INFRASTAR

Innovation and Networking for Fatigue and Reliability Analysis of Structures – Training for Assessment of Risk

Challenges in the application of concrete design codes for floating wind turbine support structures

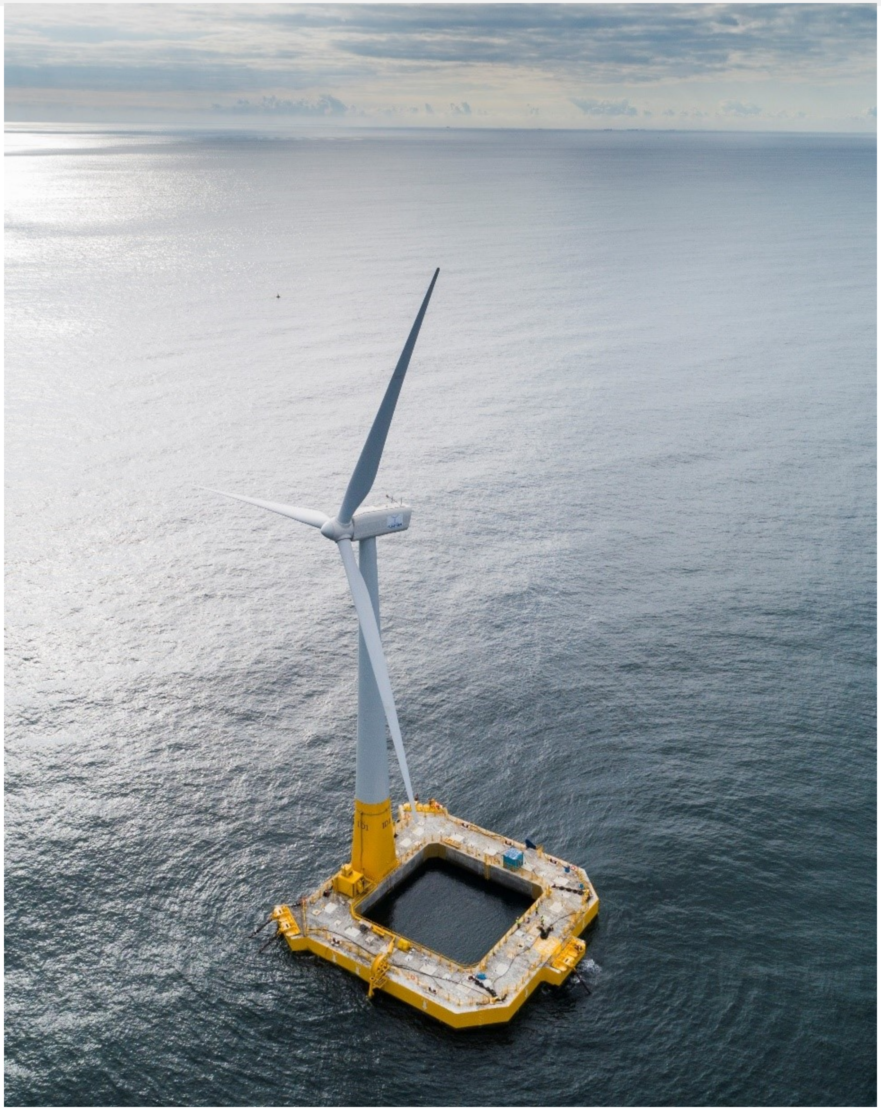
The Floatgen example

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 676139

3rd Infrastar Implementation Day, COWI Copenhagen, 26 June 2019

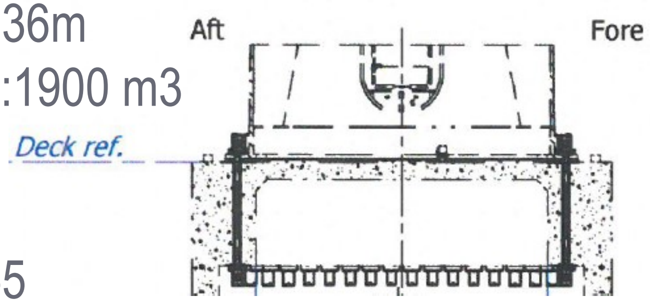
Ideol

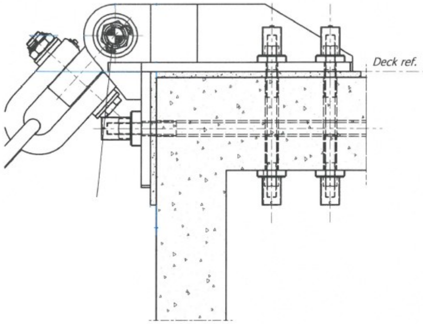
- Founded in 2010, now 60 persons – mainly engineers
- Two full scale demonstrators in France (concrete) & Japan (steel)
- Patented technology
- Wind farm demonstrator project EolMed on going – 24 MW / 4WT
- Now preparing for commercial project 250MW and more…

