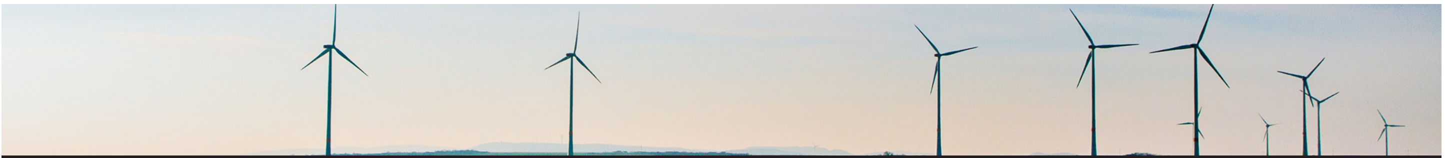
S2C Wind Turbine Tower: 200m Concrete Tower Using Climbing Formwork

May 2016



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1 INTRODUCTION

A new design of wind tower based on cast-in-place concrete techniques has been developed, through an innovative geometrical configuration that enables the reduction of costs and a shorter construction period, and which provides similar mechanical properties to the traditional truncated cone design. S2C Tower, developed by INGECID [1], is a competitive tower solution that enables wind turbines to maximize the output power by accessing stronger and steadier winds, whilst minimizing costs and amortization time of installations.

1.1 WIND ENERGY MARKET

The world market for wind power is booming like never before. The main markets are China – with an astonishing growth of more than 10 GW within six months – USA, Germany and India. Brazil showed the highest growth rate of all major markets, the country has increased its wind power capacity by 14 % since the beginning of 2015 [2].

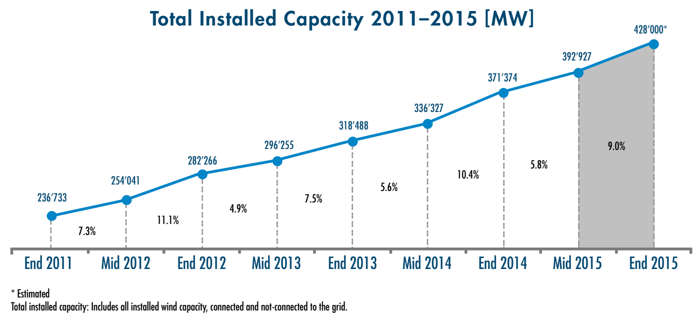


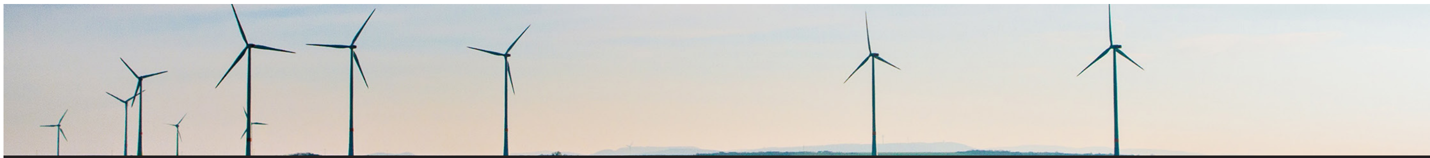
Figure 1 – Total installed capacity 2011-2015 [2].

1.2 WIND TURBINE TOWERS

In today's wind energy market, there is a rising demand for both improved efficiency and power output from wind turbines, thereby reducing the cost per unit of wind energy. Among other alternatives it has been shown that taller towers with elevated hub heights will have access to higher wind speeds and steadier less turbulent wind conditions, both of which will increase the wind energy harvesting time and the total wind-energy production. Studies have suggested that each increase of the hub height by 20 m can increase wind energy production by about 10%.

The construction of wind towers has experienced a continuous evolution since their origin. Depending on the specific conditions, different forms and materials have been used to minimize costs and increase strength: from trussed towers to tubular steel towers, or towers with a mast under tension from guy wires or hybrid solutions that combine different materials, principally prefabricated concrete and steel.

The wind power industry today is characterized by growth-not only growth in cumulative installed capacity, but also growth in turbine power ratings and rotor sizes. Recently, increasing energy capture through the use of larger, lower-specific-power rotors has been a primary factor enabling reductions in wind turbine cost of energy [3].



The consequence of these increasingly taller developments is the necessity to increase the structural strength and rigidity of the tower, which must support the weight of the turbine and the flexion forces under wind action in the tower and rotor, while providing an efficient dynamic response and avoiding resonance, induced by frequencies of vibration generated by the rotation of the sails. However, the necessary requirement of greater diameters and thicknesses in the transverse section of the tower introduces significant problems in transport and manufacture [4].

