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In-plane strength of steel arches with a sinusoidal corrugated web under a full-span uniform vertical load: Experimental and numerical investigations

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ABSTRACT

This paper reports experimental and numerical investigations used to develop a simple and accurate design method for the in-plane strength of circular steel I-section arches having a sinusoidal corrugated web under a uniform vertical load over the entire span. In deference to a flat web that can resist both shear and normal stresses, a sinusoidal corrugated web can resist only shear stresses, since its axial and bending stiffnesses are quite small. Tests are carried out to investigate the global in-plane elasto-plastic behaviour and strength of a circular steel I-section arch with a sinusoidal corrugated web under symmetric loading. A finite element model is also developed, validated by the test results, and then used to further investigate the global in-plane elasto-plastic behaviour and strength of the steel arches. Based on the test and finite element results, a design equation for predicting the global in-plane strength of circular steel I-section arches with a sinusoidal corrugated web subjected to a uniform vertical load over the entire span is proposed. It is found from the finite element results that in addition to an in-plane global failure mode, a circular steel I-section arch with a corrugated web may also fail in an elasto-plastic web shear buckling mode. Hence, elasto-plastic shear buckling of the sinusoidal corrugated web in arches must also be considered in their design.

1. Introduction

This paper concerns both experimental and numerical investigations of the global in-plane strength of a circular pin-ended steel I-section arch having a sinusoidal corrugated web under a full-span uniform vertical load (FSUVL) (Fig. 1) [1,2]. There are two major advantages of using a sinusoidal corrugated web to replace the usual flat web in steel I-section arches. Firstly, if a steel I-section arch is fabricated by welding, the flat circular web has to be cut from a flat plate, while a circular sinusoidal corrugated web can be easily curved from a sinusoidal corrugated panel because it has a very small bending stiffness. This avoids the material wastage associated with the plate cutting. Secondly, a sinusoidal corrugated web can be designed to be much deeper and thinner than a flat web in an arch because of its high out-of-plane flexural stiffness, and this improves the in-plane flexural stiffness of the I-section significantly, leading to an enhanced load-carrying capacity of the cross-section, and being especially beneficial to arches that resist large bending moments.

Previous investigations of the in-plane buckling and strength of steel arches have mainly focused on arches with a flat web. Pi and Trahair [3,4] investigated the in-plane non-linear buckling and postbuckling behaviour of elastic arches using a curved element model and found the effects of the higher-order terms in the deformed curvature were important on the buckling and postbuckling behaviour of arches. They [5,6] also studied the in-plane inelastic buckling and strength of pin-ended steel I-section circular arches and developed interaction equations for their in-plane strength design. Bradford and Pi [7], Pi and Bradford [8], and Pi et al. [9] investigated the in-plane strength of fixed steel I-section circular arches, and also developed interaction equations for their in-plane strength design. It was found that the modified slenderness of a steel arch, that is related to the in-plane elastic buckling and squash load of the cross-section, is as an important parameter in the formulation of the design equations. They also found that the linear elastic in-plane buckling load of arches [10,11] is inadequate, and introduced the non-linear in-plane buckling load [12] into the modified slenderness. Sakimoto et al. [13] carried out tests to investigate the ultimate strength of circular and parabolic steel arches, while Guo et al. [14] carried out

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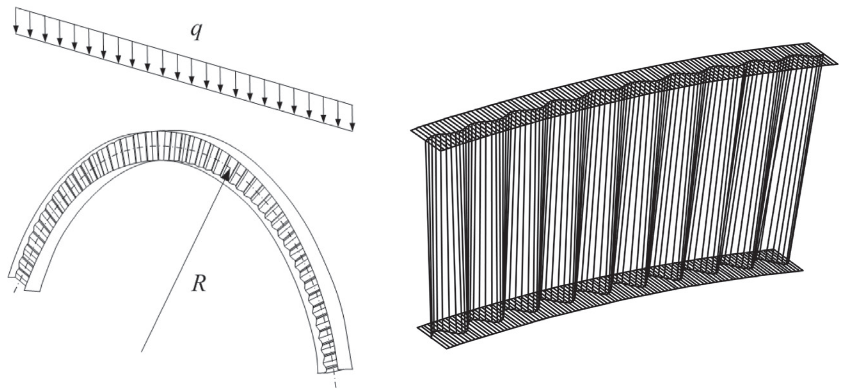