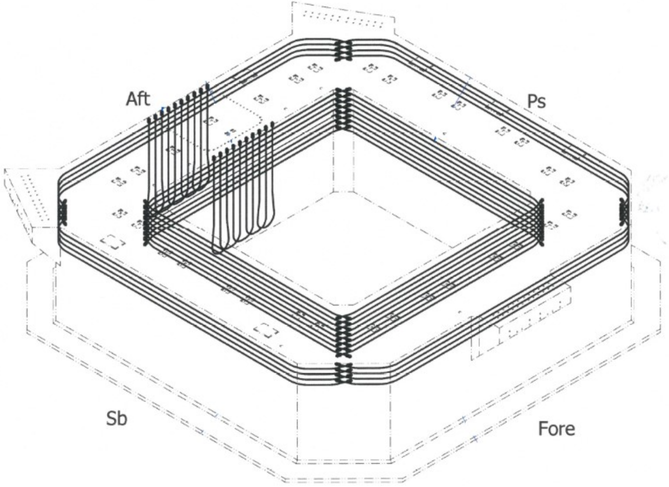


Floatgen floating wind turbine & main particulars

- Main dim: 36m x 36m
- Concrete volume:1900 m3
- Mass: 5400 tons
- Draught: 7m
- Concrete: LW C55
- Concrete density: 2000 kg/m3
- Design lifetime: 5 years
- Location: French Britanny (SEMREV)
- Certification Body: LR







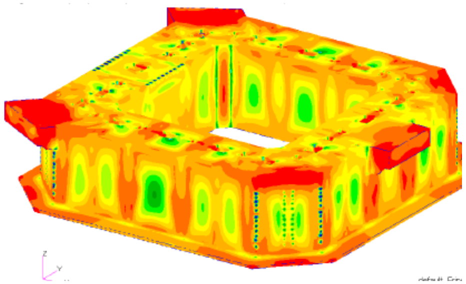
Concrete the ideal material for large scale production

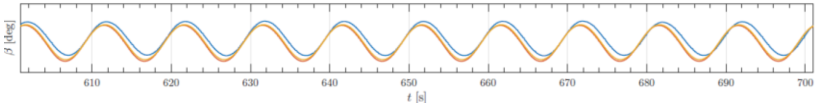
- Reinforced concrete and steel are the two only materials qualified
- Dimensions of floaters are fixed by wind turbine and seakeeping performance (hence site conditions) and not by material
- For a 20-year lifetime, both materials work. Concrete offers the possibility of larger lifetimes at low cost.
- Carbon content and cost stability are better for concrete
- In-service track-record in offshore environment and durability (OPEX)
- Local supply is offered (at least regional)
- It is harmless to the environment
- Construction methods are adaptable to large scale production
- Its price is competitive for offshore wind farms

Design process – How to de-risk an innovative project

Conceptual & Basic design

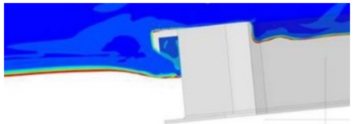
- Floater main dimensions estimate
- Mooring system selection
- Verification of main components (structure / mooring / Inter array cables)
- Estimation of weights





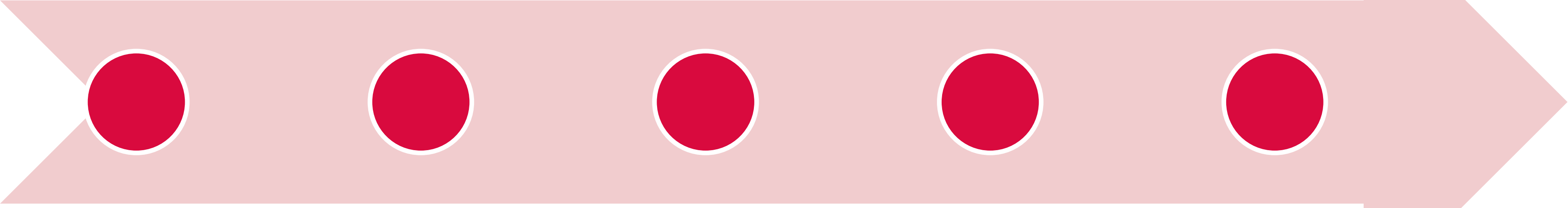
Detail design

- Design for approval
- Uncertainties related to loads and materials covered by safety factors
- Full scale CFD models for model test validation