According to [5], the increase in height of wind towers implies rethinking existing solutions taking into account the need for transportation of larger prefabricated segments and the complex processes associated with assembling and welding them on site. According to [6], steel towers of over 90 m are very difficult to manufacture. For taller structures, the problems and transport costs are multiplied, and their structural restrictions lead to an important increase in the final cost of the wind turbine.

1.3 PURPOSE OF THE NEW DESIGN

The tower is an essential component of a wind turbine assembly with a cost amounting to approximately 30% of the overall turbine costs for onshore installations [7]. The manufacture of increasingly tall wind towers is becoming more necessary so they can support more powerful wind turbines.

Although there are prefabricated, reinforced concrete towers, the use of this material for cast-in-place construction of wind towers is still at an experimental stage, requiring the development of new designs that facilitate the reduction of costs and the shortening of the installation period of onshore towers.

The optimal cross-section, for aerodynamic and structural reasons, would be as close to a circular shape as possible [8]. Therefore, the common solution is a truncated conical form. Nevertheless, the in situ construction of a truncated conical concrete tower implies every section is different because of its constant radius variation, so there are two options:

- The formwork incorporates a compensating system in each section of concrete to reduce both the section and the radius of curvature.
- The use of a new formwork with smaller radius for each section of concrete.

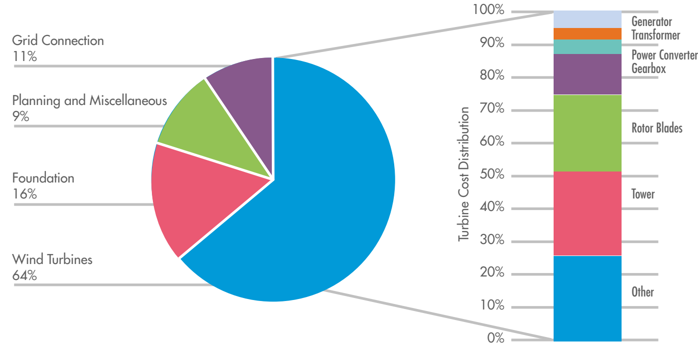


Figure 2 – Capital cost breakdown for a typical onshore wind power system and turbine

Both options make the construction process slower and more complicated and inefficient. One way to optimize the process is through the design of a geometry that enables the cost of formwork and the related tasks to be minimized.

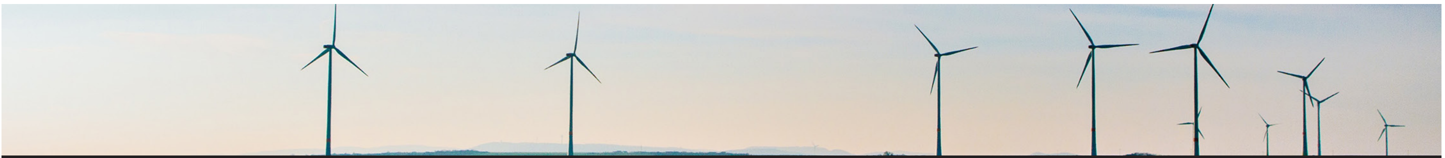
The proposed geometry consists of a square section with rounded corners at the base of the tower and a circular section at the top of the tower. The transition between both sections is achieved by reducing the straight part of the formwork and keeping a constant curvature for the corners. In this case, the S2C Tower has been designed to reach a hub height of 200 m with a 5 MW wind turbine. The tower is divided in two parts:

- Concrete from the base to 196 m. Concrete thickness has a constant value of 0.4 m from 0 m to 194 m. The last two concrete meters have a thickness value of 0.8 m. The aim of this preliminary design of the tower top is to allow the installation of the posttensioning anchorages and the steel connection piece.
- Steel connection piece of 2 m, from 196 to 198 m.

1.4 ADVANTAGES OF IN-SITU CONCRETE TOWERS

Steel tower designs above 120 m have questionable viability since is extremely costly to meet the performance requirements in terms of manufacturing costs and cost of transportation. Apart of in situ concrete construction, the actual alternatives for great height wind turbine towers are prefabricated concrete towers. The main advantages of in situ concrete towers over prefabricated concrete towers are described below:

- The total weight is greater with respect to the prefabricated solutions which have lower thickness. This means that the necessary post-tensioning and the foundation dimensions are reduced in case of in situ concrete towers.



- Considering the effects of tension stiffening, it is possible to reduce the post-tensioning needed or even eliminate it by increasing the passive reinforcement. In case of prefabricated concrete towers, it is always needed to count with certain amount of post-tensioning due to the existence of joints.
- No joints with compromised fatigue resistance.
- No associated costs due to transport of large prefabricated tower sections.
- Less costs of cranes for erection since there is no need of lifting large prefabricated tower sections.
- No need of nearby associated prefabrication plants neither on-site mechanizing. Even though in situ concrete towers need nearby concreting plants or on-site concreting plants, concrete supply is assured since it is needed for the foundations of any type of wind turbine tower.

