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Numerical Modeling for Sustainable Concrete Structures
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Design of UHPC Wind Turbines

FX. Jammes, X.Cespedes, J.Resplendino, FJ. Ulm

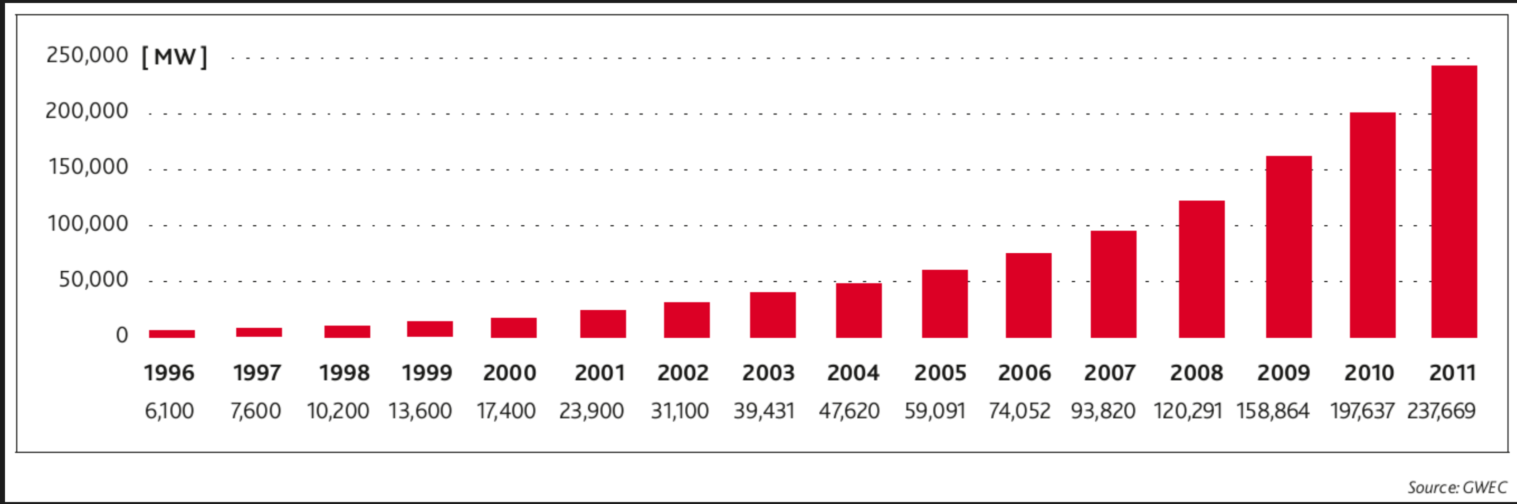
setec tpi

Massachusetts Institute of Technology

SSCS 2012
Numerical Modeling
Strategies for Sustainable Concrete Structures

Wind Energy Overview

- Worldwide capacity constantly increasing: 240 GW in 2011



- Economic competitiveness
  ➔ offshore windfarms with huge wind turbines towers

➔ Problem: Inefficient design using conventional materials

➔ Ultra-High Performance Concrete (UHPC) seems particularly suited to the challenge

UHPC Characteristics

Fatigue

- Compression:
  Outstanding behavior until the UHPC design compressive stress

- Tension:
  Problematic in fatigue only when the stress exceeds 0.5 to 0.6 times the UHPC design tensile stress

- Good overall behavior at the joint between two precast sections

➔ Great fatigue reliability when the material mostly behaves in compression

UHPC Characteristics

Durability

- Great adaptation of UHPC to its surrounding (chloride ion penetration, abrasion, alkali-silica reaction, freeze-thaw and scaling resistances)