Operation

- Precom & commissioning
- Maintenance
- Monitoring



Model tests

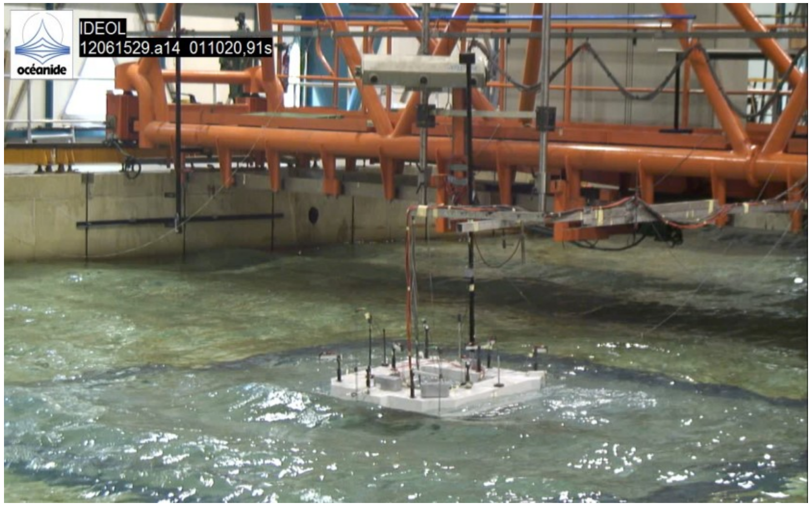
- Floater close to final dimensions
- Calibration of numerical models
- Verification of expected loads

Manufacturing of components

- Surveys and certificate for compliance with Class requirements
- Main defects related to manufacturing or material properties detected
- Mock-up to cover construction risks

Covering uncertainties related to loading: Model tests

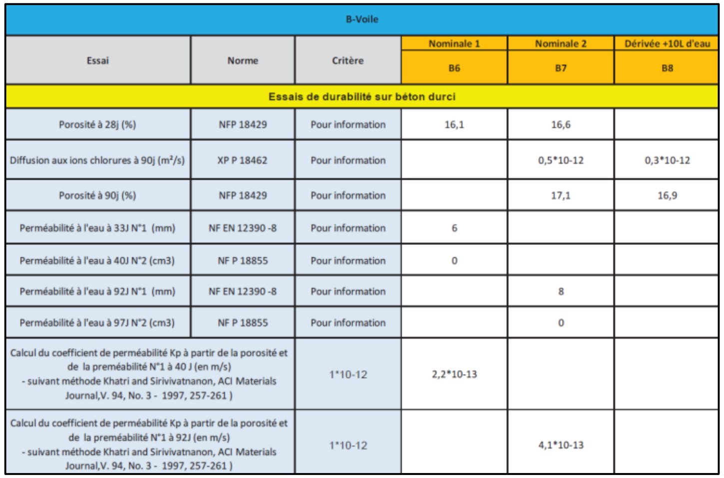
- Global design (including structure) driven by environmental loadings i.e. Metocean data
- Motions / Mooring line tensions / Greenwater / Wave impact
- Hydro / Structure coupling =>unusual for civil contractors / complex calculation methodology / no litterature for Ideol type floater
- Environemental loading design factor 1.35 (largest one)



18 december 18 storm

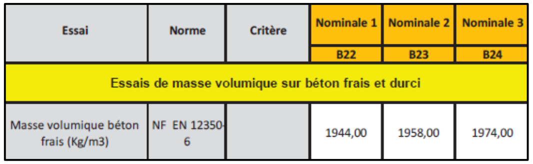
Covering uncertainties related to material: tests

- Light weight concrete density : 2000 kg/m3
- Cylinder Compressive strength: 55 MPa
- Many material tests performed
  - Hull material
  - Mooring line stiffness
  - Mooring line fatigue
  - Mooring connector steel properties
  - …
- Material factor for concrete is 1.5 (largest one)

