



## **Imperfection Analysis and Optimized Design of Tapered Spirally-welded Wind Turbine Towers**

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### **Abstract**

Current steel wind turbine towers are not designed efficiently because geometric constraints imposed by transportation limits necessitate tower geometries that are non-optimal (i.e. use more material than would be required if there were no geometric constraints). Current towers are typically fabricated into large truncated conical sections at centralized plants and then transported to the wind farm location by truck. Geometric constraints imposed by bridge clearances, among other conditions, limit the maximum diameter of a tower. As wind turbines become larger, wind turbine towers become taller and this transport-based constraint leads to increasingly non-optimal designs. A new manufacturing method based on spiral welding allows for more optimally designed tower geometries because towers can be manufactured on site thereby eliminating transport-based constraints. While spirally welded steel tubes are common in the pipeline industry, where internal and external pressure often control design, they have never been applied for use as a wind turbine tower, where flexure often controls design. Existing, non-optimized wind turbine towers are slender with diameter-to-thickness ratios ( $D/t$ ) up to 300; more optimized towers would have even larger  $D/t$  ratios (~600 for one case study of a hypothetical 120m tower). The local buckling of such slender structures is acutely sensitive to geometric imperfections, and this paper examines the variability and impact of realistic imperfection fields on the design strength of slender steel shells manufactured with spiral welding. U.S. and international design standards are examined to assess their viability in estimating the local buckling design strength of a spirally-welded slender tower.

### **1. Introduction**

The introduction of spirally-welded wind turbine towers has the potential to decrease the cost of wind energy in the United States by lowering transportation and manufacturing costs. This new manufacturing technique results in weld geometries along the tower that have previously not been encountered in wind turbine tower design. For this reason, the application of existing structural design documentation for the preliminary design of spirally-welded wind turbine towers must be investigated. The effect of these weld geometries becomes more critical in light of the slender nature of wind turbine tower designs. Additionally, the reduction of transportation

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barriers provides for the use of larger-than-average  $D/t$  ratios, increasing the sensitivity of the towers to local buckling.

This paper describes a design study focusing on the ability of existing structural design codes to capture the local buckling and fatigue capacity of spirally welded wind turbine towers. First, background information is presented on existing design documentation. Then a brief summary of Eurocode's (ENV 2007) treatment of imperfection sensitivities is given, followed by a description of the methodology used to create a preliminary tower design for a given set of parameters. The results of this small design study are then presented and discussed.

