Spirally Welded Steel Wind Towers: Buckling Experiments, Analyses, and Research Needs

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ABSTRACT

The most common wind tower structure, a tapered tubular steel monopole, is currently limited to heights of ~80m 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.

Keywords

Spiral weld; Slender Tubes; Wind Turbine Tower; Local Buckling; Imperfections;

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 $\sim 4\text{m}$ [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 $\sim 80\text{m}$ [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 Figure 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].

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

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 Figure 2.

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

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.

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.

Figure 3 identifies six existing applications for circular steel tubes and very approximately maps each application to a typical range of D/t ratios (with ranges taken from relevant design documentation e.g., [8, 9, 10, 11, 12]). The primary structural resistance of each of these applications varies, with some applications requiring the tube to resist internal or lateral pressures or axial forces. For wind towers, the primary structural resistance is flexural due to the large lateral forces acting at the top of a wind tower and the relatively small self-weight. It should be noted that local buckling slenderness is dependent on both geometry and material properties, so these D/t ranges assume consistent material properties across applications. In this paper, slenderness is represented with the variable λ^2 and is defined as, $\left(\frac{D}{t}\right)\left(\frac{F_y}{E}\right)$, where F_y is the yield stress and E is Young's modulus, which is effectively the square of the slenderness value defined in Eurocode design equations [13] and elsewhere, i.e., $\lambda = \sqrt{F_y/F_{cr}}$, where F_{cr} is the critical buckling stress. The figure shows how the potential D/t range for spirally welded wind towers includes a range of D/t uncommon to that of existing circular steel tube applications, whether spirally welded or otherwise. The uncommon slenderness range is significant because the ultimate flexural strength of circular steel tubes is known to be influenced by its sensitivity to imperfections which is, in turn, influenced by the slenderness [7].

The optimal D/t ratios for wind towers is larger than those found in pipelines, pilings, and shorter, stockier support towers (such as ski lift towers and sign support towers), and as wind towers become taller, the difference is expected to be more pronounced. For example, a previous study by two of the authors showed that for a 120 m tower subjected to a reduced subset of design load cases in IEC 61400-1 [14] and Eurocode 3 design provisions, the optimal (i.e., least weight) D/t ratio for one cross-section of the tower can be as high as 550 (for $F_y = 345$ MPa) [6]. This is much larger than the maximum D/t ratios that are common to today's can-welded wind

towers ($D/t \sim 300$ for $F_y=345$ MPa) though much smaller than other welded tubular structures like silos and tanks with D/t ratios up to ~ 2000 . This range of slenderness therefore represents a region for which there is limited experience in structural design.

Figure 3: Approximate ranges of λ^2 and D/t (for $E=200$ GPa and $F_y=345$ MPa) commonly seen for different applications of circular steel tubes.

Slender tubes with high D/t ratios are susceptible to failure by local buckling and are notoriously imperfection sensitive [15, 16, 17]. Design processes must account for the variations in geometric imperfections caused by numerous sources, including those caused by the manufacturing process. Welds are known to be a significant source of geometric imperfections, and spirally welded towers present a welding pattern that differs significantly from conventional towers [18, 19]. The design standard Eurocode 3 enumerates several design procedures to estimate the local buckling strength of circular steel tubes [13]. The procedures are based on

varying levels of sophistication and complexity and consider imperfections differently. Two of these methods are presented here in detail. The first, termed ‘Stress Design,’ is the simplest method and prescribes a conservative, empirically-based knockdown factor on the theoretical buckling stress for a slender shell under pure compression [13, 20]. The magnitude of this factor varies with the magnitude of measured geometric imperfections which are categorized into three categories (A, B and C) that are achieved based on the measurement of three imperfection types (out-of-roundness, dimples and plate misalignment) [21]. This is of particular interest since American design codes (e.g., [8, 22]) do not account for geometric imperfections explicitly, though many efforts exist in work on cylindrical members (e.g., [23, 17]), and design equations do not provide any insight on the interaction of imperfections and local buckling. The Stress Design method also distinguishes between shell strength in compression and bending, though only for long tubes with $D/t < 350$. Both AISC and Det Norske Veritas (DNV) provide design equations specific to the loading cases of axial compression and flexure [8, 24], though many standards for large-scale structures use an allowable axial stress formulation which combines the effects of axial and flexural stress (e.g., [13, 11, 10, 22]). While the Stress Design method includes explicit consideration of imperfection magnitude, it does not provide insight on the interaction of imperfection types as the magnitude of the knockdown factor depends only on the largest measured imperfection [25]. It should be noted that there are multiple approaches that have been proposed for including the effect of imperfections in design, of which the procedure laid out in Eurocode 3 is just one. For a detailed comparison of these other approaches, the reader is referred to [26].