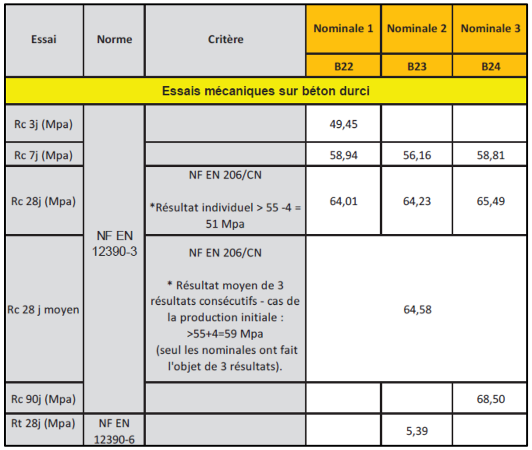


B-Voile

Essai	Norme	Critère	Nominale 1	Nominale 2	Dérivée +10L d'eau
			B6	B7	B8
Essais de durabilité sur béton durci					
Porosité à 28j (%)	NFP 18429	Pour information	16,1	16,6	
Diffusion aux ions chlorures à 90j (m²/s)	XP P 18462	Pour information		0,5*10-12	0,3*10-12
Porosité à 90j (%)	NFP 18429	Pour information		17,1	16,9
Perméabilité à l'eau à 33J N°1 (mm)	NF EN 12390 -8	Pour information	6		
Perméabilité à l'eau à 40J N°2 (cm3)	NF P 18855	Pour information	0		
Perméabilité à l'eau à 92J N°1 (mm)	NF EN 12390 -8	Pour information		8	
Perméabilité à l'eau à 97J N°2 (cm3)	NF P 18855	Pour information		0	
Calcul du coefficient de perméabilité Kp à partir de la porosité et de la preméabilité N°1 à 40 J (en m/s) - suivant méthode Khatri and Sirivivatnanon, ACI Materials Journal,V. 94, No. 3 - 1997, 257-261)		1*10-12	2,2*10-13		
Calcul du coefficient de perméabilité Kp à partir de la porosité et de la preméabilité N°1 à 92J (en m/s) - suivant méthode Khatri and Sirivivatnanon, ACI Materials Journal,V. 94, No. 3 - 1997, 257-261)		1*10-12		4,1*10-13	



Essai	Norme	Critère	Nominale 1	Nominale 2	Nominale 3
			B22	B23	B24
Essais de masse volumique sur béton frais et durci					
Masse volumique béton frais (Kg/m3)	NF EN 12350-6		1944,00	1958,00	1974,00

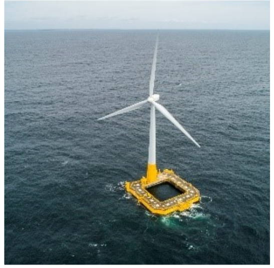


Essai	Norme	Critère	Nominale 1	Nominale 2	Nominale 3
			B22	B23	B24
Essais mécaniques sur béton durci					
Rc 3j (Mpa)	NF EN 12390-3		49,45		
Rc 7j (Mpa)			58,94	56,16	58,81
Rc 28j (Mpa)		NF EN 206/CN *Résultat individuel > 55 -4 = 51 Mpa	64,01	64,23	65,49
Rc 28 j moyen		NF EN 206/CN * Résultat moyen de 3 résultats consécutifs - cas de la production initiale : >55+4=59 Mpa (seul les nominales ont fait l'objet de 3 résultats).	64,58		
Rc 90j (Mpa)					68,50
Rt 28j (Mpa)	NF EN 12390-6			5,39	

Main challenges for floating concrete WT foundation design

Well covered by onshore civil codes (Eurocodes…)

- Ultimate Limit State structural verification
- Compressive strength in serviceability state
- Crack width opening calculation



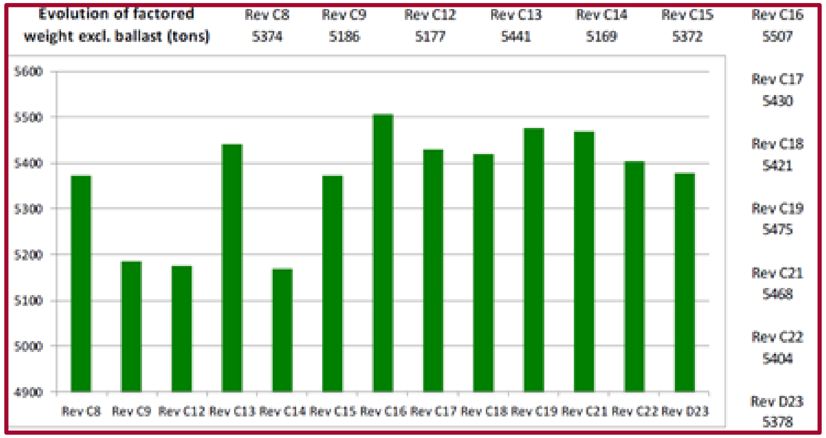
Floater shall be light enough to float!