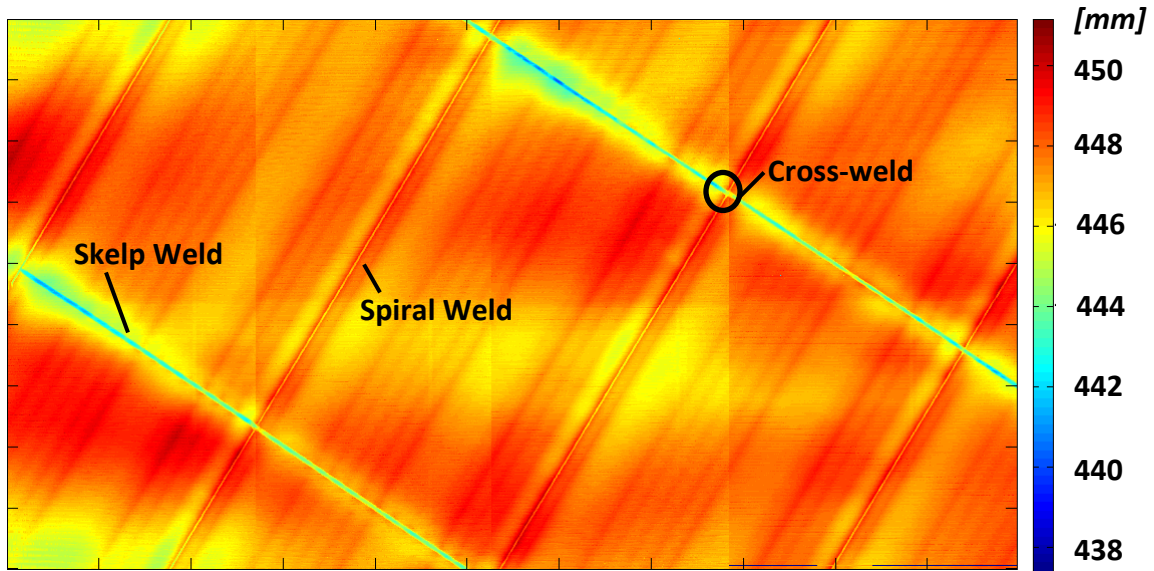
## 2. Background

The existing design documentation and codification environment for wind turbine towers in the U.S. is often ambiguous and poorly understood (Agbayani, 2011, ASCE/AWEA 2011). In addition to lingering questions about applying design codes to existing wind tower structures in the U.S., this particular spirally welded design straddles the application limits of existing codes, necessitating a careful combination of current structural design and welding codes with those governing pipeline manufacturing processes. Figure 1 shows a picture of a prototype of a tower created with spirally welded geometry.



**Figure 1: A small-scale, hand-welded demonstration tower completed with spiral weld geometry [Image courtesy of Keystone Tower Systems].**

Figure 2 shows the pertinent weld geometry details on an un-rolled geometric scan of a prismatic cylindrical section. Figure 2 shows specifically the skelp weld which joins plates of steel end to end, the spiral weld which wraps plates together vertically, and the cross-weld which is a term used to refer to the intersection of the skelp and spiral welds. The pipe that was scanned was manufactured using spiral welding with numerous skelp welds in order to reproduce the cross-weld detail several times along the specimen. While such numerous skelp welds are not normally necessary for prismatic sections, they were specifically added in this case as proof-of-concept for the manufacturability of the cross-weld geometry that is required for tapered specimens.



**Figure 2: Laser geometry scan of a prismatic cylindrical section manufactured to contain pertinent weld geometry. Color gradation shows values of inner pipe radius in *mm*. [Image courtesy of Keystone Tower Systems].**

The consideration of these weld geometries is of particular interest since wind turbine towers are slender shells and highly imperfection sensitive. The effect of imperfections induced by this manufacturing process (mainly associated with pipeline manufacture to this point) must be assessed for both fatigue and local buckling for application as wind turbine towers. In the pipeline industry, skelp welds are kept to a minimum where possible, and loading occurs mostly through internal pressurization. For the case of spirally welded wind turbine towers, there are numerous skelp welds producing cross-welds which align to form a helix along the tower, and these structures will be dominated by flexural loading. The effect of the combination of these differences in load type and weld geometry have yet to be studied.

There is a significant amount of literature addressing the measurement, characterization, and simulation of geometric imperfections and their effect on structural stability that will be integral in moving forward with more complex design methods (e.g. Singer and Abramovich 1995, Pircher and Wheeler 2003). The spiral welding process for tapered towers likely imparts a characteristic imperfection pattern along the tower that will need to be measured and characterized for future guidance in the application of existing design standards and construction of detailed finite element models.

Since Eurocode is the most commonly referenced design code currently available for use in designing wind turbine towers, existing Eurocode fatigue and buckling design methodologies are applied in this study in order to assess any deficiencies and guide future work.

### 3. Methodology

#### 3.1 Eurocode Local Buckling

Eurocode’s basic stress design methodology for designing against local buckling hinges on the assignment of a manufacturing quality class A, B, or C, which is related to imperfection measurements taken from the structure. In order to determine the manufacturing quality class for a given structure, measurements must be taken independently for three imperfection types: dimple imperfections (both weld-induced and plate waviness), cross-section out-of-roundness, and accidental eccentricities (or plate misalignment at welded joints). After measuring each of these three imperfection types, a manufacturing quality class can be assigned for each, with class A corresponding to the smallest level of imperfection and class C corresponding to the largest. The poorest of these individual manufacturing quality classes then controls the entire buckling design of the tower. The limiting values for each quality class in all of the relevant imperfection types are displayed in Table 1.