(a) Global configuration (b) Details of the corrugated web

Fig. 1. Steel I-section arch with a sinusoidal corrugated web. (a) Global configuration and (b) details of the corrugated web.

experimental and numerical investigations into the in-plane strength of welded circular steel I-section pin-ended arches and proposed an interaction equation for their design. Experimental investigations of the out-of-plane inelastic strength of circular steel I-section or box-section arches with flat webs were conducted respectively by La Poutre et al. [15], Dou et al. [16] and Guo et al. [17]. The results provided in these investigations pertain to arches with flat webs only. Because a sinusoidal corrugated web can only resist very small axial compressive and bending actions, it is questionable whether the results for arches with flat webs can be used for steel I-section arches having a corrugated web.

Steel I-section beams with a corrugated web are used in long-span roofs and industrial buildings as shown Fig. 2. Johnson and Cafolla [18] studied experimentally the shear capacity of I-girders with a trapezoidal corrugated web and derived the cross-sectional shear modulus of the web. Guo et al. [19,20] studied analytically, numerically and experimentally the out-of-plane strength and the web shear strength of I-section beams having a sinusoidal corrugated web, and proposed design formulae for predicting their out-of-plane strength and web shear strength.

Based on their studies of the strength of steel I-section beams with sinusoidal corrugated webs, Guo et al. [21] proposed the use of a sinusoidal corrugated web in steel I-section arches and carried out analytical and numerical investigations of their in-plane failure mechanisms, finding that they may fail in a global in-plane elasto-plastic buckling mode or in a local web shear elasto-plastic buckling mode. However, no experimental investigations of the strength of steel I-section arches having a sinusoidal corrugated web have been reported in the literature, and so an experimental study of their in-plane strengths is much needed to validate the theoretical studies. This paper presents such a study.

Design methods available in the literature consider arches that are subjected to combined axial compressive and bending actions, and use lower bound interaction equations for their in-plane strength design. These lower bound design equations can provide safe predictions, but are overly conservative in some cases, particularly for an arch that is subjected to a uniform vertical load over its span.

This paper, therefore, is concerned with an experimental investigation of the global in-plane strength of circular steel I-section pin-ended arches having a sinusoidal corrugated web. A finite element model is then developed and validated using the test results, and is then used to produce a body of data for the in-plane strength of such a steel arch subjected to a uniform vertical load over its span (Fig. 3). Using the test and finite element results, simple design equations for the strength limit state of global in-plane failure of steel I-section arches with a sinusoidal corrugated web under a uniform vertical load over the entire span are proposed.

2. Experimental study of in-plane arch strength

2.1. Test specimen

Tests to determine the elasto-plastic in-plane behaviour and strength of circular steel I-section arches with a sinusoidal corrugated web were carried out. The global and cross-sectional geometries of the tested arch are shown in Figs. 3 and 4 respectively, where S is the half of the developed length of the arch, L and f are the span and rise of the arch (Fig. 3), h_w is the height of the web, t_w is the thickness of the web, b_f is the width of the flange, t_f is the thickness of the flange, s_w is the developed length of one wave of the web, ℓ_λ is the wavelength along the neutral axis of the arch, and a_0 is the amplitude of the web sinusoidal wave measured at the neutral axis (Fig. 4).

Because the aim of the test was to investigate the global in-plane strengths of steel arches with a corrugated web, web shear failure needed to be prevented in the test. In addition, to prevent the corrugated web from being flattened during the fabrication of

(a) Hall having corrugated web beams (b) Parking lot having corrugated web beams

Fig. 2. Applications of beams with sinusoidal corrugated web. (a) Hall having corrugated web beams and (b) parking lot having corrugated web beams.