The potential for over-conservatism is an important shortcoming of the Stress Design method. Geometric imperfections are accounted for in the method with a knockdown factor, α , which is

determined based on lower bounds of experimental data taken largely from axial compression tests [25]. The factor also intends to account for any pre-buckling nonlinearity so that it can be combined with the elastic critical stress. The factor is set by the worst-case measured imperfection, and does not vary with load type even though different imperfections can be more severe for different loadings [20]. The European design recommendations for steel shells state that, “the power to perform such [non-linear] analyses has not yet resolved the key questions concerning the relationship between design assumptions and practical construction, and much further research and discussion is needed to address these issues” [27].

Eurocode 3 outlines additional methods beyond Stress Design which allow the calculation of local buckling strength based on application-specific analytical models. Of these additional methods, the most complex and sophisticated is GMNIA (Geometric and Material Nonlinear Analysis with Imperfections), which allows for local buckling strength to be assessed based on nonlinear shell finite element models that include geometric and other imperfections. The code recommends that the first mode buckled shape of the structure should serve as the imperfection pattern (i.e., the Eigenmode-affine pattern) “unless a different unfavorable pattern can be justified” [13]. In addition, the code also advises that “the effect of the chosen geometric imperfections has a sufficiently deleterious effect to give confidence that the lowest resistance has been obtained,” [13]. If the pattern having the most unfavorable effect cannot be identified, then “the analysis should be carried out for a sufficient number of different imperfection patterns, and the worst case should be identified” [13]. When some knowledge is available about specific imperfection types that may be relevant to a given design, the code suggests that modification of the adopted mode of imperfections should be explored to include realistic structural details, such as weld-induced axisymmetric depressions. The code notes that these

geometric imperfections included in the model are, in practice, “equivalent geometric imperfections,” and therefore must account for not only the geometric imperfections in the real structure, but also many other strength-reducing phenomena such as residual stresses, material inhomogeneities and anisotropies, construction detailing and non-ideal boundary conditions. Given the many challenging requirements of this method, many researchers have provided guidance on this method (e.g., [28, 29, 30, 31]), and have shown the situation to be subtle and complex. While the concept of a design based on the GMNIA method is attractive due its customizability, there is some ambiguity in how to reasonably and conservatively include imperfection measurements in the finite element model [29, 32]. Owing to this ambiguity and the insistence of the code to force a detailed, nonlinear, and often time-consuming computational model to provide the worst-possible results, it is a common practice to design wind towers based on the simpler and more conservative “Stress Design” method. Eurocode’s intermediate design methodology, MNA-LBA (materially nonlinear analysis and linear bifurcation analysis) has been used to provide a balance between the simplified Stress Design method and the time-consuming and complex GMNIA method [33]. In the authors’ opinion, the GMNIA design procedure is especially well-suited to the design of wind towers, since a common design is used repeatedly to support multiple turbines in a wind farm, thereby leveraging the returns of designing a more optimized structure.

It should be noted that a new procedure, reference resistance design (RRD) is to be included in forthcoming versions of Eurocode 3. This procedure seeks to use the knowledge gained from a set of pre-computed GMNIA analyses to inform the calculation of several parameters in the Stress Design methodology for specific loadings and geometries [23]. The aim of RRD is to combine the increased accuracy of design by computational analysis with the simplicity of the

Stress Design formulation. In all cases, to ensure safe tower designs, it is important to note that any improvements in tower design that trend toward more optimal (i.e., less conservative) geometries should be considered in the context of the entire design landscape which also depends on accurate load estimation and analytical models of turbine behavior.