2 STRUCTURAL DESIGN

2.1 BASIC ASSUMPTIONS

2.1.1 WIND TURBINE

In 2009, the National Renewable Energy Laboratory (NREL, USA) developed the specifications of a representative utility-scale multi-megawatt turbine known as the "NREL offshore 5-MW baseline wind turbine". This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. The gross properties chosen for the NREL 5-MW Baseline Wind Turbine are included in the table below. The wind turbine characteristics considered for the onshore 5 MW S2C Tower with hub height of 200 m are based on the NREL 5-MW Baseline Wind Turbine. They are included in the Tables 1 and 2.

Table 1 – Properties considered for the onshore 5 MW S2C Tower with hub height of 200 m

Hub height	200 m
Rotor diameter	126 m
Rotor mass	110.000 kg
Nacelle mass	240.000 kg
Blade clearance diameter	6 m
Blade clearance height	137 m

Table 2 – Gross properties chosen for the NREL 5-MW Baseline Wind Turbine

Control	Variable speed, collective pitch
Coordinate location of overall CM	(-0.2 m, 0.0 m, 64.0 m)
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Drivetrain	High speed, multiple-stage gearbox
Hub height	90 m
Nacelle mass	240.000 kg
Overhang, shaft tilt, precone	5 m, 5°, 2.5°
Rated tip speed	80 m/s
Rating	5 MW
Rotor, hub diameter	126 m, 3 m
Rotor mass	110.000 kg
Rotor orientation, configuration	Upwind, 3 blades
Tower mass	347,460 kg

2.1.2 FEM MODEL

- The structural model of the tower is a cantilever beam built from tapered sections.
- The tower is cantilevered to the ground. This boundary is represented by a point spring support with infinite stiffness in X, Y and Z direction. The rotational stiffness depends on the foundation characteristics. The foundation shall be designed to obtain a rotational stiffness between 3E+11 and 4E+11 Nm/rad since these are the values considered in this study.
- The nacelle and rotor mass is concentrated at its free end and is rigidly attached to the tower top.

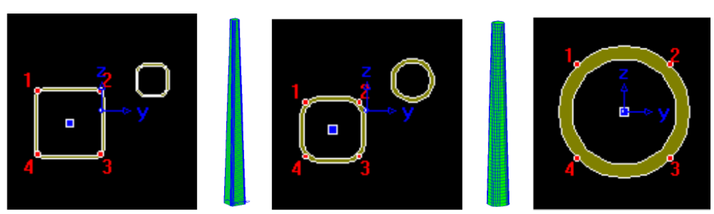
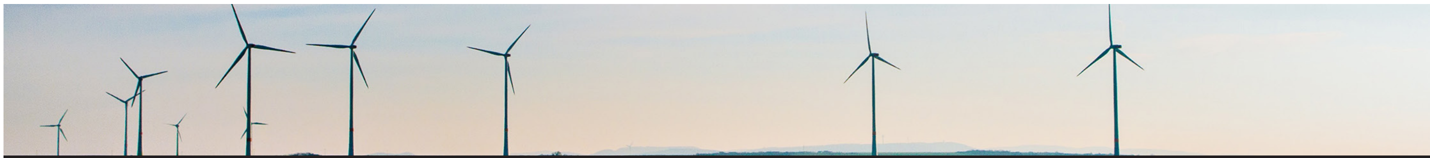


Figure 3 – 200 m S2C Tower FEM model screenshots



2.1.3 LOADS

The loads considered are:

- Gravitational and inertial loads such as self-weight of the tower or wind turbine generator.

Table 3 – Gravitational and inertial loads	
Nacelle	2,352 kN
Rotor	1,078 kN
Extra load on top	100 kN
Concrete weight density	25 kN/m3
Steel weight density	76.98 kN/m3
TOTAL SELF-WEIGHT	53,510.7 kN

- Aerodynamic loads resulting from the flow of the air. These loads are calculated according to IEC 61400-1 Wind turbines – Part 1: Design requirements.
  - Service wind loads are based on "6.3.1. Normal wind conditions".
  - Extreme wind loads are based on "6.3.2. Extreme wind conditions".
- Loads caused by the operation of the wind turbine. The extreme loads are obtained from Appendix F, Section F.1 Land-Based Wind Turbine Loads of [12]. The extreme tower top loads correspond to "Extreme events for Yaw Bearing". The operational loads (quasi-permanent, frequent and characteristic loads) are estimated from the extreme loads considered.

2.2 PRELIMINARY GEOMETRY DESIGN

There are some geometric characteristics that are imposed from the beginning, i.e. top section diameter, blade clearance maximum diameter and the hub height.