**Table 1: A review of the limiting values of the buckling-relevant geometric imperfection in Eurocode. Each imperfection type is accompanied by the ratio used to measure its relative severity.  $\Delta w$  is imperfection magnitude and  $l_g$  is gauge length as define in Eurocode.**

	Out-of-Roundness	Accidental Eccentricity	Dimple Imperfections
	$\frac{(d_{max} - d_{min})}{d_{nom}}$	$\frac{e_{accidental}}{t}$	$\frac{\Delta w}{l_g}$
<b>Class A</b>	.007	.140	.006
<b>Class B</b>	.010	.200	.010
<b>Class C</b>	.015	.300	.016

It is worthwhile to note that while Eurocode’s basic stress design methodology is currently used for this study, more in depth methods are permitted. There are several permissible analysis types, each with an increasing level of complexity. Materially nonlinear analysis, or MNA, has been shown to be inaccurate for structures of this type (Gettel 2007). MNA and all subsequent analysis methods laid out in Eurocode include the use of detailed finite element models. With this in mind, the most complex design methodology is termed GMNIA, or geometric and material nonlinear imperfection-included analysis. These methods quickly become quite complex, specifically with the necessary introduction of “equivalent” imperfections, which must account for not only measured initial geometric imperfections, but the additional effects of residual stresses and non-ideal boundary conditions. These more complex models and design methods have great potential for the optimized design of wind turbine towers, but the current study focuses on the assessment of the applicability of basic Eurocode stress design procedures. The more pertinent of the stress design method’s shortcomings include a lack of consideration of local buckling due to flexure, and assumptions that there is no interaction between the relevant imperfection types.

### 3.2 Eurocode Fatigue

Eurocode’s fatigue design hinges on the selection of a fatigue detail category. This detail category corresponds to the full-amplitude stress range, in MPa, that a welded detail can withstand for  $2 \times 10^6$  cycles. This detail category sets the S-N curve for the detail, and the fatigue-relevant design can then be completed. Each detail category may also be modified by a size effect factor,  $k_s$ , that accounts for the effect of weld size and plate eccentricity at the welded joint. It should be noted that mean stress effects on fatigue strength may be ignored for non-stress relieved weld details (ENV 2005, Nussbaumer 2011).

There is no detail category presented in the code that directly corresponds to a spiral-weld or cross-weld detail. For the remainder of this study, detail categories of 71 and 80 are used, corresponding to full-penetration butt-welds both with and without changes in plate thickness at the weld respectively. It is expected that this detail category represents the spiral weld accurately, since it is in effect a full-penetration butt-weld applied in a helical pattern. While the helical pattern places the weld at an angle to applied stress, resulting in both shear and normal stresses at the weld under flexure of the tower, it is expected that this effect will be negligible due to the small angles occurring in practice ( $4\text{-}10^\circ$ ). The use of these detail categories introduces one additional critical assumption; that the cross-weld detail behaves in a similar way under fatigue loading as does the spiral weld. Tests will be needed to assess the validity of this assumption, but it is important to interpret any results with these assumptions in mind.

### 3.3 Current Design Study Methodology

The current study aims to design a tower for the support of a wind turbine rated at approximately 5 MW. The pertinent tower design parameters common to all designs are listed in Table 2. A set of characteristic ultimate and fatigue loads along the tower height were verified using NREL’s FAST wind turbine modelling program (NWTC 2013).

**Table 2: Tower design parameters common to all design iterations.**

<b>Tower Height</b>	<b>120 m</b>
<b>Turbine Power</b>	<b>~ 5 MW</b>
<b>Plate Width</b>	<b>2 m</b>
<b>Top Diameter</b>	<b>3.75 m</b>

Towers were designed for numerous base diameter sizes, and different combinations of manufacturing quality class, detail category, and accidental eccentricities.