- Low porosity explained by the ultra-dense C-S-H packing

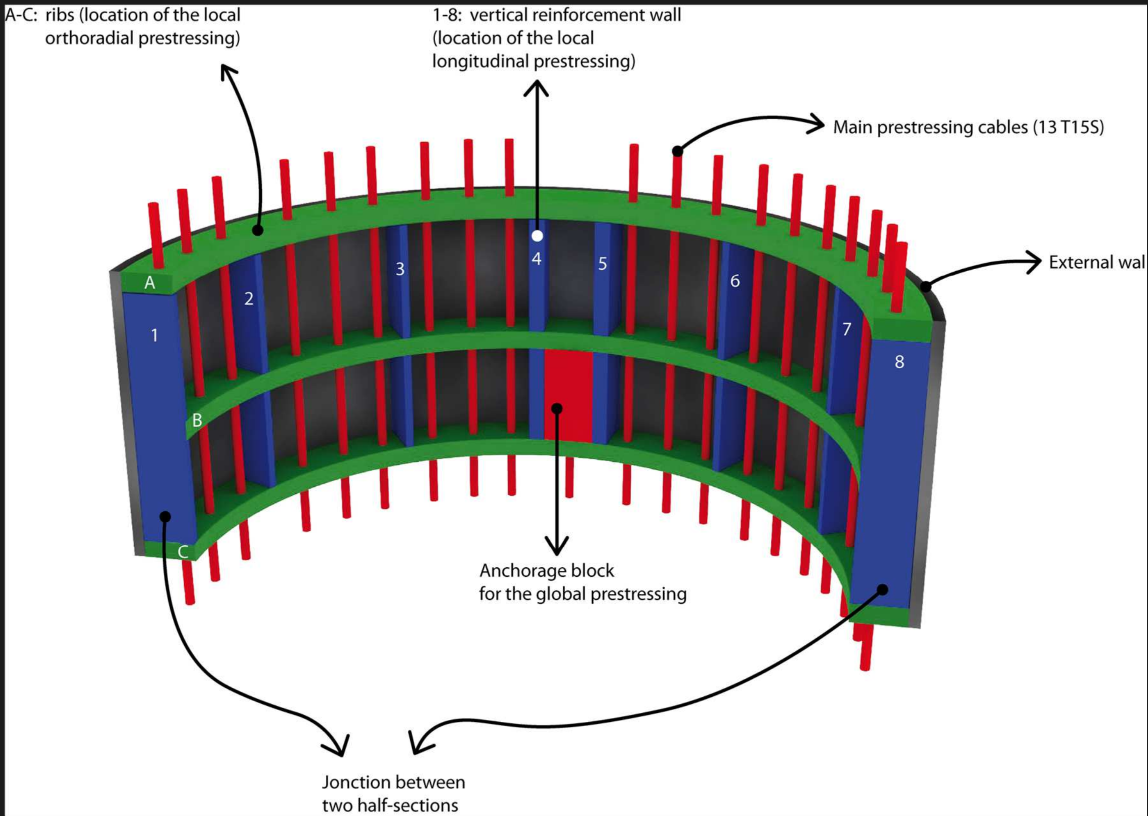
- High rate in Portlandite accounting for a carbonatation delay