Table 4 – Gravitational and inertial loads	
Top diameter	3.87 m
Blade clearance diameter	6 m
Blade clearance height	137 m

It is important to assess the dynamic interaction between the wind turbine and its supporting structure. If the operating frequency of the wind turbine is close to one of the natural frequencies of the structure the operation of the wind turbine may lead to structural damage or failure. This is the first criterion employed for the geometry design.

According to Figure 6 the frequency range considered to be appropriate for the tower 1st and 2nd frequency is:

- f < 0,1 Hz
- f = 0,2 Hz – 0,24 Hz
- f > 0,6 Hz

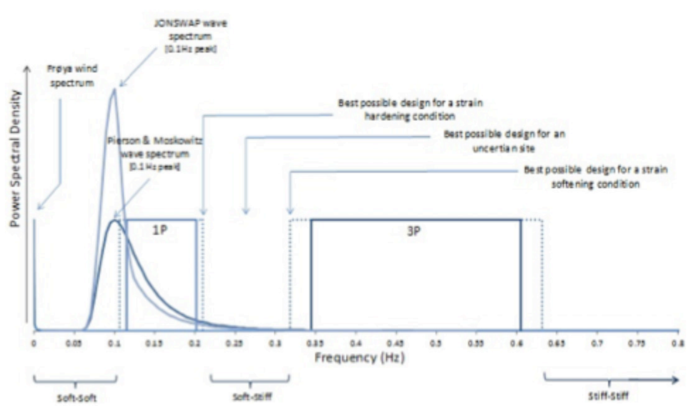


Figure 4 – Forcing frequencies plotted against the power spectral densities for a 3 bladed NREL standard 5 MW wind turbine. 3P stands for blade passing frequency [9].

The first alternative studied corresponds to a base diameter of 11 m, with constant slope. However, the first frequency for this alternative is between 0.1 and 0.2 Hz, so it has to be rejected. The following iteration consists of increasing the base diameter to 14 m. Because of the blade clearance condition, it is necessary to vary the tower slope.

Table 5– First alternative studied

1st section (0 m – 137 m)		2nd section (137 m – 194 m)		3rd section (194 m – 196 m)	
Base diameter	14 m	Base diameter	6 m	Base diameter	3.94 m
Top diameter	6 m	Top diameter	3.94 m	Top diameter	3.87 m
Thickness	0.4 m	Thickness	0.4 m	Thickness	0.8 m

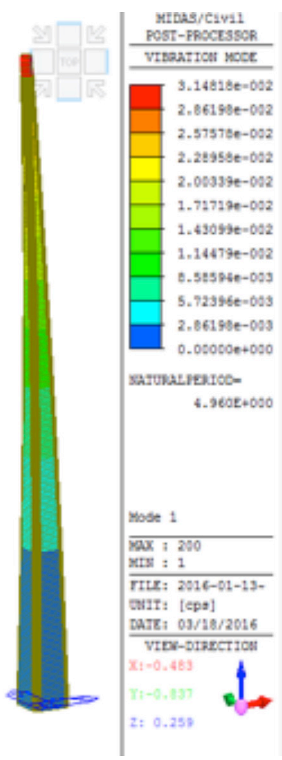
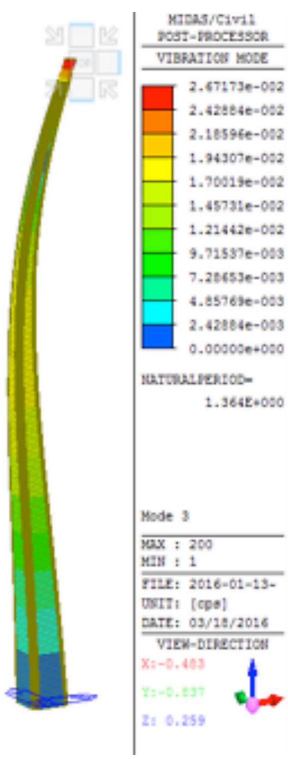
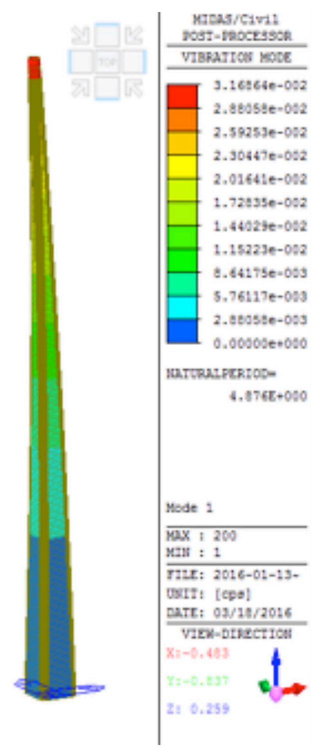
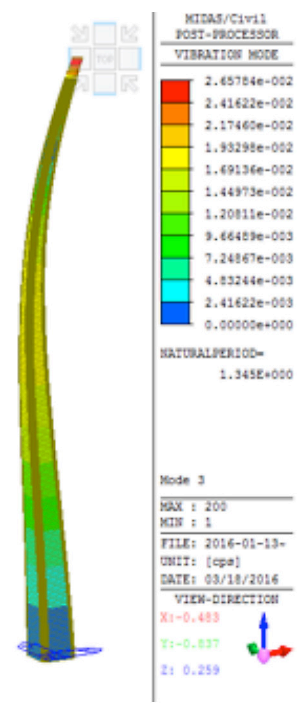
In this case the results obtained are widely within the established frequency range, so the next step is to optimise this alternative adjusting the geometry to the frequency range limits. The preliminary geometry solution consists of a tower with a base diameter of 12.5 m, and the following geometrical definition.