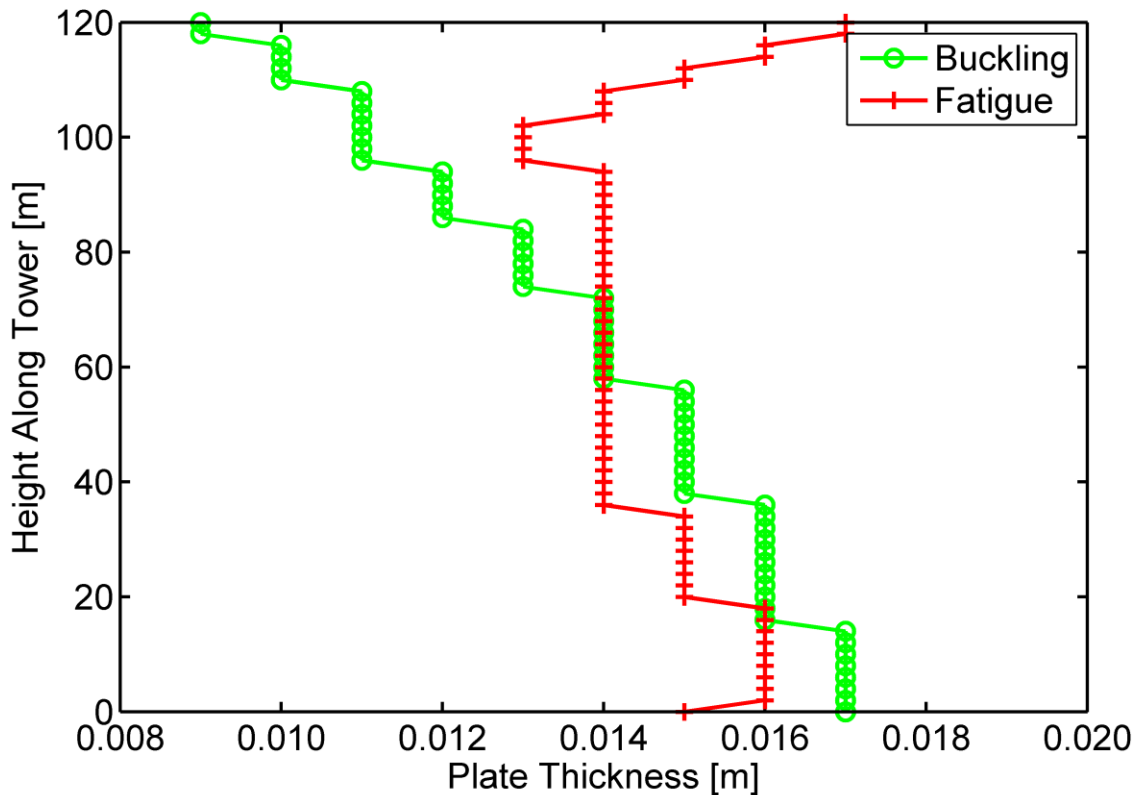
For each set of calculations, the desired manufacturing quality class and representative fatigue detail category was chosen. Then for a given base diameter, the minimum required plate thickness was calculated along the height of the tower to satisfy Eurocode local buckling and fatigue design provisions. This process was then repeated for a range of base diameter sizes.

The design process can then also be repeated for different buckling manufacturing quality classes, fatigue detail categories, and eccentricity effects. These calculations result in tower designs with minimum material weight for the initial given set of parameters. The results focus

on trends in these optimal-weight towers which relate to the initial imperfection-related parameters.

#### 4. Results

Figure 3 shows the design results for a single tower design. The results for each tower include a set of required plate thicknesses along the height for both fatigue and buckling, where the final design thickness would be the larger of the two required thicknesses at each point along the height. It is also interesting to note that the particular case shown in Figure 3 is an example where both fatigue and buckling control the required thickness for different parts of the tower.