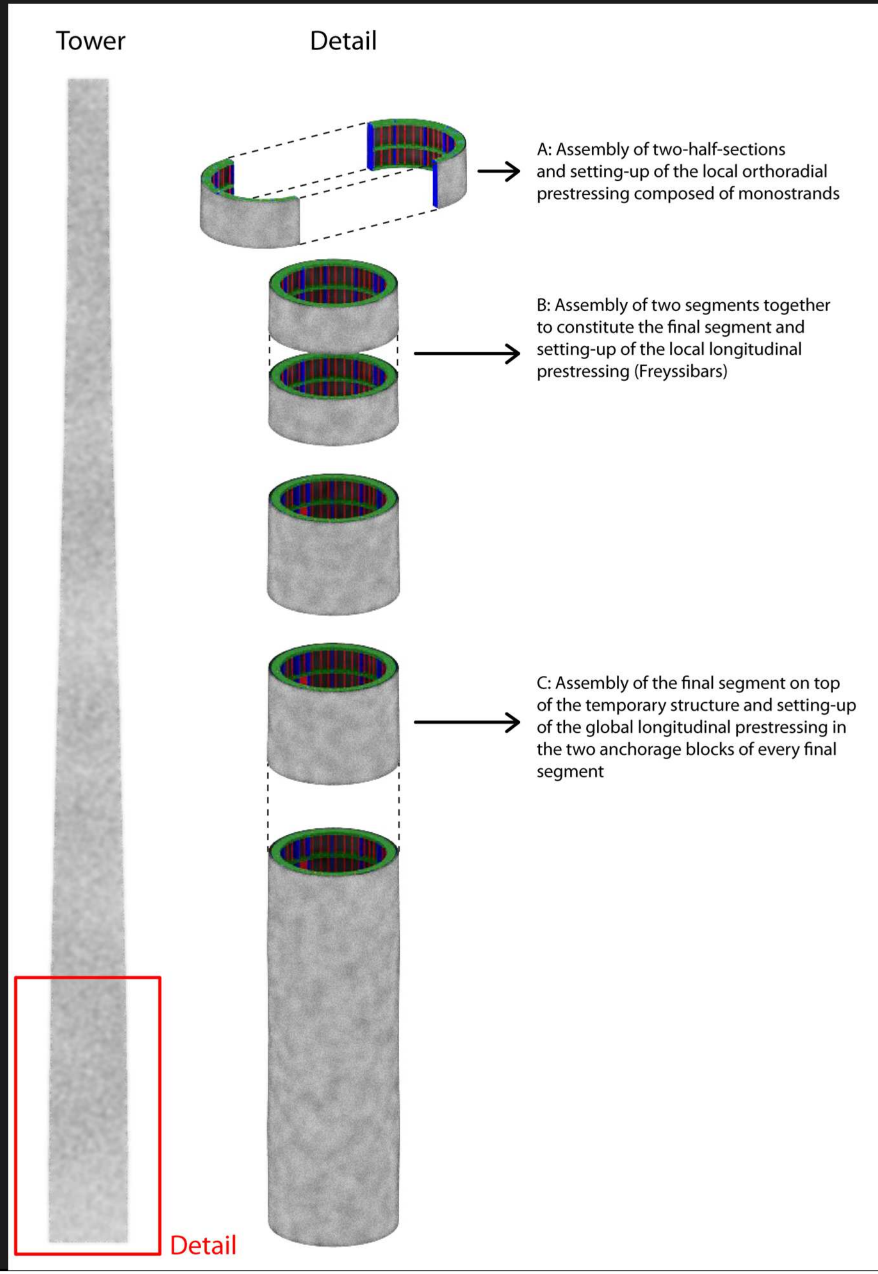
➔ Outstanding durability properties

➔ To be confirmed by additional investigations

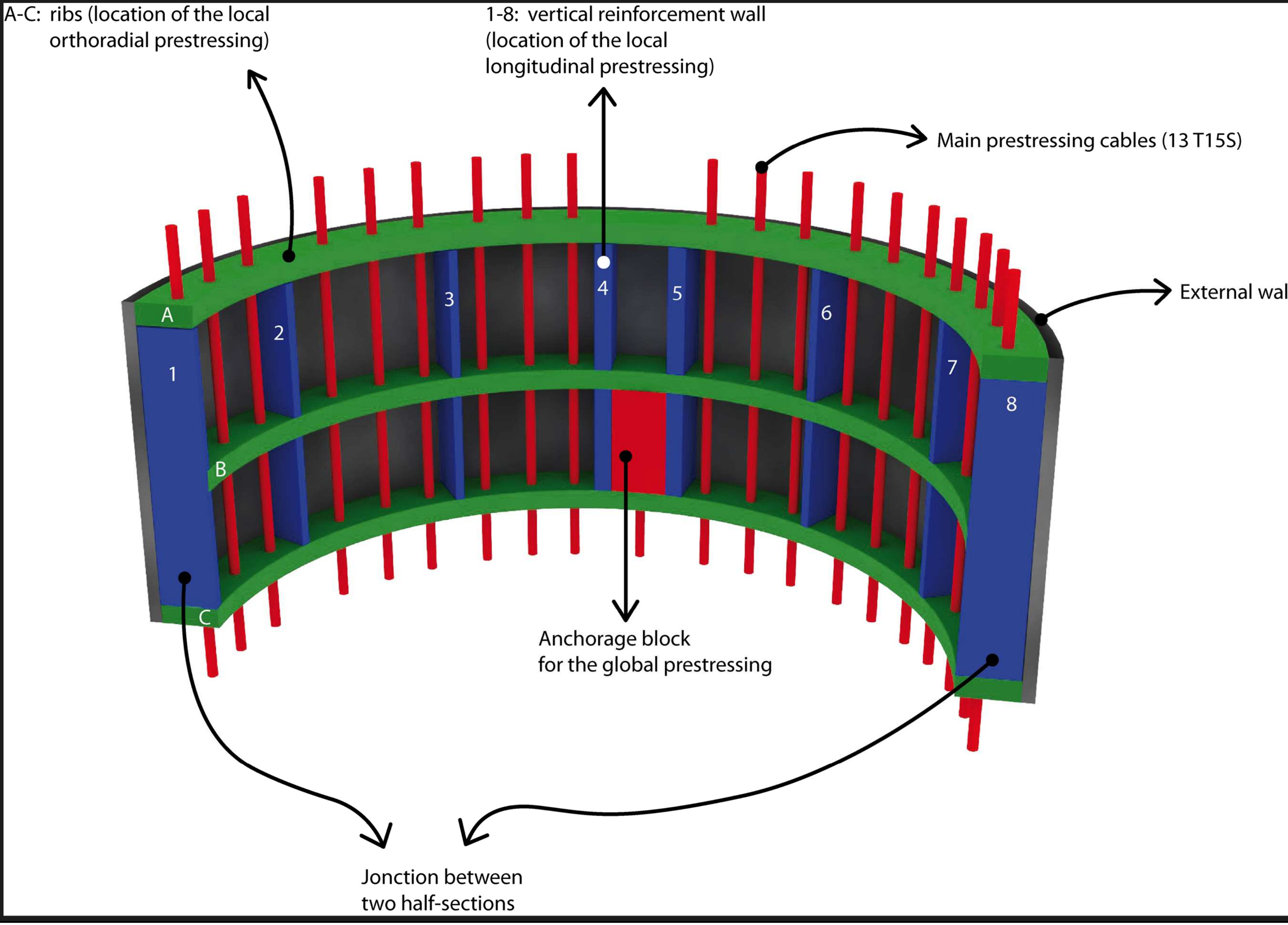
➔Towards an Innovative Design for a UHPC Tower…