Additional investigation for offshore applications could help the design

- Fatigue of concrete (number of cycles 10^6 vs 10^8)
- Watertigthness
- Cathodic protection and collateral effects
- Steel / concrete interface for offshore type loads (large dynamic loads)
- Evolution of concrete (construction / transport / operation)

Design : Weight, the floater driving parameter

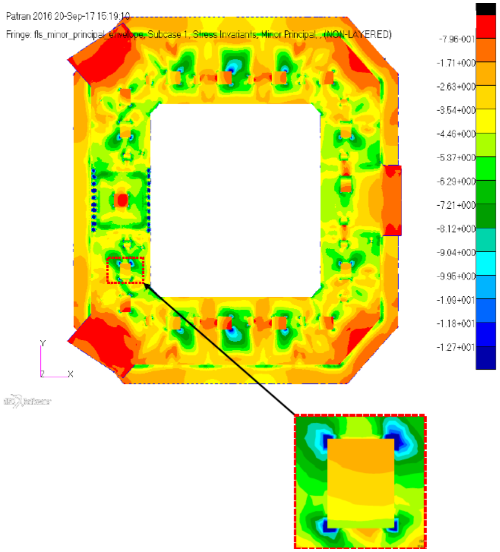
- Dimensions of floater are driven by stability and seakeeping, mass distribution is the key parameter
- CoG location shall be stricly controlled during design and manufacturing
- Cost are driven by construction duration and size of floater (materials / float off means)
- Use of lightweight concrete & thin shells is likely to make some congested areas appear.
- Classic solution to ease congested area design is to locally thicken walls or slabs => dimensions increase
- Weight shall be controlled during the construction process => quite unusual for Civil Contractors
- Density of light aggregate will vary during construction => such uncertainty shall be accounted for during design

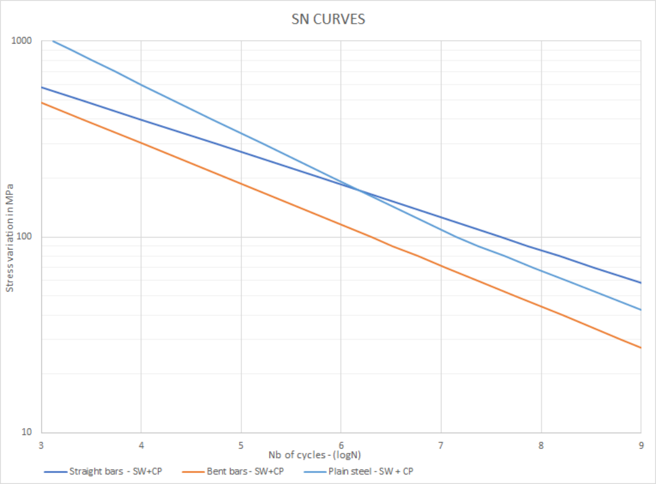


- Main challenge is to keep weight and consequently floater dimensions under control.
- To be efficient, design shall remain simple, so will be the construction

Fatigue

- Number of fatigue cycles much larger for offshore structures (around 1E8 cycles vs 2E6)
- All dedicated equipment needs to be qualified (prestressing / rebar connectors or even fatigue of welded connection of rebars)
- Areas in the vicinity of wind turbine foundation are driven by fatigue
- The bigger the wind turbine, the larger the area concerned by fatigue
- Representative fatigue tests will ease future design and costs
  - Flexural fatigue in seawater (compression-compression/compression-tension)
  - Fatigue of bent bars …

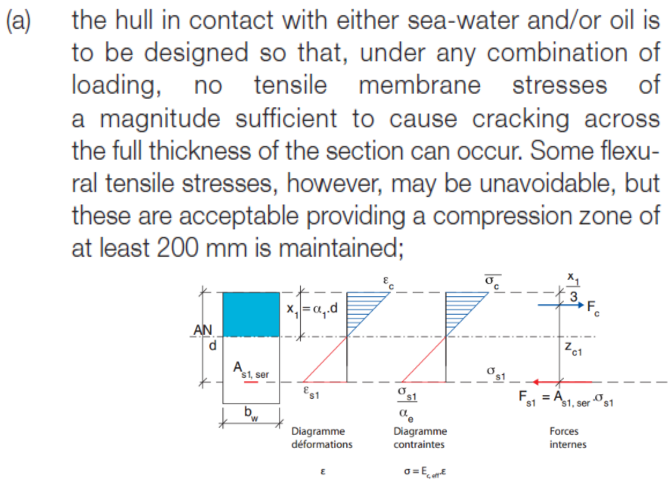




Watertightness

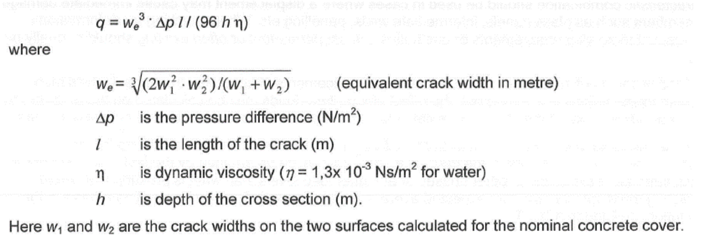
- Watertightness is the key condition to stability
- Minimum compressive thickness is required, so the water cannot pass through the cracks
- Criterion is reached by prestressing
- Today, Rules approach is very pragmatic (rather than scientific) => overdesign?
- Indeed, too much prestressing can be detrimental to the overall quality/safety of the structure => congestion / tensile stress / manufacturing deffects
- Floatgen remained watertight during 1st winter. Good basis for future design.
- May depend on Concrete history from pouring to operation at sea