Table 6 – Second alternative studied

1st section (0 m – 137 m)		2nd section (137 m – 194 m)		3rd section (194 m – 196 m)	
Base diameter	12.5 m	Base diameter	6 m	Base diameter	3.94 m
Top diameter	6 m	Top diameter	3.94 m	Top diameter	3.87 m
Thickness	0.4 m	Thickness	0.4 m	Thickness	0.8 m

The dynamic analysis of this tower depending on the concrete type and the rotational stiffness of the foundation is summarized in Tables 6 and 7.

Table 6 – Natural frequencies analysis (C35/45)

Concrete C35/45 **Rotational stiffness:** 3.5E+11 Nm/rad		**Concrete C35/45** **Rotational stiffness:** 4.0E+11 Nm/rad	
1st mode	2nd mode	1st mode	2nd mode
0.202 Hz	0.733 Hz	0.205 Hz	0.743 Hz
			

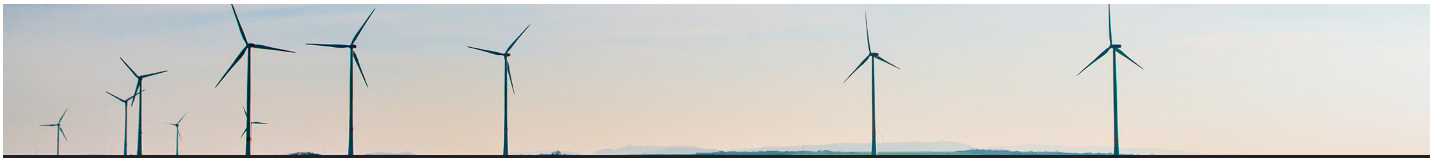
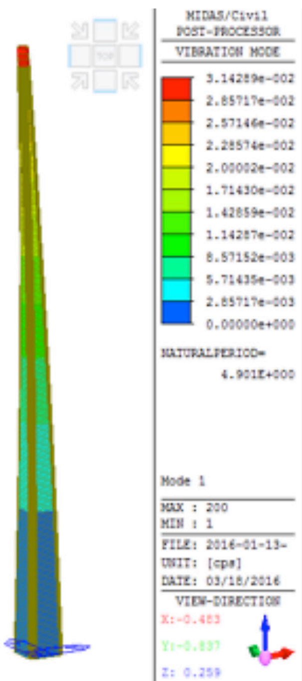
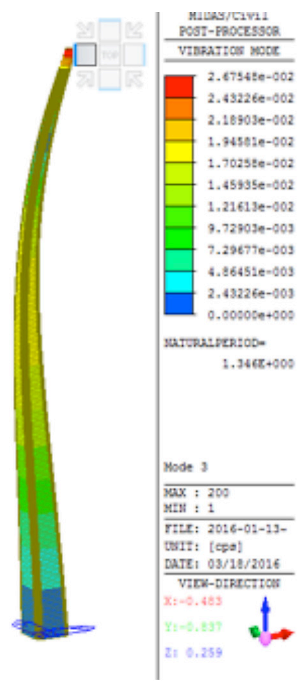
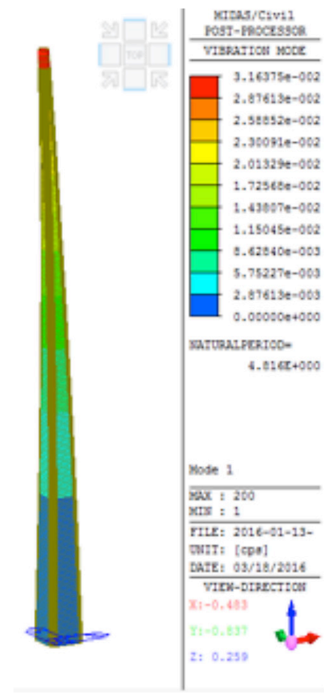
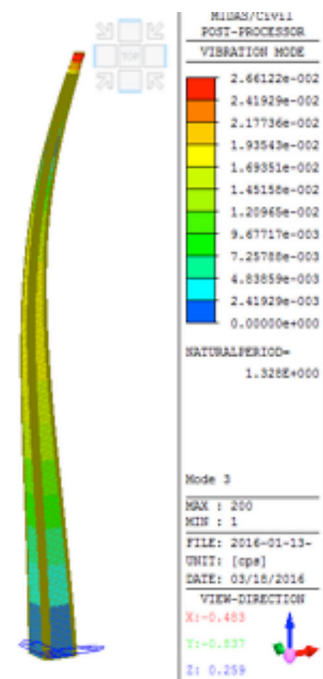