A Revolutionary Construction Process





A Revolutionary Construction Process



Basic Assumptions

UHPC Design Parameters

	UHPC Characteristic
Density	2500 kg/m^3
Compressive strength	150 MPa
Flexural strength	30 MPa
Direct tensile strength	8 MPa
Young's modulus	50 GPa
Poisson ratio	0.2
Shrinkage	550 µm/m
Creep coefficient	0.3
Thermal expansion coefficient	11.8 µm/m/°C

Basic Assumptions

Design Loads

Load characteristics	Load values
Dead load	$d_{UHPC} = 2500\ kg/m^3$
Nacelle and rotor weight F_{vt}	4000 kN
Rotor horizontal thrust F_{ht}	1200 kN
Wind Load q_w	$1/2.\rho.V^2.C.B$ kN/ml

➔ Values validated by the National Renewable Energy Laboratory (NREL) and Det Norske Veritas (DNV)

Basic Assumptions

Tower Geometry

- Entirely defined by 5 parameters:

  $h = 120$ m
  $t_{w,bottom} = 0.12$ m
  $t_{w,top} = 0.06$ m
  $r_{o,bottom} = 4$ m
  $r_{o,top} = 2$ m

  linear evolution of both the thickness and the outside radii between the bottom and the top

- Composed of 40 segments of 3m high bonded together with:

  → Post-tensioned cables all along the tower (global prestressing)

  → Longitudinal/orthoradial prestressing cables for every segment (local prestressing)

→ 3 different types of prestressing

Basic Assumptions

Design Combination Approach

- Limit State Design (ULS and SLS) approach preferred to the Design Load Cases (DLC) (International Electrical Commission)

  ➔ULS Load Coefficients: 1.35 for dead loads
  1.5 for live loads

Analysis Sequence

- Global Analysis:
  ➔Global structural checkout
  ➔Design of the global prestressing cables

- Local Analysis:
  ➔Section checkout
  ➔Design of both types of local prestressing cables

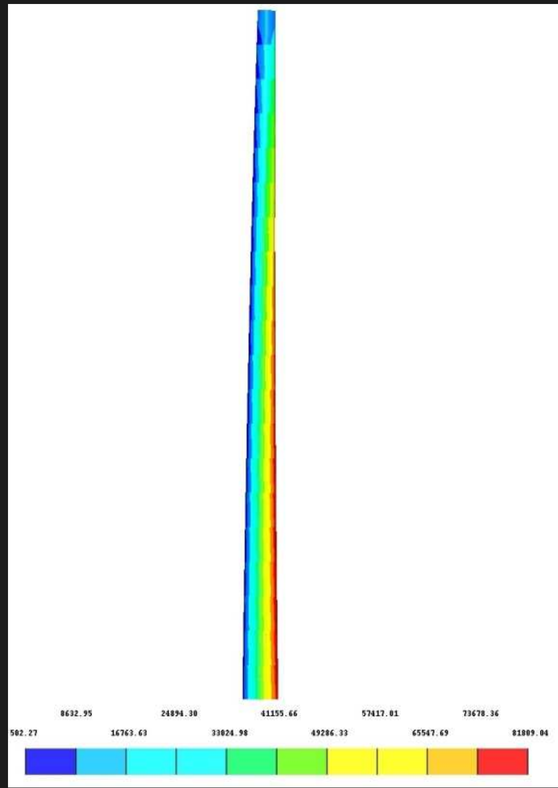
Global Analysis

Model Characteristics

- Tower = cantilever beam according to the beam theory
- Global Prestressing force = centered point load whose value linearly increases from the top to the bottom of the mast