Lloyd's Register approach



(a) the hull in contact with either sea-water and/or oil is to be designed so that, under any combination of loading, no tensile membrane stresses of a magnitude sufficient to cause cracking across the full thickness of the section can occur. Some flexural tensile stresses, however, may be unavoidable, but these are acceptable providing a compression zone of at least 200 mm is maintained;

NS3473E approach



$$q = w_e^{3} \cdot \Delta p \, l \, / \, (96 \, h \, \eta)$$

where

$w_e = \sqrt[3]{(2w_1^2 \cdot w_2^2)/(w_1 + w_2)}$ (equivalent crack width in metre)

Δp is the pressure difference (N/m^2)

l is the length of the crack (m)

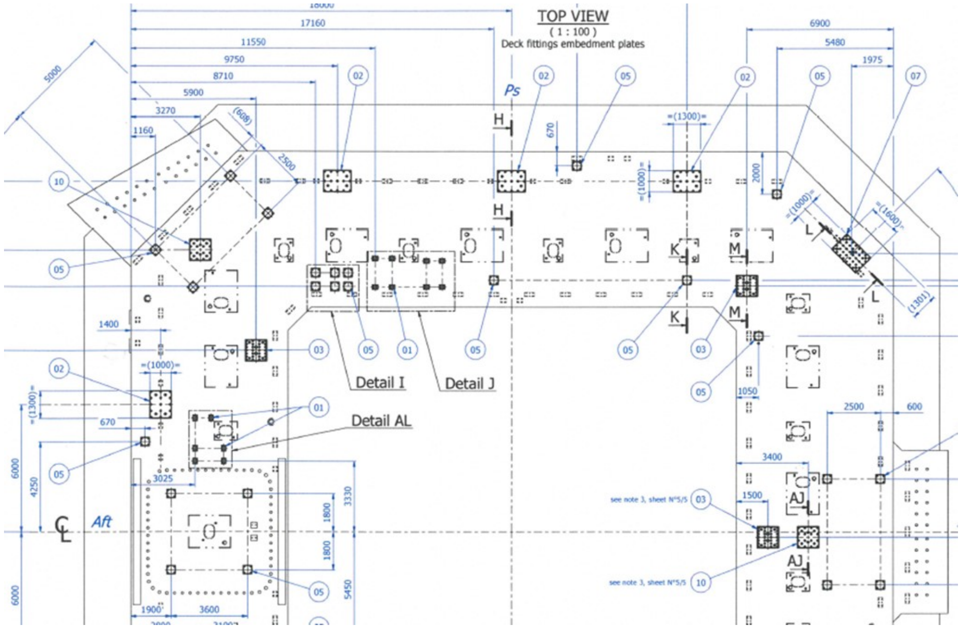
η is dynamic viscosity (η = 1,3x 10^{-3} Ns/m^2 for water)

h is depth of the cross section (m).