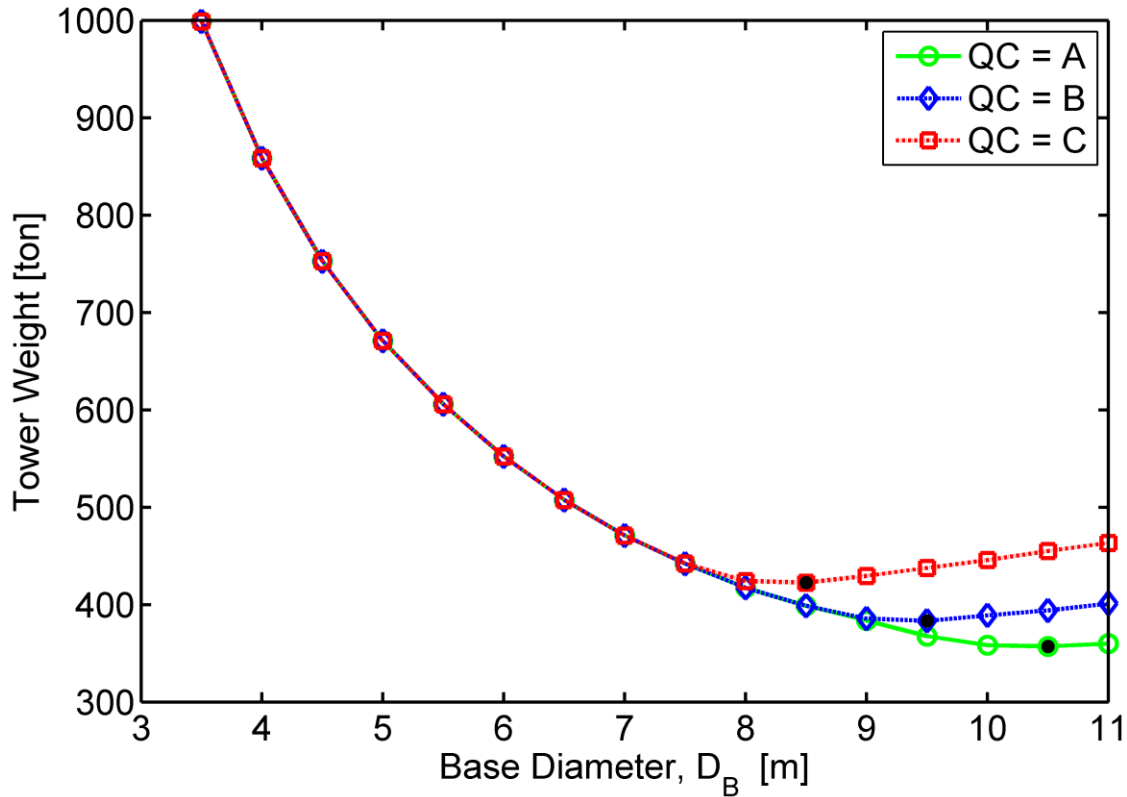


**Figure 3: Design results for the lowest weight tower: Base diameter of 10.5m, quality class A, and a detail category of 71 with no eccentricity.**

With this set of thicknesses, the tower weight can be calculated for each design. Comparing this resulting tower weight from designs completed over a range of base diameters provides a measure of how “optimal” a tower design is at a given base diameter.