Table 7 – Natural frequencies analysis (C40/50)

Concrete C40/50 **Rotational stiffness:** 3.5E+11 Nm/rad		**Concrete C40/50** **Rotational stiffness:** 4.0E+11 Nm/rad	
1st mode	2nd mode	1st mode	2nd mode
0.204 Hz	0.743 Hz	0.208 Hz	0.753 Hz
			

2.3 VERIFICATIONS

2.3.1 POSTENSIONING

According to [9], for components of prestressed concrete the verification of decompression shall be provided for the quasi-permanent combination of actions. The necessary posttensioning force to achieve the verification of decompression is 57,500 kN.

2.3.2 NATURAL FREQUENCIES

In accordance with [9] for towers of reinforced and prestressed concrete, load-dependent stiffness reduction due to cracking shall be taken into account for the calculation of the natural frequencies of the tower.

However, this verification can be omitted for the calculation of the natural frequencies when decompression is verified for the quasi-permanent combination of actions. This means that the natural frequencies obtained are those included in section 3.2, which corresponds to the gross stiffness of the tower.

2.3.3 TIP DISPLACEMENT

The tip displacement obtained for the considered service loads corresponding to a 1% of probability of exceedance is 1.029 m. The maximum tip displacement which is obtained with the extreme loads is 2.263 m.

2.3.4 FATIGUE

According to [11], fatigue design must ensure that any fatigue-endangered cross-section, the expected damage D will not exceed a limiting damage Dlim. Since it is not possible to estimate the fatigue loads without more information, the maximum equivalent fatigue loads for the tower are calculated. The following table shows the maximum fatigue load for each section considering 107 cycles. Two different types of concrete are considered: C35/45 and C40/50.

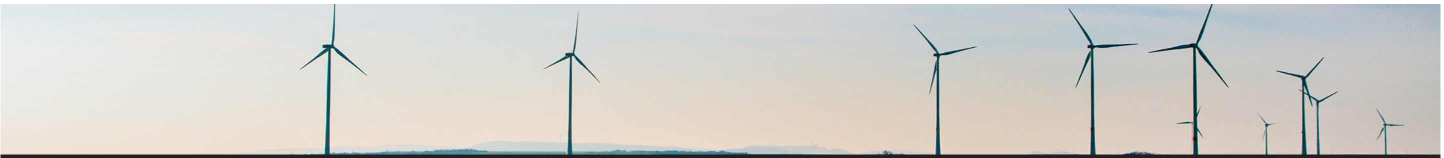


Table 8 – Maximum fatigue equivalent loads per section (N=107)

h (m)	MMC10,C35 (kNm)	MMC10,C40 (kNm)
0	450,000	505,000
72	210,000	250,000
96	150,000	180,000
137	65,000	80,000
194	10,000	15,000

2.3.5 PASSIVE REINFORCEMENT

Passive reinforcement is calculated in accordance with [13]. Vertical passive reinforcement consists of 20 mm diameter bars separated 15 cm and homogeneously distributed along the outer and inner perimeter with a concrete cover of 6 cm.

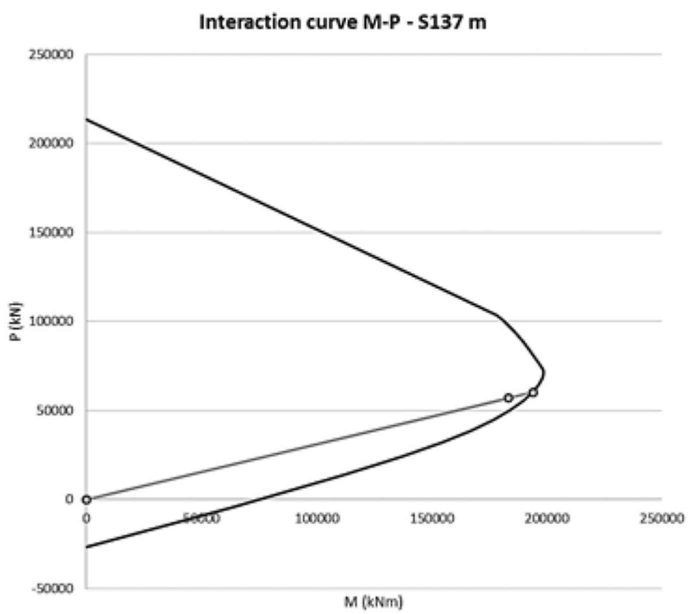


Figure 5 – Interaction curve M-P for section h=137 m, ELU verification

The following graph represents the interaction curve M-P for the most unfavourable section (137 m). This curve shows that for this section the checking ratio is 0.945, being 1 the upper limit of this ratio.