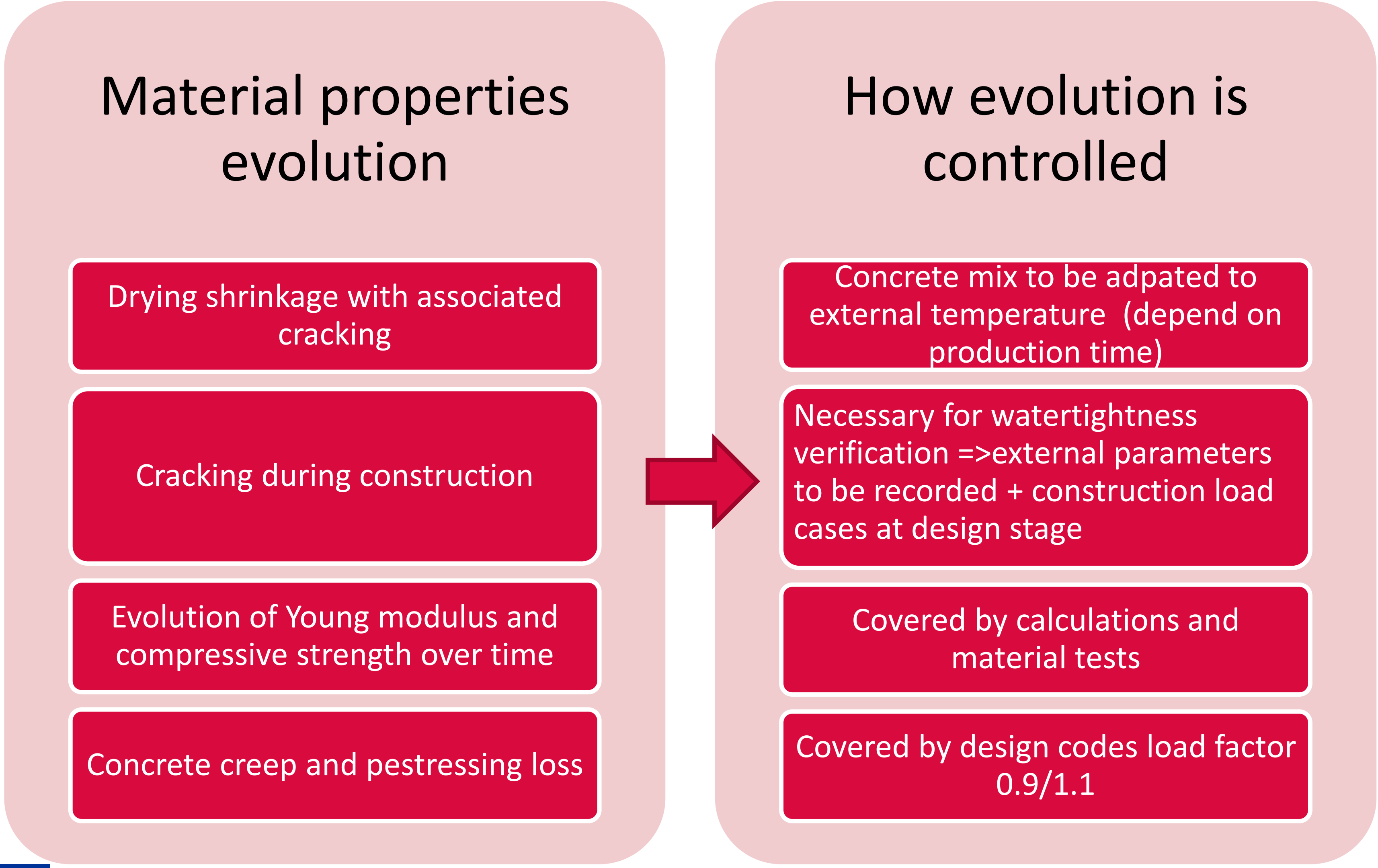
Here w_1 and w_2 are the crack widths on the two surfaces calculated for the nominal concrete cover.

Steel connections: anticipation required

- Equipement location shall be anticipated early in the design
- Steel equipement can be bolted or welded on embdement plate
- Challenging points:
  - Steel / concrete friction coefficient
  - Bolts behaviour with cathodic protection
  - Change location of embedment plates (Installation contractors)
  - Congested areas
  - Tension loss in short bolts



Reliability: concrete properties evolutions over project life



Material properties evolution

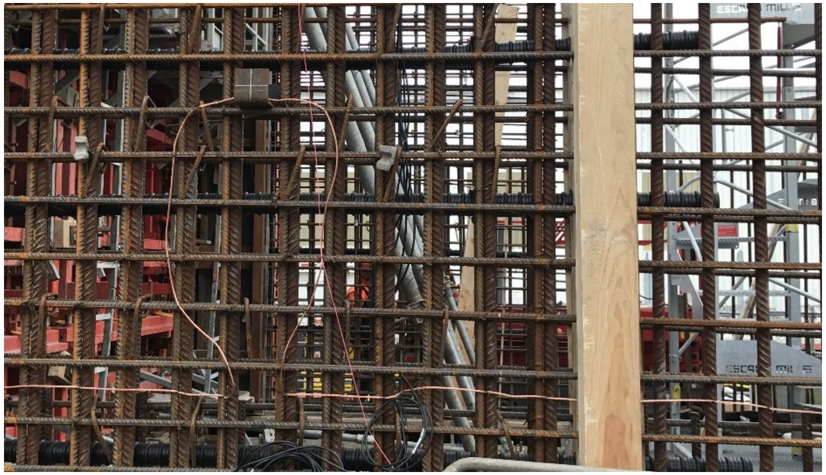
- Drying shrinkage with associated cracking
- Cracking during construction
- Evolution of Young modulus and compressive strength over time
- Concrete creep and pestressing loss

