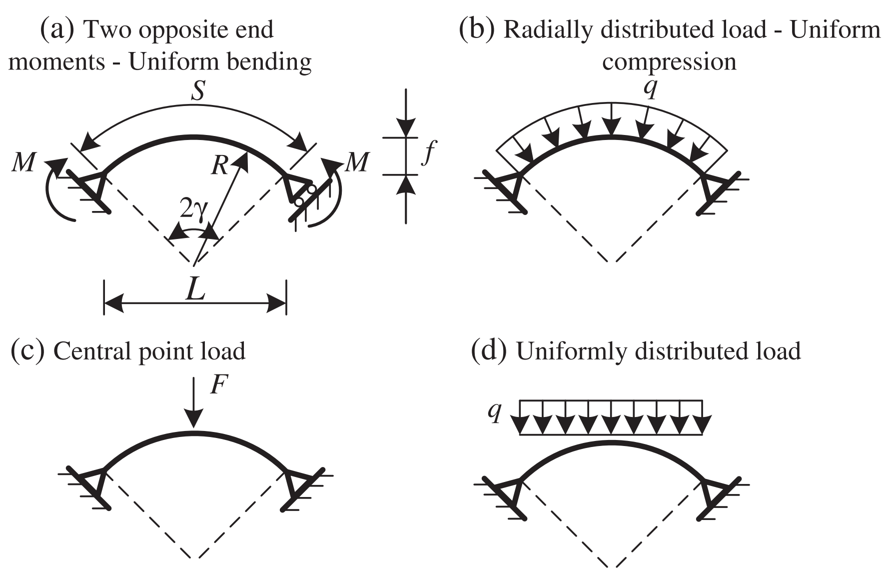

Fig. 2. Load cases under investigation.