Necessary shear reinforcement corresponds to the minimum quantity defined in Eurocode 2, which means 12 mm diameter bars separated 200 mm. Stirrups consist of 8 mm diameter bars which confines vertical reinforcement bars.

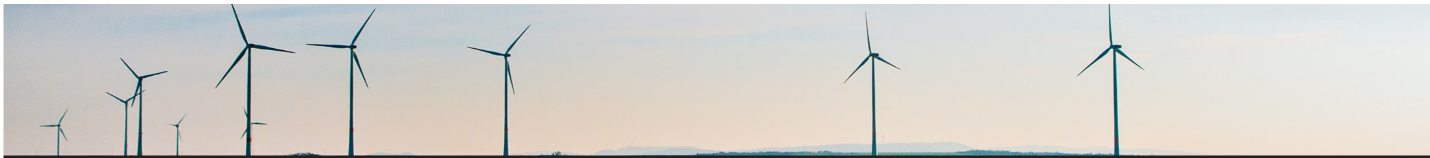
3. CONSTRUCTION PROCESS

3.1 DESCRIPTION

The main advantage of the S2C tower geometry is that it allows the use of a climbing formwork system for its construction. This type of construction system is commonly used in vertical walls and high concrete structures, since it allows the repetitive use of the same formwork for identical or very similar sections.

Figure 6 – Climbing formwork elements

Climbing formwork system requires that the formwork stands in the previous layers of concrete so a new layer can be casted and poured. This process is repeated in successive pouring lifts. The S2C tower geometry allows the reduction of the successive sections by performing simple operations on the formwork panels. This reduces significantly the time and consequently the costs of the tower construction.



Climbing formworks for vertical walls or towers are composed of inner and outer panels, in order to get a hollow section. Outer panels rest on the outer climbing console, and have two working platforms fixed - outer middle platform and outer pouring platform. Inner panels rest on the inner climbing platform. The inner pouring platform is located above it, and the trailing platform is hanging below it. For the particular case of S2C tower, the formwork is adjusted in each lift, by the removal of a piece of each panel. Pieces are removed on the straight part of the formwork, until the cross-section becomes a circular section.

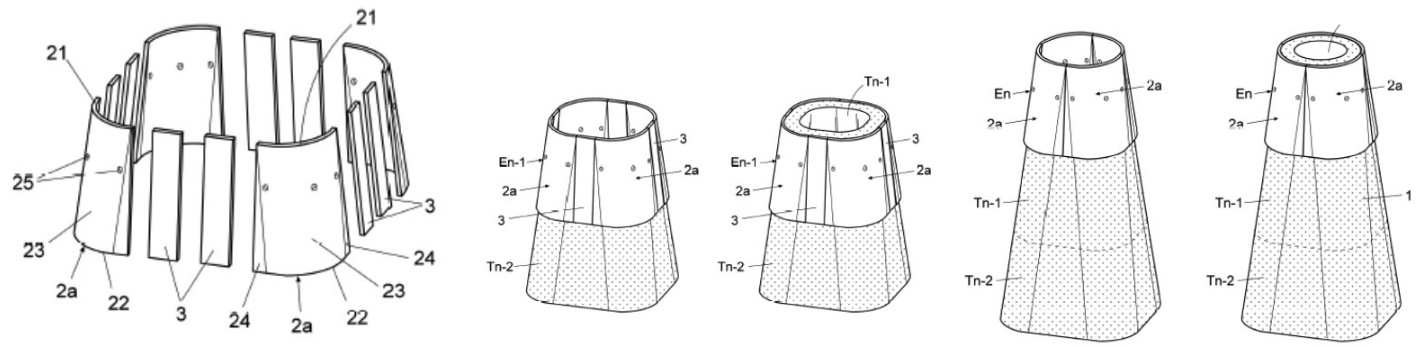


Figure 7 – S2C climbing formwork

3.2 LIFT CYCLE

The main operations to perform a single lift are: formworks stripping off, formworks preassembly, platforms climbing, formwork and rebar cage installation and concrete pouring. Simultaneously, preassembly of steel reinforcement cage will be performed on the ground, using an assembly mould.

The operations are restricted to wind speeds lower than 15 m/s, in order to ensure that operations are carried out in safe conditions. Additionally, the start of the climbing cycle is conditioned to achieve the required concrete strength in the previous lift (10 MPa).