SLS Combination

- Prestressing force F_P designed so that there is no tension for SLS
  ➔ F_P = 155MN i.e. 50 cables 13T15S at the bottom
- The normal stress remains between 0.3 MPa and 82 MPa



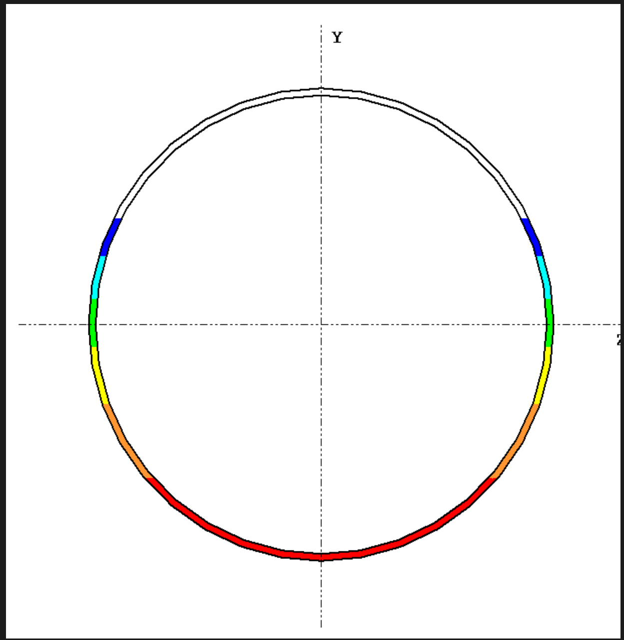
σ_{SLS} with prestressing

Global Analysis

ULS Combination

- The material is considered not to behave in tension because of the joints
  ➔ The sections equilibrate the external loads through compression exclusively

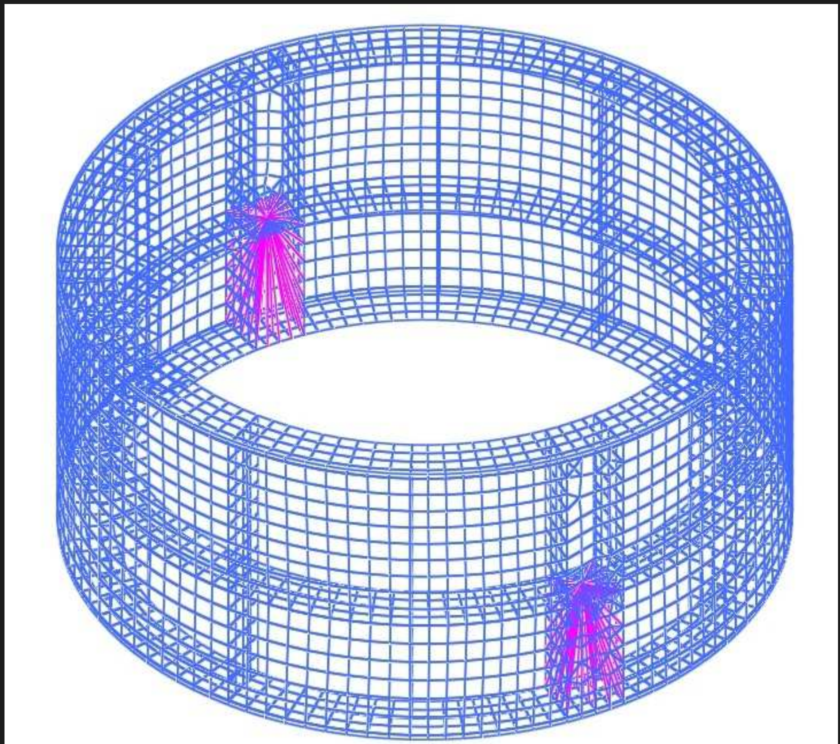
Constitute law for ULS taken as provided by the AFGC interim recommendation



