Full length article

Imperfection measurements to predict buckling behavior of slender steel tubes

Fariborz Mirzaie, Andrew T. Myers*, Angelina Jay, Abdullah Mahmoud, Shahabeddin Torabian, Eric Smith, Benjamin W. Schafer

* Northeastern University, Dept. of Civil and Environmental Engineering, 360 Huntington Ave., Boston, MA 02115, USA
b Johns Hopkins University, Dept. of Civil Engineering, 17 Latrobe Hall, Baltimore, MD 21218, USA
c Keystone Tower Systems, 10855 Dover St., Ste. 700, Westminster, CO, USA
d Johns Hopkins University, Dept. of Civil Engineering, 208 Latrobe Hall, Baltimore, MD 21218, USA

A B S T R A C T

The objective of this paper is to advance the design of slender steel tubes by developing a practical approach for utilizing high-resolution measurements of geometric imperfections to estimate the buckling location and strength of such tubes in bending. This approach includes a novel measure of imperfection severity that is designed to be insensitive to noise. The ability of this measure to predict buckling behavior of slender tubes in bending is assessed through comparison with eight large-scale tests, and, for this set of data, the predictions are promising. This study is intended to be a starting point in the development of a simple, but accurate, design method to quantify the impact of imperfections on the buckling behavior of slender tubes.

1. Introduction

Spiral-welding is an innovative manufacturing process with potential to enable the on-site production of tapered steel tubes. The process may be useful for wind towers, which are usually made from slender tapered steel tubes with maximum diameter-to-thickness ratios (D/t) between 300 and 500 [11]. The manufacturing process influences the pattern and magnitude of geometric imperfections, which, in turn, influence buckling behavior. This paper considers high-resolution measurements of geometric imperfections of eight large-scale tapered tubes manufactured with spiral-welding and recently tested in pure bending by the authors [12]. The measurements are analyzed to predict the buckling location and strength observed for each of the eight tests, which have diameters between 0.7 m and 1.1 m and D/t ratios between 230 and 350. The eight tubes are slightly tapered with a taper angle ranging between 0.67° and 0.86°. A novel measure of imperfection severity for slender tubes is proposed and is used to predict the location of buckling and flexural strength. A comparison of the predictions and measurements of the buckling locations and flexural strengths for the eight large-scale tests considered here shows that the predictions are reasonably accurate. In terms of strength and buckling location, the predictive ability of the new imperfection measure, which is designed intentionally to be insensitive to noise and outliers in high-resolution measurements of imperfections, is shown to have some advantages compared to the dimple imperfection measures in [6] (abbreviated herein as Eurocode).

The method proposed here is conceived as a potential design tool that allows strength to vary based on manufacturing quality. In this way, the tool fairly rewards precise manufacturing, allowing for more structural economy, and fairly penalizes imprecise manufacturing, allowing for more expedited manufacturing. There are also two methods in Eurocode which explicitly allow for strength to vary based on manufacturing quality: the first, termed the Stress Design Method, prescribes variable, empirically-based knockdown factors to theoretical calculations for strength, and the second, termed Geometric and Material Nonlinear Analysis including Imperfections (GMNIA), is based on shell finite element analyses with explicit modeling of geometric imperfections. While the first method is relatively easy to implement and popular, it is based largely on results from compression tests, and, as such, may lead to an overly conservative design for highly slender tubes in bending. The second method is more sophisticated and has potential for more accurate customized designs, but it is complex and requires considerable expertise with nonlinear analysis. This paper adopts the idea of the Stress Design Method and tries to provide more reliable and specimen-specific knockdown factors in bending based on high-resolution imperfection measurements and test data.

https://doi.org/10.1016/j.tws.2017.11.016
Received 26 June 2017; Received in revised form 27 October 2017; Accepted 9 November 2017
0263-8231/ © 2017 Elsevier Ltd. All rights reserved.
Regarding the GMNIA method, Eurocode states that the shape of the first buckling mode of the structure should serve as the imperfection pattern in the absence of more particular knowledge about specific imperfection types pertinent to a given design and that the chosen imperfection pattern should have “a sufficiently deleterious effect to give confidence that the lowest resistance has been obtained” (EN 1993–1–6). The code further suggests that imperfections known to relate to the manufacturing process should also be considered and carefully notes that the geometric imperfections included in the model must account for not only the geometric imperfections in the real structure, but also other strength-reducing phenomena such as residual stresses and non-ideal boundary conditions if not explicitly included in the model. Many researchers including Holst et al. (9) and Schneider (18) have provided guidance on this method and have shown it to be subtle and complex. With that in mind, the objective of this paper is to advance the design of slender cylindrical tubes by developing a practical method for using imperfection measurements to estimate the buckling strength and location for slender tubes in bending.

This paper is organized as follows: first, a review of the literature on geometric imperfections in metal tubes is provided, followed by a description of eight large-scale tests that are used here to assess the accuracy of methods for predicting buckling behavior. Next, measurements of the geometric imperfections of the eight specimens in these tests are presented along with calculations of the magnitudes of dimple imperfections based on definitions in Eurocode. This is followed by a description of a novel imperfection measure to predict buckling behavior. The predictive abilities of the proposed measure and Eurocode measures are then compared with test data, and this is followed by conclusions.