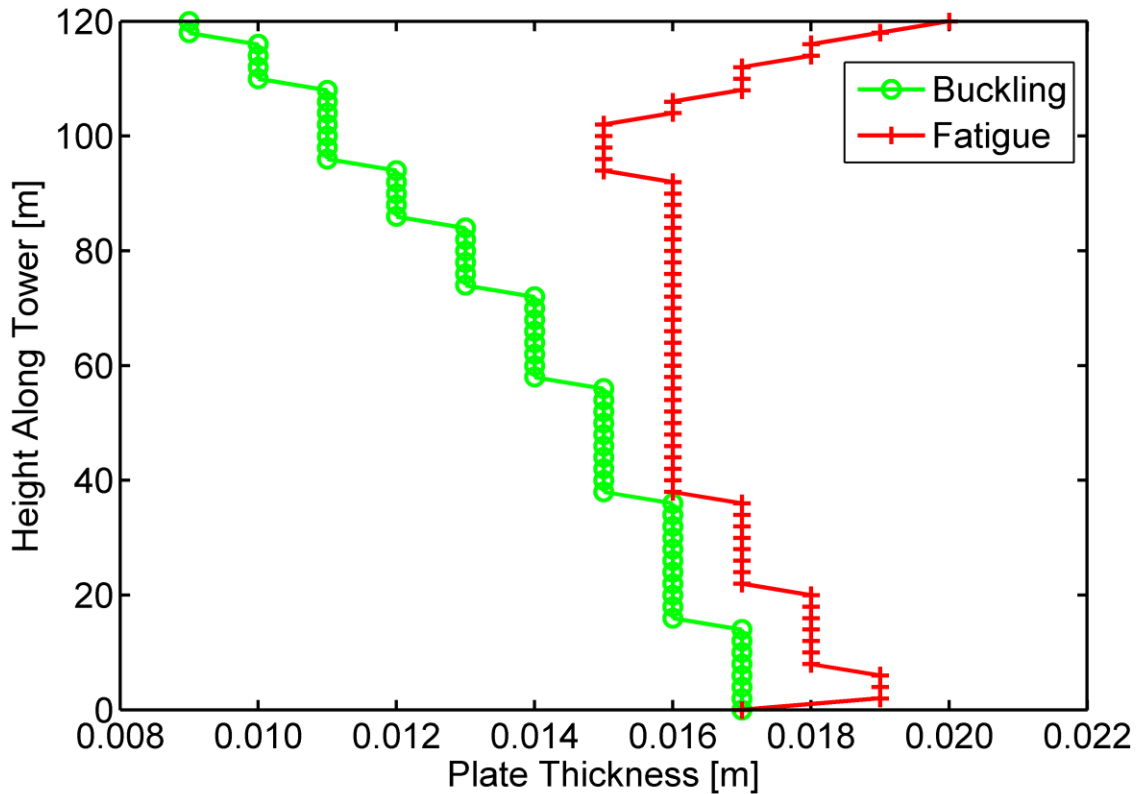
Figure 4 shows the results of the design study for a range of base diameters with fixed fatigue characteristics and varied local buckling manufacturing quality class. As expected, a higher manufacturing quality class yields lower weight, more optimal towers with larger base diameters. For towers with smaller base diameters, fatigue controls the design and therefore no difference is found between the different buckling manufacturing quality classes. This is reasonable, since increasing the base diameter reduces the stress, therefore increasing fatigue capacity. Conversely,

even though the stress is decreasing with larger base diameters, the buckling capacity is also decreasing. Additionally, Figure 4 also shows some of the potential benefit of implementing a manufacturing process that eliminates current transportation limits. The ability to design steel towers with base diameters larger than the currently transportable limit of approximately 4m provides significant material savings, especially for taller towers.



**Figure 4: The effect of buckling manufacturing quality class on optimal tower weights for a fixed fatigue detail category of 71. Filled circles indicate the optimal tower for each manufacturing quality class.**