3. Experiments

Conventional design equations for the local buckling of slender circular tubes utilize empirically-based knockdown factors that reduce the strength predicted by theoretical equations to account for imperfections. Although more modern design approaches (e.g., GMNIA) allow for computational prediction of buckling strength, codes require that such predictions be compared with experimental results from programs with conditions similar to the application being considered. For these reasons, a review of existing experimental research is an important foundation for the development of a method for designing wind towers made from spirally welded circular tubes. Results from the most relevant tests are presented in Figure 4. The figure was assembled by searching the literature for tests which met the following criteria: static, flexure-dominant loading (either pure flexure or cantilevered bending) of un-pressurized, hollow, circular steel tubes with taper angles less than 5° . In total, 140 tests from 18 studies meeting these criteria were found. The studies are summarized in Table 1 in order of increasing slenderness (with the exception of two studies specific to spirally welded steel, which will be presented separately). Figure 4 shows the ratio of experimental ultimate or peak moment to plastic moment, M_u/M_p , versus tube slenderness, λ^2 . The slenderness plotted for each test in Figure 4 is based on measured values of F_y . Superimposed on Figure 4 are design curves for ultimate flexural capacity from Eurocode 3 for fabrication tolerance quality classes of A, B and

C, assuming the tube is medium length (i.e., the length to diameter ratio is less than $0.18\sqrt{\frac{D}{t}}$, per the definition in Eurocode 3). The figure also includes the flexural local buckling design equation for circular hollow tubes from AISC as well as slenderness boundaries for slender, noncompact and compact sections under flexural loading based on AISC [8]. In all cases, the design curves are for $E = 200$ GPa and $F_y = 345$ MPa and do not include resistance or safety factors and therefore represent expected strengths for sections with actual (as opposed to nominal) yield strength. Tests are distinguished between whether the applied loading is pure bending or cantilevered bending, and whether the specimen was fabricated with spiral welding or other manufacturing methods. Marker size indicates the diameter of each test specimen. Additionally, shaded regions highlight ranges of D/t ratios (for $F_y = 345$ MPa) for conventional wind towers and for spirally welded wind towers.

Table 1: Summary of static flexural testing programs for hollow circular steel tubes with no internal pressurization.

Reference	No. of Tests	D/t	λ^2	Length/D	D [mm]	F_y [MPa]	Loading
<i>Steinmann (1989)</i> [34]	3	42 - 64	0.07 - 0.09	--	168	286 - 387	--
<i>Dimopoulos (2012)</i> [35]	6	100	0.13	6.5	400	270	Cantilever
<i>Poonaya (2009)</i> [36]	6	21 - 43	0.04 - 0.07	--	47 - 75	206 - 354	Simple Bend**
<i>Sherman (1984)</i> [37]	5	24 - 75	0.05 - 0.12	4.0 - 4.5	457 - 610	314 - 401	4-pt Bend
<i>Korol (1978)</i> [38]	10	29 - 80	0.04 - 0.14	1.5-8.0	114 - 508	298 - 376	4-pt Bend
<i>Jirsa (1972)</i> [39]	3	46 - 78	0.08 - 0.15	5.4 - 6.7	273 - 508	343-383	4-pt Bend
<i>Sherman (1976)</i> [40]	7	35 - 111	0.05 - 0.16	--	273	287 - 421	4-pt Bend, Cantilever
<i>Sherman (1987)</i> [41]	21	23 - 90	0.05 - 0.19	3.6 - 10.8	457 - 610	294 - 434	4-pt Bend, Cantilever

<i>Schilling</i> (1965) [42]	10	34 – 137	0.06 – 0.17	--	89 – 125	245 – 394	--
<i>Elchalakani</i> (2002) [43]	12	36 - 122	0.07 - 0.26	3.6 – 6.9	87 -110	365- 412	Simple Bend**
<i>Kiyamaz</i> (2005) [44]	6	46 - 145	0.14 - 0.27	2.3 – 4.8	103 - 220	337 - 602	4-pt Bend
<i>Guo</i> (2013) [45]	13	75 - 300	0.08 - 0.30	4.0 – 7.5	150 - 600	190	4-pt Bend, Cantilever
<i>Jiao</i> (2004) [46]	12	16 - 48	0.10 - 0.31	5.3 – 12.6	32 – 76	1284 - 1398	Simple Bend**, 4-pt Bend
<i>Sim</i> (2014) [47]	1*	333	0.45	11.0	2000	270	Cantilever
<i>Seide</i> (1965) [48]	6	800	1.06 – 1.42	0.5 – 1.0	406	273 – 367	Simple Bend**
<i>Stephens</i> (1982) [49]	2	298 - 444	0.56 – 0.67	1.0	1523 - 1529	306 - 376	4-pt Bend

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-- Information is omitted where uncertain or unavailable from reference

* tapered specimen with taper angle equal to 1°, max D/t reported.

** Simple Bend refers to pure flexure applied through end rotations.

Figure 4: Experimental results for 140 tests from 18 studies (see Table 1 and Table 2) on static, flexural buckling of hollow circular, unstiffened, non-pressurized steel sections. Pure bending tests, represented with hollow circles, include 4-pt bending tests and simple bending tests (the latter is defined as flexure achieved by applying end rotations). All spiral weld tests are loaded in pure bending and are depicted with gray markers. For all tests, marker size is related to specimen diameter through an inverse power relationship of 2.5.

The upper horizontal axis in Figure 4 compares directly to that of Figure 3, and demonstrates the applications, and corresponding D/t ratios (for $F_y = 345$ MPa), for which existing experimental data are most relevant. The comparison shows a lack of test data for slender cross-sections ($\lambda^2 > 0.31$) with only 8% of tests falling within this range (11 tests in total). It should be noted that, as shown in Figure 4, the design equations in AISC provide a maximum slenderness limit above which the equations no longer apply. The limit, $\lambda^2 = 0.45$, corresponds to a slenderness ratio below those common for both conventional and spirally welded steel wind turbine towers. This,

in addition to terminology in AISC limiting the application of these equations only to the circular hollow tubes tabulated in Part 1 of the Steel Construction Manual [8], has prompted a recommended practice published by ASCE and AWEA to recommend removal of this restrictive terminology [10]. Inspection of Figure 4 shows that a majority (76%) of flexural tests of circular steel tubes have considered noncompact sections. Figure 4 includes tests with a wide range of length to diameter ratios (from 0.5 to 32.1; see Table 1) and, therefore, the strength indicated in the figure is influenced to varying degrees by the effects of ovalization [50], which reduces the elastic buckling strength for tubes with large length to diameter ratios [50, 51], such as the tubes used as wind turbine towers. The Eurocode 3 predicted strength is also effected by the length-to-diameter ratio and it should be noted that the design curves shown in Figure 4 are for medium length tubes while wind towers would likely be classified as long tubes, corresponding to a decrease in predicted strength. The Figure also includes a large range in specimen size across tests, with more than 79% of test specimens having a diameter smaller than 500 mm. Size effects are non-negligible in shell buckling problems, and European design recommendations, among others, caution designers against using test data from specimens that are not similar in size and manufacturing method to the final structure when designing large scale structures, stating:

“... care must be exercised when design methods are derived from experimental data (e.g. using a lower bound on test results) where the test specimens have been fabricated in a manner that is different from the full-scale manufacturing process ... The relationship between laboratory geometric imperfections and full-scale imperfections is still an active area of scientific research, and data on imperfections in constructed shells is both rare and highly sought after to assist in improving the reliability of the design method,” [52].

Figure 5 includes photographs from various testing programs as an example of these differences in size. Additionally, not all test programs provide detailed imperfection measurements of the

test specimens; restricting the potential to use this data for the validation of shell finite element models.

(a)

(b)

(c)

Figure 5: Photographs from a sampling of experimental programs depicting the range of specimen size and manufacturing method for (a) tests currently being conducted by the authors ($D \approx 1.0\text{m}$ and tapered), (b) tests by Elchalakani et al. ($D \approx 0.1\text{m}$) [43] and (c) tests by Guo et al. [45] ($D = 0.6\text{m}$).

For design purposes, it is common practice to utilize high-slenderness pure compression tests as a point of reference for critical stress in flexure [53], as there is more test data at high slenderness for pure compression than for bending. This practice is reflected in the Eurocode 3 buckling equations which, as already mentioned, do not distinguish between flexural and compressive loading when $D/t > 350$. Miller reviews axial compression tests in [54], and lists 47 tests for slender ($\lambda^2 > 0.31$), unstiffened specimens; more than 4-times the number of flexural tests for slender members. Historical test data has shown the use of axial test results as a basis for flexural design to be conservative (e.g., [55, 20, 48]). The imperfection-sensitive nature of shell buckling may be somewhat ameliorated in the case of flexure because the tension in the shell serves to anchor any buckling displacements, and a much smaller circumferential segment of the shell is subjected to the highest compressive stresses. These effects together cause the buckling mode to be more localized. To relate flexural data to axial compression data, a multiplicative factor of 1.3 on the axial compression data is commonly suggested in the literature, but other work has shown that not all flexural data are well represented by this method [48] and the value of this factor can vary. In any case, the extent of the conservatism inherent in the use of axial tests has not been firmly established.

Figure 4 includes 17 tests of spirally welded circular tubes from two testing programs. Since the nature of geometric imperfections in spirally welded wind turbine towers is expected to be related to those of spirally welded steel tubes, two test programs specifically on spirally-welded tubes are summarized in Table 2.

Table 2: Summary of flexural testing programs on unpressurized spirally welded tubes.

Reference	No. of Tests	D/t	λ^2	L/D [mm]	Diameter [mm]	F_y [MPa]	Loading
<i>Zimmerman</i> [56]	2	49- 81	0.13 - 0.20	4.2	762	483 - 552	Simple Bend*
<i>Pueppke</i> [57]	15	65- 121	0.14 - 0.29	7.6	1065 - 1071	340 - 570	4-pt Bend

* Simple Bend refers to pure flexure applied through end rotations.

Review of Table 2 shows that none of these tests are wholly applicable to spirally welded wind turbine towers, as the D/t ratios and slenderness are low in comparison to those found in wind turbine towers. Testing by Pueppke and Gresnigt included tubes with D/t ratios up to 120 [58, 57] and with relatively high slenderness values (λ^2 from 0.14 to 0.29 due to the high yield stress). The study included 15 test specimens and incorporated detailed measurements of initial geometric imperfections for each specimen. The measured imperfections were categorized as either weld features or “characteristic humps” that were attributed to rolling of the plates. These characteristic humps were found to be the most likely location of buckling initiation, with 14 of the 15 tests buckling at a characteristic hump and one buckling at a weld feature. For all 15 specimens, the mean measured imperfection was 11% of the thickness of the tube.

Testing by Zimmerman et al. included static flexural tests and considered specimens with D/t ratios of 48 and 82 [56]. Note that while the D/t ratios for these specimens was relatively low, the slenderness range is relatively higher (λ^2 from 0.13 to 0.27), within the AISC range for classification as noncompact, because of the high yield stress.

For both sets of tests, visual inspection of Figure 4 shows that these results (data shown with gray solid fill markers) are consistent with test results for non-spirally welded circular tubes at

similar slenderness as all results fall within the scatter of the other flexural tests plotted in Figure 4.

4. Analyses

The promise of using GMNIA-type analyses to reduce conservatism in the design of wind towers is appealing. However, as mentioned previously, there are many subtleties and complications which pose a barrier to the widespread use of these GMNIA-type analyses. Such analyses require that modeled geometric imperfections somehow account for the effects of actual geometric imperfections, residual stresses, and non-ideal boundary condition effects while attempting to determine the lowest possible strength prediction. In this section, the state-of-the-art relevant to the analytical prediction of the strength of spirally welded wind turbine towers is summarized.

Over the past 15 years, several studies have been published on the imperfection-sensitivity and local buckling behavior of slender tubes (e.g., [28, 59, 30, 60, 29]), including research aiming to provide meaningful guidance on the modeling of imperfections in a way that accurately depicts their influence on the ultimate behavior of the structure. This work is summarized here first for cases relevant to wind towers generally and then more specifically for spirally welded circular steel tubes. There has not been any analytical research published on the specific case of spirally welded wind towers (i.e., towers with large D/t , slight taper, and weld-induced geometric imperfections), so research on structures with similar features will be highlighted.

4.1. Wind towers

For nominally identical geometries, spirally welded wind towers differ most noticeably from conventional can-welded towers in the manufacturing process, and therefore the manufacturing-induced imperfection pattern. Spirally welded towers have two continuous, nearly perpendicular

helical welds (i.e., the spiral seam weld and the cross weld indicated in Figure 1) that cross numerous times along the height of the tower, as explained in more detail in Section 1.

Historically, Eigenmode-affine imperfection patterns have been the most common method, or at least the starting point, for characterizing geometric imperfections in a computational model (e.g., [29, 16, 61, 62]), and they are recommended for GMNIA analysis in Eurocode 3 [13, 20]. The use of buckling mode shaped imperfections began with Koiter's work [61] where it was first shown that even small imperfections, on the order of $0.1t$ (where t is the plate thickness), could lead to large reductions in the buckling strength of thin walled cylinders. This imperfection pattern remains attractive due to its theoretical basis, relative ease of implementation in finite element models, and clear relation to a physical characteristic of the structure. Performing analyses using geometric imperfection patterns that are specifically related to manufacturing may be overlooked in much of the research due to the amount of effort needed to obtain a generalizable set of imperfections that accounts for additional weakening effects beyond geometric imperfections. However, it can be argued that research on the characterization and modeling of manufacturing-related imperfections is more relevant in the case of spirally welded wind towers because similar designs of such structures are expected to be used repeatedly, possibly justifying the additional upfront effort to develop rigorous GMNIA guidelines.

Apart from Eigenmode-affine imperfections, the most common method for introducing imperfections is by consideration of weld-induced imperfections [18]. These weld-related imperfections can be applied as a single cylindrical ring imperfection (e.g., [63, 60, 32, 64, 65]), where imperfections are introduced into the model as a single circumferential ring dent, or the imperfections could follow the pattern of welds in the structure (e.g., [18, 32]). In all cases, imperfections are introduced to mimic measurements of weld-induced imperfections. Numerous

references provide further discussion on the comparison between imperfection types and the nuances of codifying imperfection modelling (e.g., [16, 28, 29]).

Welds are one of the more common and more significant instances of manufacturing-related imperfections [32]. For this reason, the ability to model weld imperfections is an important aspect in the design of spirally welded wind towers. Although little research is available in the literature specific to spirally welded wind towers, there is relevant research motivated by the design of steel silos, which are commonly manufactured by welding together small rectangular plates in a regular brick-like running bond pattern, causing T-shaped weld patterns and having characteristic D/t ratios greater than 1000 (see Figure 1 for a visualization of relevant D/t ranges). The combination of large D/t ratios and patterned weld imperfections makes steel silos an insightful comparison for spirally welded wind turbine towers. Rotter and Teng proposed a shape equation for weld-induced imperfections that was established from a large set of imperfection measurements on steel silos [18, 19, 66]. The equation has two free parameters for a given section geometry: the amplitude of the imperfection (w_0) and the extent of moment continuity at the center of the weld (ζ ; varying between theoretical limits of a hinge, which creates a very sharply pointed imperfection profile, and a fully restrained moment connection, which provides a smoother shape with zero slope at the maximum). In addition to these free parameters, the shape also depends on the half-wavelength (λ_0) of the Eigenmode of the tube, measured in the axial direction. This shape equation has been used by a number of other researchers (e.g., [60, 64, 32, 23]), and is expressed as,

$$w(x) = w_0 \cdot e^{-\frac{nx}{\lambda_0}} \left[\cos\left(\frac{\pi x}{\lambda_0}\right) + \zeta \sin\left(\frac{\pi x}{\lambda_0}\right) \right]$$

Hübner et al. found that this weld imperfection shape equation combined with a GMNIA-type analysis gave similar results to Eurocode 3 design equations [60] for axial compression strength of silos, and Pircher et al. found that all parameters involved in defining the weld imperfection for a given tube geometry (both amplitude and shape) influence the overall strength reduction of wind-loaded cylinders [64]. Berry et al. [65] used this weld shape equation to model circumferential welds and created a model where the amplitude of the weld shape equation was calibrated to measurements of weld imperfections. The buckling strength prediction of the model agreed well with experimental compressive tests on high-slenderness ($\lambda^2 \approx 1$) steel tubes. Recent analytical studies have begun to assess the use of this imperfection shape when designing tubes for flexure [23, 67]. While this work is ongoing, no studies yet have been found validating the efficacy of models with this weld imperfection shape against experimental data.

4.2. Spirally Welded Steel

Recently, researchers have studied methods for analytically modeling the buckling of spirally welded circular tubes [68, 57, 69]. When modeling spirally welded slender shells, both geometric imperfections and residual stresses may follow a helical pattern which presents some modeling complexity in addition to that present for the modeling of slender shells generally. Three relevant studies were found [68, 57, 69] and are summarized below.

Sadowski and Rotter [68] discuss this additional complexity and propose a method for meshing cylindrical finite element models with helical features. The Sadowski and Rotter analysis applies the previously mentioned axisymmetric weld depression shape first proposed by Rotter and Teng

[18]. In this case, the imperfection shape is oriented helically and applied to a thin-walled steel cylinder ($D/t = 2000$) loaded in pure axial compression. The amplitude of the imperfection was varied from 0 to $3t$. In these analyses, local buckles were predicted to have principal direction perpendicular to the weld imperfection, and strength reductions were found to be larger for shallower helical orientations (i.e., for spiral welds that are more circumferential). Additionally, the authors note that failures initiated at or near the boundaries of each specimen for all models since the helical weld imperfection is present at every cross-section of the tube. In general, the amplitude of spiral weld imperfections was found to reduce the buckling strength less than circumferential weld imperfection of the same amplitude.

Pueppke [57] created models of 15 spirally welded steel tubes that were used in experimental bending tests, loaded in flexure, with D/t ratios between 65 and 121. The models in this study had a fine square mesh (as opposed to a helically oriented mesh as presented by Sadowski and Rotter [68]). Imperfections were included in the model following the Eigenmode buckling shape of the perfect tube and scaled based on measurements of real imperfections. Imperfections based on the first 12 mode shapes were applied, in addition to combinations of these, for one particular specimen model, and the worst-case mode shape was applied to all other models. It is worth noting that, in all cases, the first buckling mode shape did not cause the most severe reduction in buckling strength. These analyses include explicit modeling of residual stresses induced by the rolling of the steel plates using a stress distribution from Vasilikis and Karamanos [70]. Residual hoop stresses were modeled with maxima equal to approximately $0.8F_y$, and residual longitudinal stresses were modeled with maxima equal to approximately $0.3F_y$. Both maxima were located at approximately mid-thickness, with the maximum compressive residual stress at approximately $0.4t$ and the maximum tensile residual stress at $0.6t$. Buckling of the experimental specimens was

well predicted by the models, though the buckling shapes in the test were slightly skewed to follow the spiral welds. The authors found that including imperfections had a significant impact on both the critical moment and corresponding curvature as predicted by finite element models. Vasilikis et al. expanded on this work [71], using the validated modelling procedure to carry out an extensive parametric study. This work used an Eigenmode-affine imperfection pattern to validate the models against test data, where the magnitude of the imperfection was taken from measurements of the test specimens. The extended parametric study included the investigation of the effect of a dimple-type imperfection on the strength of the tube. The dimple was introduced by applying a load to the middle of the tube in an initial loading step which is then removed before bending is applied. This imperfection was found to decrease the strength and rotation capacity of the tube. Again, in this study all models were relatively stocky compared to wind towers (imperfection parameter study carried out on a model where $D/t = 67$) [71].