2. Background

The pattern and magnitude of imperfections of metal tubes and the extent of the influence of imperfections on buckling behavior vary with both the D/t ratio of the tubes and the manufacturing process. In this regard, an extensive literature review is performed by Sadowski et al. (17) and this is summarized here with a focus on the dimensions and D/t ratios of previously investigated tubes. Pioneering research by (1) on the measurement and analysis of geometric imperfections in slender cylindrical tubes was focused on shells designed for aerospace applications and these have differences in scale, manufacturing process, and characteristic imperfections compared to shells for civil engineering applications. For example, the original research by Arbocz et al. was on seamless, electroformed copper tubes with a diameter of 200 mm, length of 200 mm, and thickness of approximately 0.1 mm (D/t equal to 2000). The first imperfection research focused on shells designed for civil engineering applications was by Clarke and Rotter (4) who studied the geometric imperfections of a thin-walled cylindrical steel silo. Soon afterwards, Ding et al. (5) proposed an imperfection measuring technique for silos based on a moving trolley that measured imperfections with an LVDT. They measured and analyzed the imperfections of three steel silos with D/t ratios of 960–2000. Later studies, by Berry et al. (2) on six steel silos with D/t ratios between 1100 and 1600 and by Pircher et al. (15) and Teng et al. (19) on the same three silos that Ding et al. (5) had previously studied, showed that the dominant imperfections in welded steel silos are axisymmetric depressions at circumferential weld lines. At that time, these axisymmetric depressions had already been shown to have a detrimental effect on the strength of slender cylindrical tubes by the analytical and computational studies of (10) and (12).

In more recent studies, some researchers have used harmonic analysis to characterize imperfections of slender cylindrical tubes in a more general way and to determine the characteristic imperfections caused by the manufacturing process. As an example, Chryssanthopoulos et al. (3) adopted this approach, combined with a probabilistic methodology to account for the random nature of initial imperfections. They measured imperfections for 24 small-scale stringer-stiffened cylinders with a diameter of 320 mm and D/t ratios between 380 and 510 and used two-dimensional Fourier series analysis to determine the dominant imperfection modes. They also proposed simplified relationships between different modal amplitudes and probabilistic distributions for the modal amplitudes and phase angles of dominant modes based on their imperfection data. In a more recent study, Sadowski et al. (17) analyzed the imperfections in spiral-welded steel tubes with D/t ratios between 65 and 120 and used two-dimensional Fourier series analysis to show that these spiral-welded tubes exhibit systematic imperfection patterns caused by the manufacturing process. Kameshwar and Padgett (13) proposed a stochastic modeling scheme for geometric imperfections in aboveground storage tanks, based on a Fourier series representation of the imperfection data. They modeled the coefficients of the Fourier series as random variables, with distributions determined based on imperfections measured for four full-size tanks and silos with diameters between 6 m and 42 m, and D/t ratios between 1000 and 4000. Most of the abovementioned studies were focused on identifying characteristic geometric imperfection patterns using Fourier analysis, and eventually proposing imperfection models to generate artificial geometric imperfections consistent with the manufacturing processes. In contrast, this paper concentrates on identifying and measuring the localized geometric imperfections (i.e., dents and dimples) which correlate most strongly with metrics of buckling behavior for use in designing tubes when the geometric imperfections are measured.

Research in the aerospace industry also provides useful context for the study here. Recent studies by Wang et al. and Hoe et al. have considered the design of slender tubes to identify realistic geometric imperfections that reduce the buckling strength by the greatest degree. Wang et al. (20) performed a numerical study to identify such imperfections based on the Single Perturbation Load Approach (SPLA; (10)), which considers the imperfections caused by a single perturbation load located at midspan of a tube. Hao et al. (7) introduced the concept of the Worst Multiple Perturbation Load Approach (WMPLA), which optimally identifies a finite number of perturbation loads that minimize the buckling strength of a tube. This is similar to the method proposed here, although the objective of WMPLA is to identify the worst possible combination of local imperfections, while the objective of the method in this paper is to identify the worst existing local imperfection in measurements of a manufactured tube. Wang et al. (21) studied these approaches on the buckling strength of a cylindrical stiffened tube and considered finite element models with Eigenmode-shape, SPLA, WMPLA, and measured imperfections, and showed that the strengths predicted with measured imperfections and WMPLA matched measured strengths most closely. The WMPLA has potential to improve the design of slender tubes when imperfections are not measured and when significant computational effort is accessible. In contrast, the method proposed here is intentionally designed to require minimal computational effort, however, this method requires that imperfections are measured.

3. Specimens

Imperfections and flexural buckling characteristics of eight spirally-welded tapered tubes are considered in this study; see Table 1 for more details. A schematic of the manufacturing process for these specimens is depicted in Fig. 1 and involves cutting steel plates into trapezoids, welding the non-parallel edges of the trapezoids (i.e., the cross weld), rolling the trapezoids into the desired radius, pushing the rolled plate radially inward or outward so that the parallel edges of the trapezoids align with those of the adjacent trapezoids, tack welding the parallel edges of the rolled trapezoids from the inside of the specimen, and then welding the parallel edges of the trapezoids from the outside of the specimen (i.e., the spiral seam weld). All spiral seam welds are inspected for their penetration, and additional welding is performed from the inside of the specimen at any location where welds did not penetrate fully. Although this process involves some limited welding from...
دریافت فوری
متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات