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Niobium-Containing Wind Tower Structural Steel Comparison to Conventional Steels and Pre-Stressed Concrete

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Abstract

Wind tower construction growth is projected to continue for the next several decades in both mature and evolving global markets in the quest to reduce carbon emissions and preserve the environment. Many countries embrace wind energy as a sustainable, cost effective and environmentally-friendly green solution. During this decade, designers are increasing the height of wind towers presenting new material and civil engineering challenges. The wind tower end users require better power generation efficiency which requires construction of towers to higher elevations. The materials design choice of microalloyed Niobium-containing value added steel is currently being applied to meet these demands. Over 5 million tons of Niobium-containing wind tower plate steels have been produced to-date globally for these wind tower support structures. The wind tower supply chain demands improved fatigue resistance, better fracture toughness, improved formability, less yield-to-tensile ratio variability and better weldability. The Low Carbon Low Alloy Niobium approach successfully meets these demands and has demonstrated improved fatigue, fracture toughness, low temperature toughness compared to alternative microalloyed structural steels and concrete.

Introduction

The prospects for growth in this market results in its impressive market value of more than USD 19 billion by 2019. Segmentation by type and analysis of the wind tower market is divided into tubular plate steel, concrete, hybrid and steel lattice towers. Market research estimates the tubular steel towers segment to dominate over all the other segments. Growth in this segment is envisaged to be driven by factors like its cost effectiveness and its ability to provide strength to the wind turbine structures, which results in its impressive market share of almost 92% by 2019. [1]

In the past 15 years of wind energy growth, the current trends of the industry have been elevations of 80, 90 and now over 100 meter towers being introduced in China, Europe and North America. Turbines have increased in elevation and size from 2.0MW, 2.5MW, 3.0MW and now increasing to 4.5MW. The dead load of these higher elevation structures are surpassing 2600kN (600kips). Consequently, structural dynamics, frequency response, fatigue and fracture toughness properties of materials and soil-structure interactions become increasingly important. These towers will have to accommodate larger capacity turbines and rotor blades. The amount of energy available to a wind turbine increases at the cube of wind speed. With these industry demands, the designers and fabricators must consider the current market demographics including such issues as budget constraints, alternative materials and supply availability for these higher towers, the necessity for cost-effective design and materials of construction integration. Low carbon niobium-containing structural steel applications are meeting several of the structural demands for improved mechanical properties demanded by architects, civil engineers, designers and fabricators when steel is selected as the material of choice for tower supports.

The fatigue and fracture toughness limitations of traditional higher carbon (exceeding 0.11%C) and V-bearing structural supports initially attracted designers to consider substituting carbon fiber composite and pre-stressed concrete towers for higher elevations. Part of the problem to incorporate such steels was the lack of reliable or no fatigue and fracture toughness data for currently produced high performance low carbon microalloyed structural steels available. Hence, with this situation, the opportunity opened for consideration of carbon fiber composite and high performance reinforced concrete substitution for the standard HSLA S355 (ASTMA572, EN10025, Q345) structural steel supports. It was at this time that CBMM embarked on a project with several steel mill customers to develop a new Niobium-containing steel material design was commercialized to halt the material substitutional threat. [2]

With the proven success of the structural beam technological development and application globally, the Nb-Low Carbon Low Alloy (Nb-LCLA) beam approach was successfully cross-applied and industrially produced as hot rolled windtower plate. Fatigue and fracture toughness data was generated for the Nb-containing steel. Niobium-containing steel provides a viable, cost effective, environmentally-friendly solution compared to alternative materials, such as aluminum or composite graphite or reinforced concrete and keeps the support structure in steel. The cost-benefit and carbon footprint life cycle inventory analysis favors these new Nb-containing structural steel products when compared to alternative structural materials of construction.