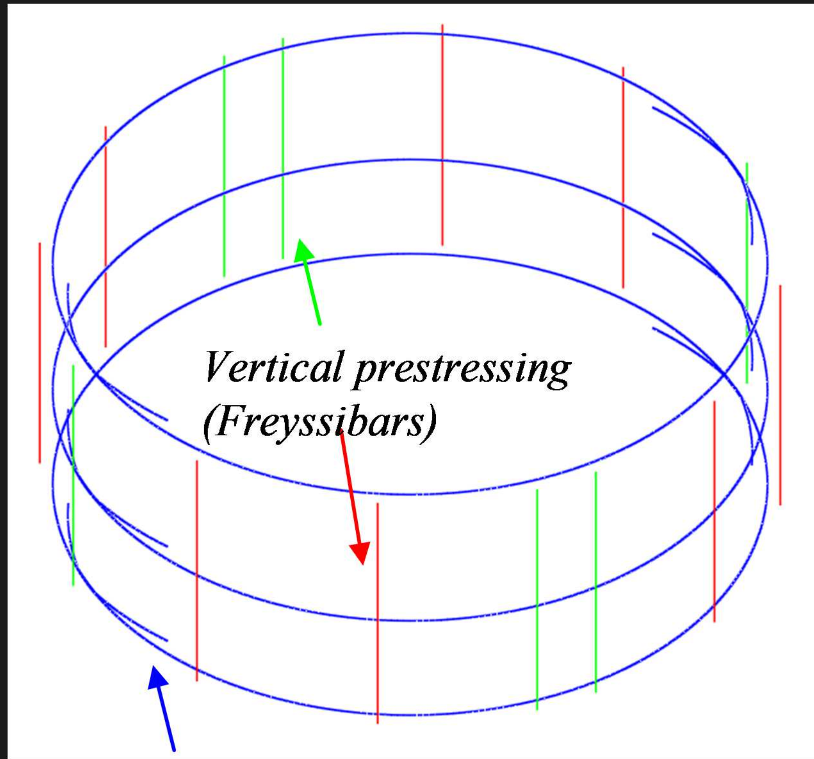
σ_{ULS} in a particular section

Local Analysis

FE Model Characteristics



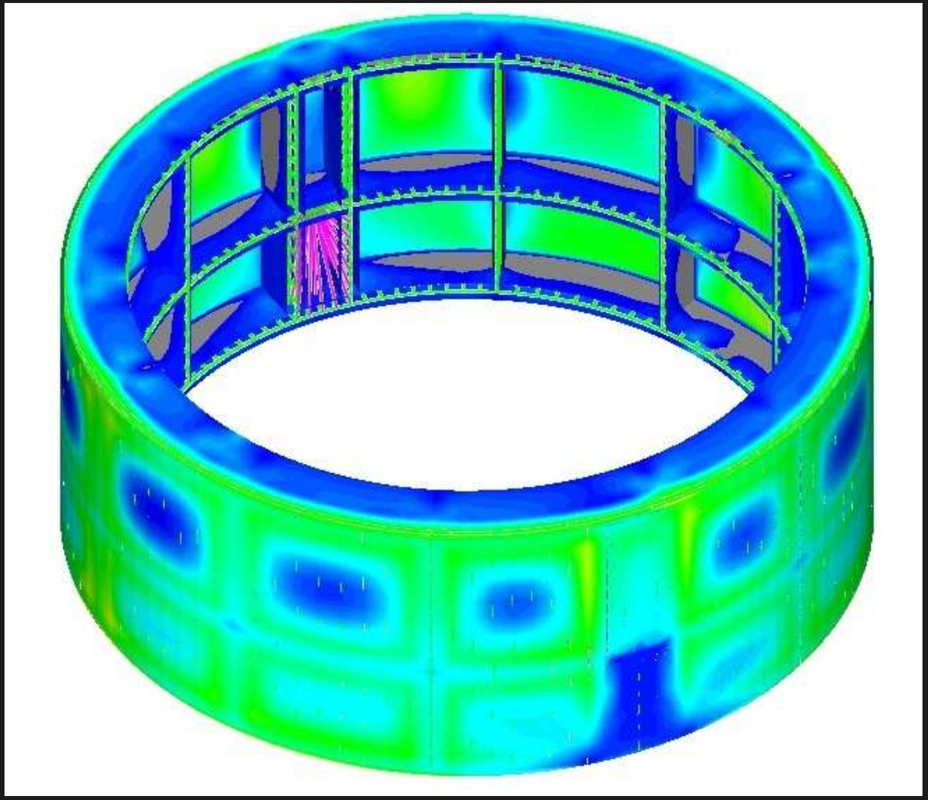
Geometry of the section



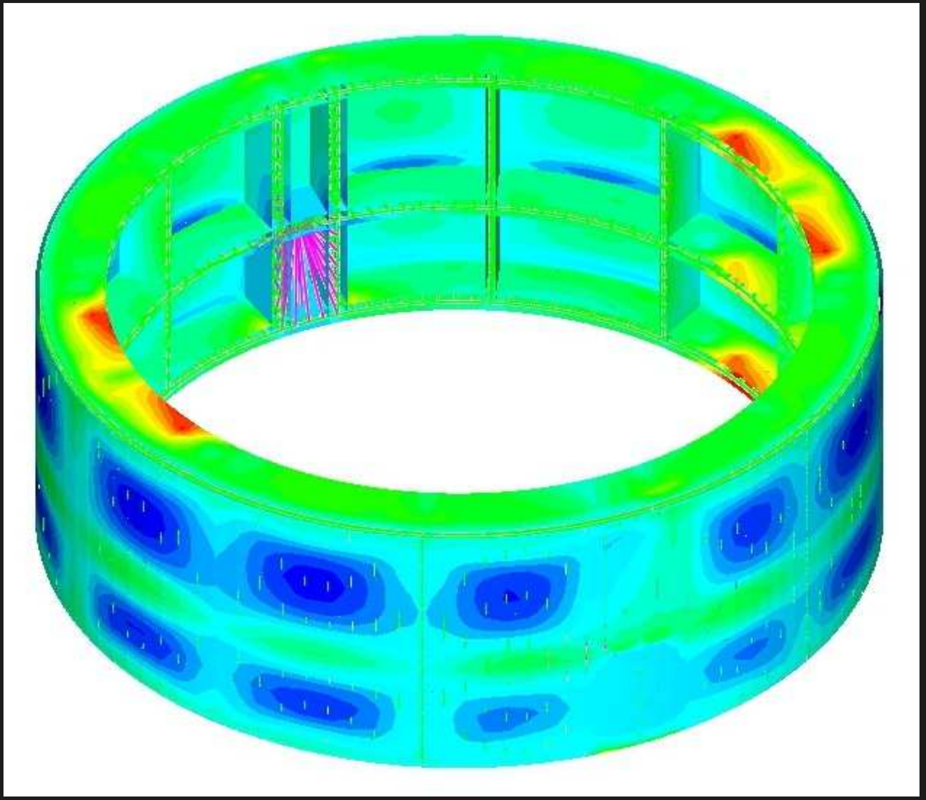
Layout of the local prestressing

Local Analysis

Construction Phase



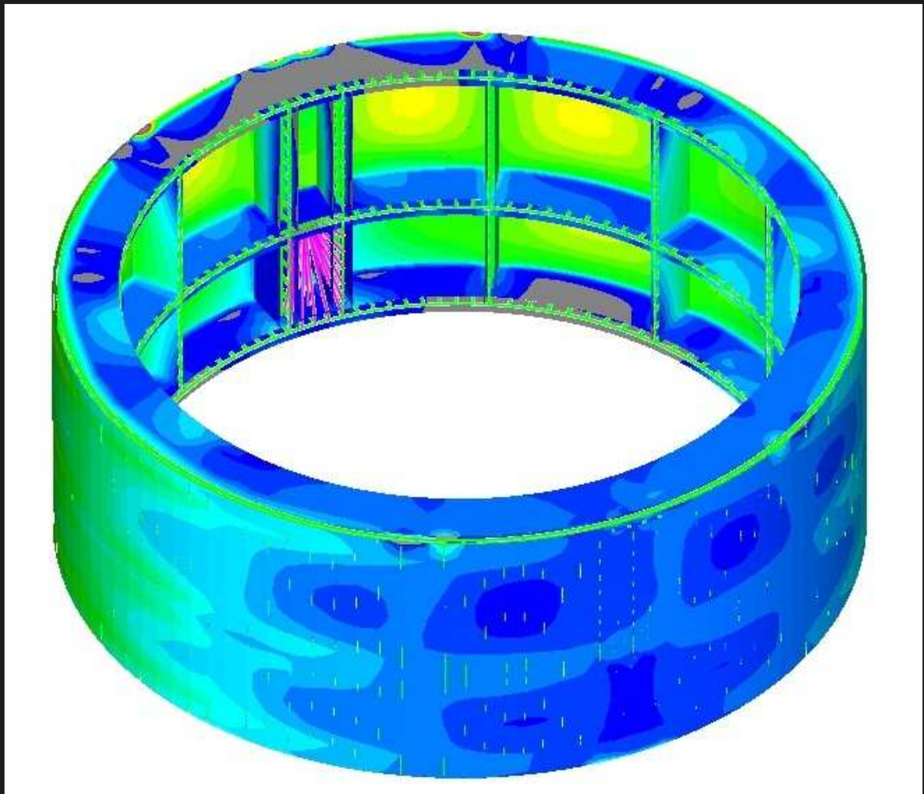
σ_{xx} *during the construction phase*



σ_{yy} *during the construction phase*

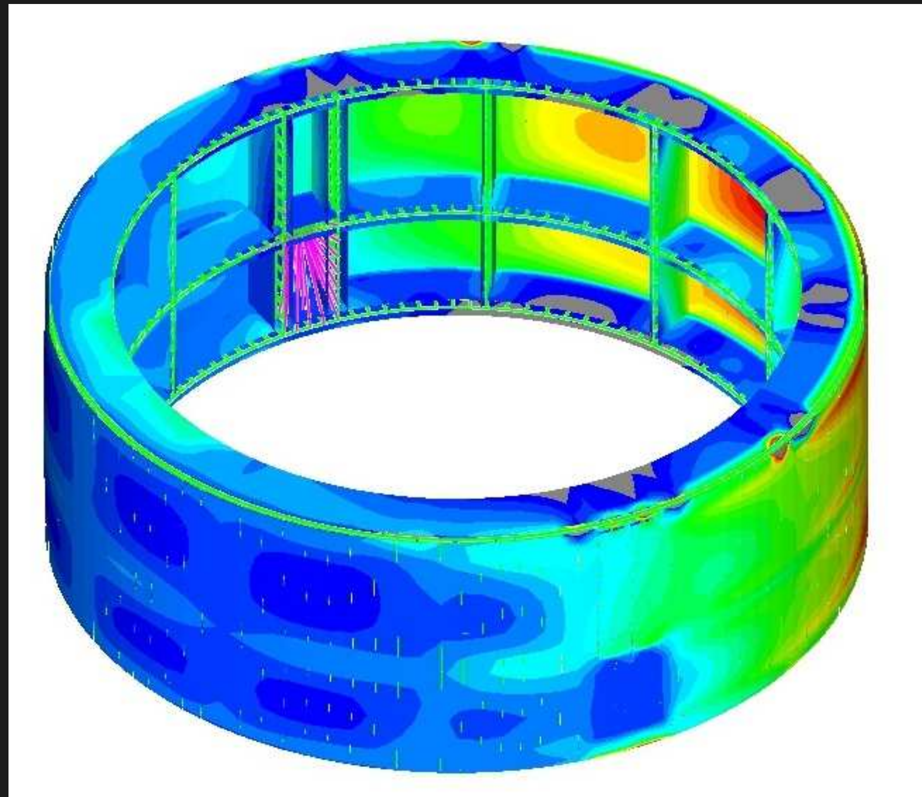
Local Analysis

Final Phase (SLS and ULS)



σ_{xx} during the final phase

(ULS Combination – configuration 1)



σ_{xx} during the final phase

(ULS Combination – configuration 2)

Prestressing Summary

Prestressing Denomination	Prestressing Characteristics