Mahmoud et al. [69] present an alternative modelling protocol for modelling spirally welded thin walled tubes that is preliminary and meant to be expanded to tapered spirally welded tubes in the near future. The study included both square and helically oriented meshes. Parametric studies were carried out covering element type, element aspect ratio, element inclination (likely mirroring helical weld inclination), and element size for the cases of axial compression and pure flexure. The study found that shallow helix angles combined with square meshes (with element size on the order of $0.35\sqrt{Dt}$) can yield satisfactory results. Larger helix angles were more sensitive, requiring smaller element sizes (on the order of $0.071\sqrt{Dt}$). For comparison, the theoretical buckling half-wavelength of a circular hollow steel section in flexure is approximately $1.22\sqrt{Dt}$ [72].

5. Future Research Needs

A review of existing experimental and analytical work on the buckling of spirally welded tubes and wind towers suggests that there are several areas worthy of further research. Current design documentation in the U.S. is prohibitive to the design of spirally welded towers. Structural steel codes in the U.S. currently include language limiting their applicability to circular hollow tubes with D/t ratios significantly lower than those seen in wind tower design [8, 12] and nascent efforts to improve the state-of-the-art in U.S. wind tower design limit their application to can-welded steel towers specifically [10]. Future research into the flexural buckling behavior of steel tubes should assess these restrictions.

Furthermore, current U.S. design standards for the flexural strength of circular tubes do not explicitly consider the magnitude of geometric imperfections. The spiral welding process introduces several types of manufacturing related imperfections into a structural member, including those induced by the rolling and welding of steel. The availability of large D/t ratios in spirally welded circular tubes, in addition to the efficiency of large D/t ratios in flexure, make spirally welded circular tube structures particularly susceptible to local buckling, a behavior highly dependent on geometric imperfections. Future experimental research (e.g., [73, 74]) should improve the understanding of the impact of imperfections on buckling strength to reduce reliance on potentially overly conservative approaches. Additionally, design equations for high slenderness tubes, such as Eurocode 3's Stress Design are based mostly on compressive test data which have been used for flexural loading as a conservative design approach. More tests are needed to assess the extent of this conservatism, especially for slender sections where little flexural data exists.

To improve upon existing design approaches that can be overly conservative, future tests should be designed with eventual GMNIA implementation in mind. The current computational design

procedures are somewhat misguided in that they seek a deterministic, worst-case answer to a fundamentally probabilistic situation. The development of an alternative approach that explicitly considers the probabilistic nature of the problem requires more large scale tests on slender tubes in flexure to validate a GMNIA-type approach and a better understanding of imperfections (both geometric and material) including their stochastic nature and influence on buckling. Protocols governing the use of finite element analyses in imperfection-sensitive cases can then be developed, both generally and in the case of spirally welded slender shells, to ensure realistic modelling.

6. Conclusions

This review has summarized the state-of-the-art in both experimental and analytical research relevant to assessing the local buckling strength for the design of spirally welded wind turbine towers. Existing design documentation in the U.S. [8] and Europe [13] contain language complicating the use of design procedures for spirally welded tapered tubes designed as wind turbine towers. In addition, shortcomings, also present for the design of conventionally-manufactured towers, persist. A literature survey found 140 tests on unpressurized circular steel tubes loaded in flexure. Only 8% of these tests were on circular tubes classified as slender per AISC. This lack of slender test data highlights the current use of compression test data to conservatively estimate flexural strength of slender sections. The extent of the conservatism remains unclear.

Analytical work was also summarized with a focus on the modeling of imperfections to predict buckling strength of circular hollow tubes following a GMNIA-type approach. Complexities in existing codification of computational design methods were discussed, and the most common methods of accounting for imperfections (Eigenmode-affine patterns, circumferential ring dent,

and weld pattern imperfections) were summarized. Difficulties inherent in modelling spiral features were also discussed and ongoing efforts at overcoming these difficulties were summarized.

The applicability of existing design processes and the future implementation of computational modelling in design require more test data at relevant slenderness ratios including detailed measurements of both buckling strength and imperfections. Additional testing should inform the applicability of existing design procedures for this purpose, as well as assess its level of conservatism. With more tests, computational modelling procedures can also be improved and used to better understand the probabilistic nature of the multitude of factors influencing the design of slender tubes.

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