Construction Plates for Windtowers

Toughness, fatigue and fracture toughness limitations of traditional higher carbon (>0.11%) structural tower supports moved designers to consider alternative materials such as carbon fiber or high performance reinforced concrete. As a result of this threat of carbon fiber and concrete substitution for the HSLA S355 structural steel supports, a new steel material design was required to halt the threat. With the proven success of the beam applications, the Nb-Low Carbon Low Alloy (Nb-LCLA) as hot rolled product provided a viable, cost effective solution. Table 1 compares the mechanical properties of strength and toughness for low and medium C-Nb or -V for 20mm plate thickness. [2]

Table 1. Mechanical Properties of Low and Medium C Plate

Steel	Orientation	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation in 200mm (%)	CVN@-15°C (Joules)
Low C-Nb	L	436	514	29.7	384
	T	450	521	28.1	371
Med C-Nb	L	439	561	21.9	103
	T	442	569	23.3	42
Med C-Norm	L	384	528	28.3	243
	T	391	530	27.6	132
Low C-V	L	404	492	25.8	390
	T	404	491	23.9	149
Med C-V	L	394	522	24.5	88
	T	393	523	26.1	33

ASTM A572 & A709-50 min requirement		345	448	18	34@ -12°C
EN10025-2 S355 min requirement		345	468-627	20	41@ -20°C

Note the isotropic CVN toughness at 15°C for the low C-Nb compared to the anisotropic toughness behavior of the medium C-V in the transverse direction.

A closer analysis of the upper shelf energy difference between the Nb and V is quite remarkable. A significant difference is exhibited in upper shelf CVN energy performance for the Nb LCLA compared to the low carbon V wind tower constructional plate in both directions. The comparison of low carbon-Nb and low carbon-V wind tower construction plates is illustrated in Figure 1(a) and 4(b). [2,3]

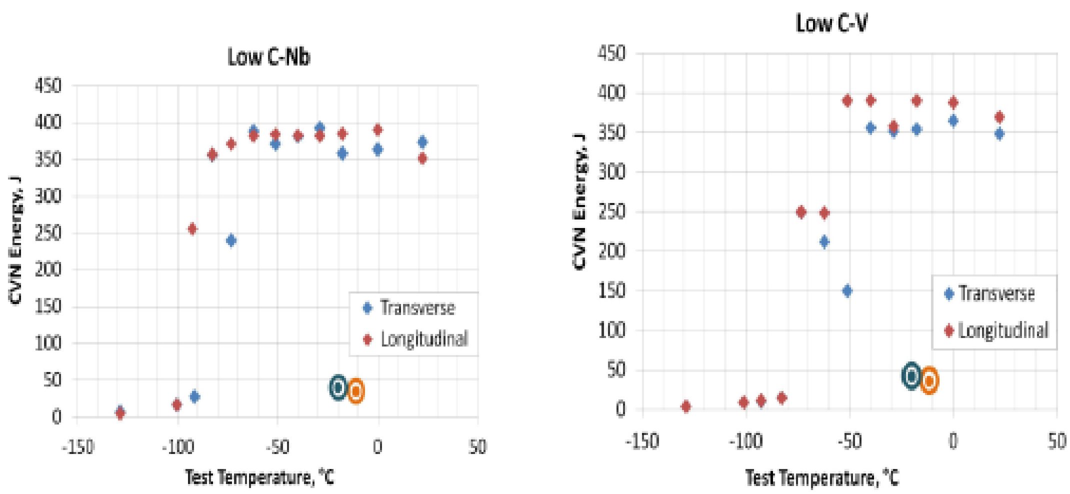

Figure 1. (a) Low C-Nb transverse and longitudinal impact toughness

Figure 1. (b) Low C-V transverse and longitudinal impact toughness

At -65°C test temperature, the CVN energy of the Nb wind tower supports is 400 Joules in both directions compared to V wind tower plate which is only 250J in the longitudinal direction and 200J in the transverse direction. With the Nb-containing microstructure, the isotropic properties are excellent with 400 Joules in both the longitudinal and transverse directions. Based upon the superior isotropic Nb-LCLA, the fatigue and fracture toughness was measured.