How evolution is controlled

- Concrete mix to be adpated to external temperature (depend on production time)
- Necessary for watertightness verification =>external parameters to be recorded + construction load cases at design stage
- Covered by calculations and material tests
- Covered by design codes load factor 0.9/1.1

About corrosion protection

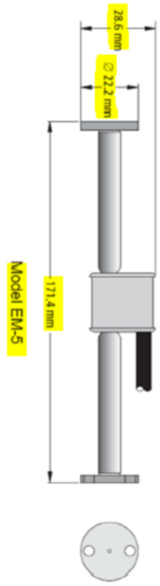
- Steel components shall be protected against corrosion
- Floatgen corrosion protection:
  - Concrete cover + paint on steel components
  - Anodes
  - Rebars eletrically connected together
- Effects of cathodic protection
  - Beneficial to fatigue for steel reinforcements
  - Beneficial to durability
  - Detrimental to bolts (HISC – brittle failure)
- Environmental impact is limited for floating concrete structure (questions being raised in France)
- Alternate solutions
  - Coated bars is generally not a preffered solution
  - Galvanized / stainless teel rebars => cost
  - FRP bars (Manufacturing anticipation & stiffness)

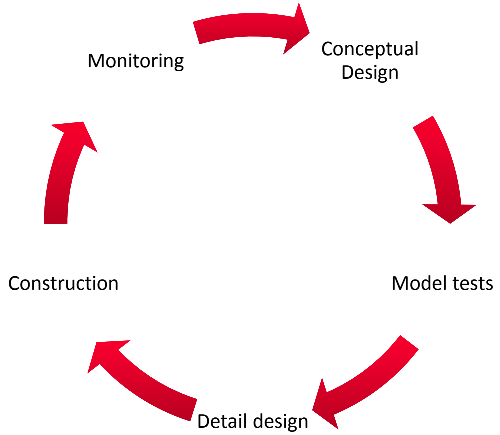


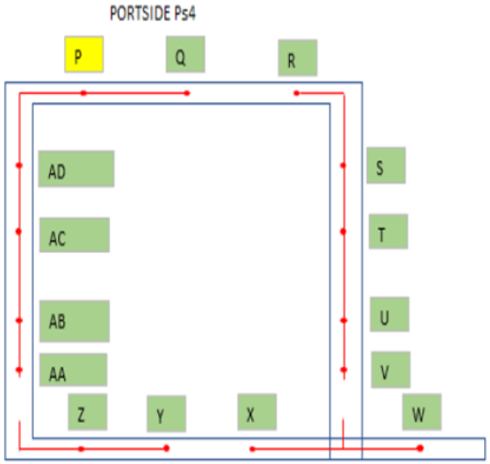
The corrosion protection approcah shall remain global. Floatgen feedback will be essential for future design.

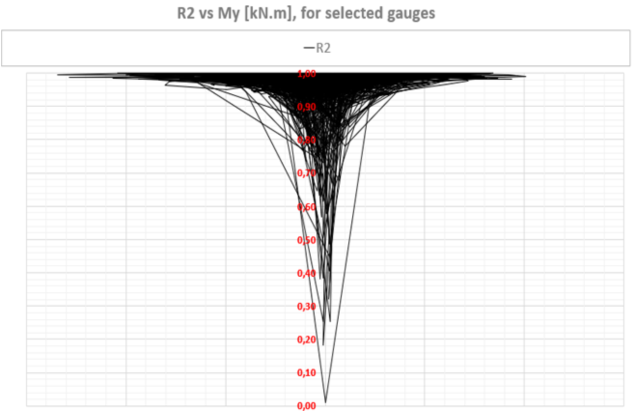
Monitoring : comparison between calculations and main events

- Strain gauges to measure global loads and local pressure
- Comparison between global loads expected during storms and calculations predictions
- Necessary for technology validation




Monitoring
Conceptual Design
Model tests
Detail design
Construction





Conclusion : Future of floating wind: Serial production

- Cost shall be kept low for renewables. Cost target will be met by means of serial production and swift design. Cost is driven by construction duration per floater
- Experience gathered by offshore Oil & Gas industry is much valuable but the risk of overdesign shall always be considered.
- Cost of faulty component manufactured in large quantity would be rather significant: manufacturing surveys, full size demonstrators and test campaigns are fundamental to cover such risk
- Simplicity in construction is crucial to accelerate floaters delivery and ensure a proper manufacturing quality

Thank you for your attention

ideol

Simon VASSEUR
Manager - Structural and Mechanical Engineering
Responsable - Ingénierie structure et mécanique

Espace Mistral, bât B - 375 avenue du Mistral
13600 LA CIOTAT (FR)
Tel : + 33 (0)4 86 20 80 59

Stay tuned http://infrastar.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 676139