Journal of Constructional Steel Research 125 (2016) 218–226

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Review

Spirally welded steel wind towers: Buckling experiments, analyses, and research needs

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A R T I C L E I N F O

Article history:
Received 4 July 2015
Received in revised form 22 June 2016
Accepted 23 June 2016
Available online 1 July 2016

Keywords:
Spiral weld
Slender tubes
Wind turbine tower
Local buckling
Imperfections

A B S T R A C T

The most common wind tower structure, a tapered tubular steel monopole, is currently limited to heights of ~80 m due to transportation constraints which arise because tower sections are manufactured at centralized plants and transported to site for assembly. The need to transport the sections imposes a limit on their size, whereby maximum tower diameters are dictated by bridge clearances rather than by structural efficiency. New manufacturing innovations, based on automated spiral welding, may enable on-site production of wind towers, thereby precluding transportation limits and permitting the manufacture of taller towers, which can harvest the steadier, stronger winds at higher elevations. Taller towers, however, are expected to have cross-sections with slenderness that is uncommon in structural engineering (i.e., diameter-to-thickness ratios up to ~500) and much larger than those of conventionally manufactured towers (i.e., diameter-to-thickness ratios up to ~300). Tubular structures with highly slender cross-sections are imperfection-sensitive, and the welding process is known to influence imperfections. To account for this sensitivity, slender tubes are usually designed based on empirical knockdown factors, however there are few experiments of tubes in flexure with slenderness as high as what is expected for spirally welded wind towers, and there are no experiments on tubes within this slenderness range and manufactured with spiral welding. This paper reviews the state-of-the-art for designing spirally welded tubes as wind towers and identifies deficiencies. Relevant experimental and analytical research is summarized and research needs to efficiently design tapered spirally welded steel tubes as wind towers are identified.

Contents

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http://dx.doi.org/10.1016/j.jcsr.2016.06.022

1. Introduction

Wind turbines are commonly supported by monopole towers that are made from slender, tubular, tapered steel sections. Such sections are currently manufactured using conventional "can-welding" methods by first cutting steel plates, rolling them into truncated cones and then seam-welding them into so-called "cans." Several cans are then welded circumferentially into larger sections, and flanges are attached to each end. These tower sections are manufactured at centralized plants and then transported to site where they are assembled by bolting the flanges together. The need to transport the sections limits the maximum can diameter to ~4 m [1]. The effect of limiting the diameter is that cross-section thicknesses are increased to provide the required flexural strength and the overall area of the section is larger than that of a section with larger diameter. Because of the constraints imposed by these methods, conventional monopole towers typically have maximum diameter-to-thickness (D/t) ratios of ~300 and heights of ~80 m [2].

An innovation in tapered tube manufacturing has enabled the potential for on-site fabrication of wind towers using automated spiral-welding [3]. Using this manufacturing process, tubes are fabricated from constant-width steel sheets that are first cut into trapezoids, welded end-to-end and then spirally welded into a tapered tube (see Fig. 1). In this paper, the former weld is referred to as a cross weld while the latter is referred to as a spiral seam weld. The automation possible with spiral welding renders the possibility that the tubes could be manufactured on-site with a portable manufacturing facility, following a similar strategy employed by the steel pipeline industry [3].

The steel pipeline industry uses automated spiral welding to manufacture pipelines [4], and has demonstrated the economic benefits of employing a fully automated welding process and the ability to transport the steel in standardized rolls or plates, eliminating the need for expensive, specialized transportation vehicles. For wind towers, on-site manufacturing would preclude current transportation constraints and allow for larger base diameters and more optimal tower designs, enabling taller towers with the potential to capture more energy and to expand the regions where it is economically viable to harvest wind energy [5]. To be efficient, taller towers are expected to have cross-sections with higher slenderness (due to larger diameters) than conventional towers [6].

The proportioning of wind towers is typically controlled by a combination of ultimate bending strength, fatigue and resonance avoidance. Under ultimate bending demands, the limit state of most tower sections is local buckling (either inelastic or elastic depending on the geometry of the section and the material properties). An example of this type of failure for a wind turbine tower is shown in Fig. 2.

Within the context of local buckling, spirally welded wind towers have two important distinctions compared to towers manufactured with conventional methods: first, spirally welded wind towers are expected to have sections with larger diameters and D/t ratios and therefore potentially greater sensitivity to imperfections [7], and, second, spirally welded towers will have a different weld pattern than conventional can-welded towers and therefore are expected to have a different pattern of weld-induced imperfections. As tower diameters and D/t ratios increase, the proportioning of wind towers becomes more likely to be controlled by ultimate bending strength rather than fatigue because fatigue capacities are unchanged for larger diameters and larger D/t ratios while the buckling stress capacity is reduced [6]. For this reason, this review paper focuses on the state-of-the-art for assessing the local buckling strength of spirally welded tapered tubes with D/t ratios within the range expected for application as a wind tower.

Fig. 2. Example of a wind turbine tower failing by local buckling.

The intent of this review is to summarize experimental and analytical research relevant to establishing a design basis for wind towers made from spirally welded tubes with highly slender cross-sections and to highlight the complexities and limitations of existing design methodologies. The review is organized as follows: first, background is provided on conventional methods for designing structures with circular tubes and on current applications of spirally welded circular tubes with emphasis on the important differences in geometry for current applications compared to wind towers. Next, a literature review of 140 bending tests on slender shells is presented with emphasis on the slenderness range of these tests compared to both the slenderness range of towers made with conventional methods and the range expected for towers made with spiral welding. In the following section, a literature review is presented on finite element analyses to estimate the local buckling strength of slender shells including imperfections. Finally, remaining research needs are outlined if spirally welded tubes are to be efficiently designed for use as wind towers.

2. Background

It is insightful to view wind turbine towers within the context of all structural applications of circular steel tubes including both those made by spiral welding and by can-welding.

Fig. 3 identifies six existing applications for circular steel tubes and very approximately maps each application to a typical range of D/t

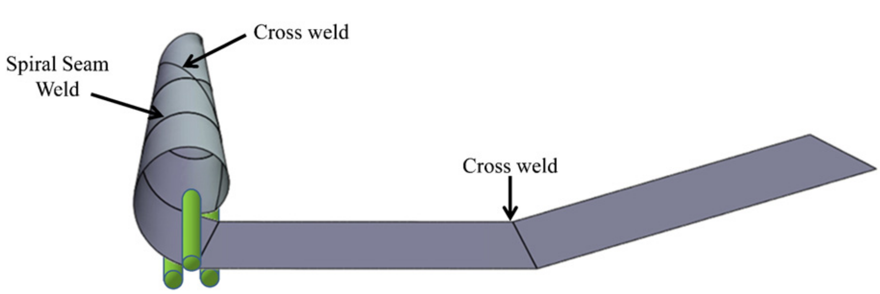

Fig. 1. Schematic depicting spiral welding procedure for tapered tube sections.