Table 2. Fatigue and Fracture Toughness Comparison [2,3]

	Endurance Limit (MPa)	Fracture Toughness (ksi-in$^{-1/2}$)
Low C-Nb	303	375
Med C-Nb	269	235
Med C-Normalized	245	250
Low C-V	245	Invalid test J integral*

* due to anisotropy and microstructure inhomogeneity

The weldability of these low C-Nb plates is significantly improved as well with the move from Zone II for the medium carbon which requires preheating into Zone I which does not require any preheating as shown below in Figure 2.

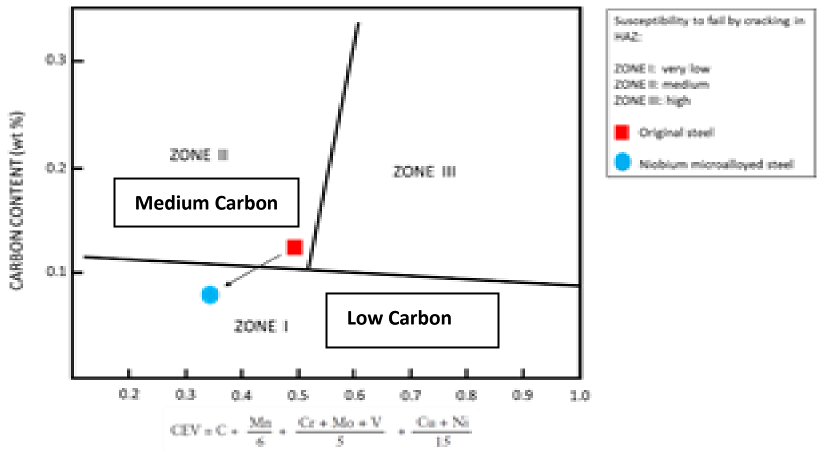

Figure 2. Graville Diagram [2]

Alternative Materials Fatigue Performance Considerations

The threat of alternative wind tower materials that may replace steel is driven by five major reasons: 1) standard higher carbon structural materials are used to compare with alternative materials instead of newly developed low carbon steels; 2) lower fatigue and fracture toughness of higher carbon construction materials may increase probability of tower buckling and leading to gear box failures; 3) geographic centered reluctance to incorporate improved low C-Nb higher strength microalloyed steels due to perceived higher cost; 4) ignoring carbon footprint effects and Life Cycle Assessment(LCA) analysis of candidate material and 5) support plate member width restriction for transport over road due to use of low strength (S275 and S355) instead of Nb-containing S355, S420 and S460) for elevations of 100m or higher.

More data is needed to study the fatigue behavior or reinforced concrete structural members compared to steel support members. For example, in reinforced concrete members, it has been shown that fatigue failure in concrete slab-like members is always induced by the fracture of steel reinforcement bars (rebars). [4] The rebars are significantly more fatigue vulnerable than concrete which shows no or minor local fatigue damaging [5,6]. Therefore, the knowledge on the fatigue behaviour of rebars is of fundamental importance for safety evaluation of RC elements and should also be a high focus of study for reinforced concrete wind towers for comparison purposes.

Concrete Windrowers

A major research effort has been focused on reducing the capital, production, and maintenance costs through the use of taller wind turbine towers. Today's turbines often consist of 262 ft (80 m) steel towers. As taller towers become more desirable, material and transportation costs associated with steel tower designs grow significantly. The increase from 262 ft (80 m) to 328 ft (100 m), allows turbines to access the improved wind conditions that exist at higher elevations. [7] Concrete as a material of construction has played a role recently in consideration of its potential for higher wind towers. The demand generated by the limitations of the current technologies of the steel towers has led to the development of technologies for precast concrete wind towers of high-energy performance that can overcome heights and weights not achievable by steel towers. [7] One of the steel limitations is the lack of incentive for steel mills to promote higher strength wind tower plate materials such as S460. Because of the lack of motivation to increase wind tower structural steels from S355 to S460, there has been a trend in the higher towers exceeding 100 meters towards he use of reinforced concrete. The switch is also being driven by the demographics of the geographic region restricting the maximum transport width of the steel plate for the steel support member to a construction windfarm site.. As towers increase to 100 meters, the lowest tower segment has a larger diameter because it is fabricated from a wider plate. Since concrete is durable, this property of concrete plays an important role if the wind towers are located in remote areas or in areas with aggressive environment like that of a marine environment. This change in size has also imposed very strict conditions for wind turbine components, including steel towers.