Global longitudinal prestressing	-50 strands 13 T15S at the bottom and 10 strands 13 T15S at the top of the tower with a linear repartition -2 global anchorages per final segment
Local longitudinal prestressing	-1 Freyssibar for every vertical reinforcement wall anchored at every two temporary segment (Freyssibars Φ 40 and Φ 26.5 per reinforcement for the lower final segment) -2 local anchorages per reinforcement wall per final segment
Local orthoradial prestressing	-Monostrands for every horizontal ribs anchored at the junction section (2x10 Monostrands T15S per rib for the lower final segment i.e. 60 T15S per section) -2 local anchorages per rib


Siemens Press Picture
with the courtesy of Siemens AG

Overall Project Overview

Contact Author

François-Xavier Jammes, Setec TPI
jammes@tpi.setec.fr

Award

Honorary mention at EFCA Young Professional Competition (European Federation of Engineering Consultancy Associations), 2012

Conferences

SSCS Conference, Aix-en-Provence, France, May 29 - June 1, 2012

18th IABSE Congress, Seoul, Korea, September 19-21, 2012

Papers

Design of wind turbines with Ultra-High Performance Concrete, FX. Jammes and FJ. Ulm, MIT Thesis, Massachusetts Institute of Technology

L'avenir des éoliennes offshore passe par le Béton Fibré à Ultra-Haute Performance, FX. Jammes, L. Tosini, X. Cespedes, J. Resplendino, Revue Travaux, March 2012