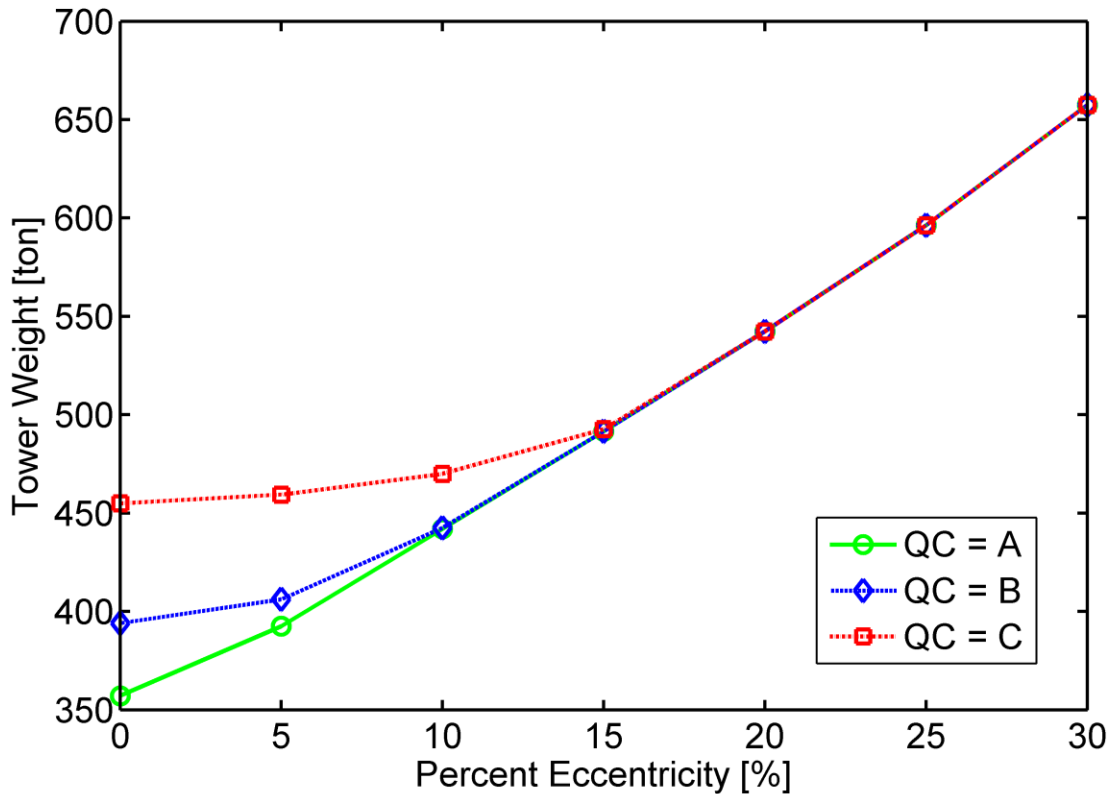
The effect of introducing fatigue-related eccentricity into the design presented in Figure 3 can be seen in Figure 5. Comparing these two figures demonstrates that the introduction of significant accidental eccentricities results in fatigue controlling the design plate thickness over the entire height of the tower.



**Figure 5: Thickness required for buckling and fatigue for a base diameter of 10.5 m, a buckling quality class of A, and a detail category of 71 with 5% eccentricity.**

The results of considering fatigue-related eccentricity for each buckling manufacturing quality class are shown in Figure 6. As expected, increasing eccentricity causes fatigue to control the design, removing any differentiation between buckling manufacturing quality classes. At ten percent eccentricity, there is no longer any distinction between manufacturing quality classes A and B. This transition point is consistent with the transition from A to B of the buckling-related eccentricity measurements.





**Figure 6: The effect of changing fatigue-related percent eccentricity for each buckling manufacturing quality class**

## 5. Conclusions

As expected, this preliminary design study demonstrates that spirally welded wind turbine towers would indeed become more economical as initial geometric imperfections are decreased. Since the most basic Eurocode design methods were used, many more nuanced imperfection sensitivities are lost. The effect of the shape of each weld-induced imperfection has been ignored. Additionally, the interaction between imperfection types has also been ignored. These simplifications, while consistent with Eurocode stress design for buckling, suggest that, while the results may provide a suitable preliminary approximation, more detailed work is needed to ensure an effective final design.

There also remains a lack of knowledge regarding the performance of a cross-weld type detail in fatigue. Since this cross-weld geometry occurs repeatedly along the height of a spirally welded wind turbine tower, it is important that this fatigue behavior be better understood moving forward in the design process. The validity of the results presented in this study rely heavily on the initial assumption that the cross-weld detail can be accurately captured using a detail category of 71. If this is not the case, the results may change significantly. Experimental tests and finite element models are needed to inform future designs.

While in general more detailed modeling and testing of spirally welded wind turbine towers is needed, this simple design study provides insight into the areas of existing design documentation

where support is lacking for the preliminary design of spirally welded wind turbine towers. The study also demonstrates the potential for spirally welded wind turbine towers to provide considerable weight savings when designing large towers. Current stress design buckling methodologies can be applied as written, using measurements taken from the structure. The existing Eurocode fatigue methodology could potentially be used if future testing can provide or verify a detail category for the cross-weld. Alternatively, detailed finite element models could provide for the use of Eurocode's geometric stress fatigue method.

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