A new tower concept has been developed using Ultra-High Performance Concrete (UHPC) and other high strength concrete materials that would allow taller wind turbine towers to be transported to wind farm sites easily within the current transportation limitations. [7] However, by utilizing different combinations of these materials, each design offers unique benefits related to costs, tower weight, connection design, etc. The use of concrete as the primary material for large-scale wind turbine towers is a relatively new concept that has come about as a result of the hub height elevations currently being targeted by turbine manufacturers for the potential economic benefits. To this day, nearly all erected utility-scale turbines use steel towers. These towers are transported to site in three segments, where they are then bolted together.

Niobium-Microalloyed Steel Solution to Transport Plate Width Restrictions

As tower heights increase, the steel segment making up the bottom of the tower reaches a limit at which it is no longer feasible to transport on the highway system due to width restrictions. The maximum allowable tower base diameter corresponds to a 262 ft (80 m) tall tower, which makes up a majority of the newly constructed turbines today. However, there is a steel solution. If higher strength Nb microalloyed plate were incorporated into the 100m design, it may be possible to meet the diameter restriction for the tower base. Also, there exists the possibility to move to a four segment, instead of the current three segment design. The challenges associated with further dividing steel segments have opened the door for concrete solutions to begin taking hold. These concrete designs are addressed for the 100 m limitations currently facing steel towers. If steel producers and designers consider upgrading towers from the current S275 and S355 grades to some combination of S355, S420 and/or S460Mpa design, the lower segment transport plate width restriction is no longer a problem. Also, the known fatigue and fracture toughness performance is well established in lower elevation towers constructed of Nb-microalloyed steel towers.

Life Cycle Inventory Analysis

A life cycle inventory analysis of steel and steel-reinforced concrete construction finds that for the initial equivalent designs for a particular location, the materials design with the lower environmental effect depends on the life cycle assessment (LCA) calculation methodology and assumptions. The expected design life comparison does indicate that recycle and the beneficial reuse of steel towers may result in lower annualized environmental effects. One material might be recommended over the other due to engineering, aesthetic and/or economic criteria, regardless of overall environmental effects. [8] The traditional criteria for a particular design include specific engineering requirements, initial and life cycle costs, experience with and availability of a particular material or technology, aesthetics, and the ability to erect the structure under local environmental conditions (climate, topography, transportation logistics, etc.). With a steel and steel-reinforced concrete comparison, the environmental implications of a particular wind tower material, fabrication and design requires study on a case-by-case basis.

Factors often ignored in the LCA involve dust emissions, water usage, nonhazardous solid waste generation and disposal, generation and disposal of hazardous waste by type, environmental effects of landfills, noise and vibration, and visual impacts. If these (and other) environmental effects would have been included, assessment results change dramatically yielding different conclusions. [8] Often, the data used in such a wind tower analysis analysis have large uncertainties associated with them, and they reflect past economic and environmental performance. Therefore, a similar assessment using different designs and baseline years may yield different conclusions. Wind towers should be built from the material that has comparably the lowest environmental burdens and safest performance. Although not prudent, in particular applications, however, engineering, aesthetic, or economic criteria might incorrectly outweigh the environmental factor.

Conclusions

The application of Low C-Nb wind tower plate is well established and offers enhanced fatigue and fracture toughness properties and isotropic low temperature toughness behaviour compared to alternative materials. Consideration of alternative materials, such as concrete, composite graphite, aluminium, etc. has been compared in many cases to outdated medium carbon structural plate materials. The materials engineering and LCA design should compare the most current high quality steel materials with alternatives for wind towers to ascertain the correct assessment.

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