The cycle begins therefore with the inner formwork stripping off, starting with the inner pouring platform, and followed by inner panels.

The geometry of the inner climbing platform is adjusted and lifted, together with the trailing platform, to the new position. Once it is installed, outer formwork panels are stripped off and laid on the ground. Each of the four parts of the outer climbing consoles are hoisted, and the geometry is adjusted when necessary.

Therefore, all the panels are laid down on the ground, where they are cleaned up and adjusted for the new lift. The panels are modified by means of removal of the pieces on the straight part of the formwork, to reduce the cross-section. The rounded corners remain constant for all lifts.

The inner panels are pre-assembled on the ground, and the pouring platform is installed. The inner formwork is hoisted and positioned on top of the tower. Then, the rebar cage, pre-assembled on the ground, is hoisted and placed outside the inner formwork.

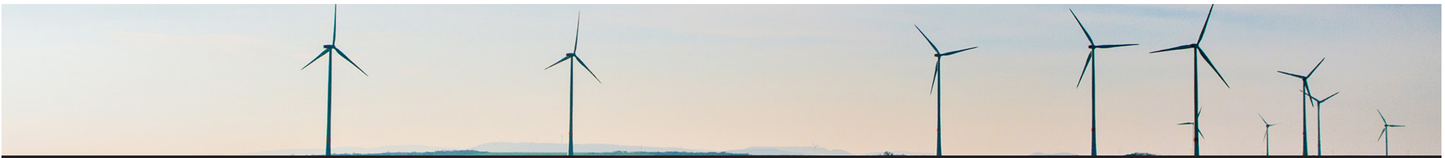
Subsequently, each of the four outer panels is hoisted and placed, until the outer formwork is closed. The formwork is plumbed and the concrete pouring is carried out using a pump and/or a craneable skip with a tremie pipe.

The lift cycle is repeated daily, achieving lifts of up to 6 m per day. The described process has been well proven during the construction of the POLICONO tower prototype in Alaiz (Spain), a 120 m height tower. The construction process has been certified by GL Renewables Certification (GL RC).

3.3 MATERIALS, EQUIPMENT, AND PERSONNEL REQUIRED

In order to provide with the approximate value of the materials required for the construction of the S2C tower, the quantities of the main materials are specified in the following table.

The construction requires de use of a tower crane, integrated into the foundation of the tower. The tower crane is attached to the tower, with a hook height of 212 m and a lifting capacity of 25 t.



Two assembly moulds are planned for the pre-assembly of the rebar cage, including auxiliary scaffolding and one lifting frame.

Other auxiliary equipment is listed below:

- Boom truck
- Generator
- Thermocouple system

The 6 m daily rate requires 10 formwork workers and 5 steel fixer on the construction of the tower as direct labour. Furthermore, it is required one construction manager and one site foreman.

4 CONCLUSIONS

Climbing formwork is a system widely used for the construction of skyscraper central core, bridge piles and towers, for heights up to 828 m (Burj Khalifa, Dubai). The described process, in which the section of the tower is reduced gradually with height, has been used in the construction of the POLICONO tower prototype, in Alaiz (Spain), proving that a daily rate of 6 m is achievable as it has been certified by GL Renewables Certification.

It can be concluded that the construction of an in situ concrete tower of 200 m height, or more, reaching rates of 6m per day, is achievable. The geometry and construction process of the S2C tower provides a technical and cost effective solution for wind turbines installed at great height.

One of the limitations for the use of very tall towers is the availability of lifting cranes with capability for installation/servicing of heavy equipment (rotors, nacelles) , in uneven terrain and high wind conditions, making hard to find calm periods for lifting with cranes. The cost to produce, mobilize such special cranes and perform the liftings is a major barrier for the application of very tall towers nowadays. The availability of more economical lifting technology is therefore key to decrease the cost of installation of very tall wind turbine towers. A new device for the installation of the nacelle and rotor is being developed, named ZEUS Heavy Lifting. Zeus system uses the tower as support, and allows the lifting and installation of the wind turbine at any height.

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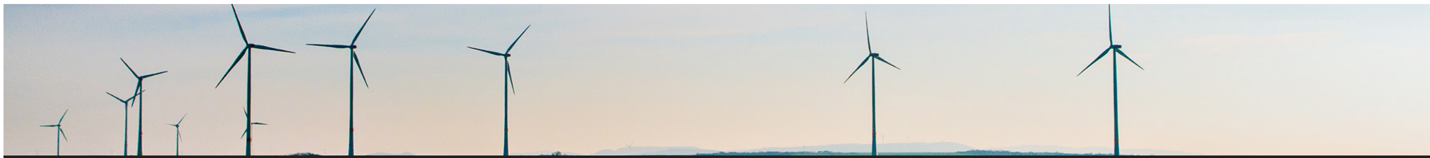

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