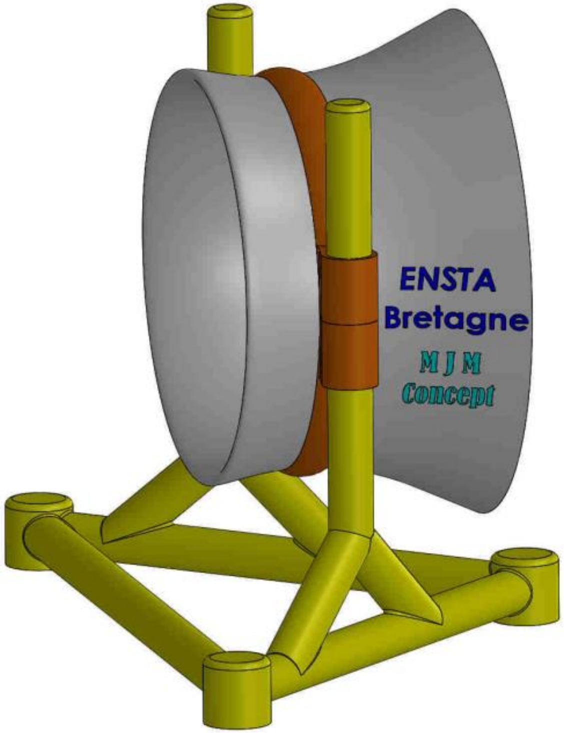
Simulation et Optimisation pour les Energies Marines Renouvelables
10-12 Janvier 2018, Paris France.

Composite Tidal Turbine Design: From the hydrodynamic efficiency to the structural safety of the MJM concept



Presented by:

M. AIT-MOHAMMED*[2], M. TARFAOUI[2], J.M. LAURENS[2]

*AREVA NP Mechanical Engineering | DTIMRT-F | AREVA NP

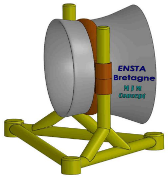
[2]IRDL - CNRS - FRE - 3744

Dept. of Ship Structure Mechanics Center

ENSTA Bretagne, France.

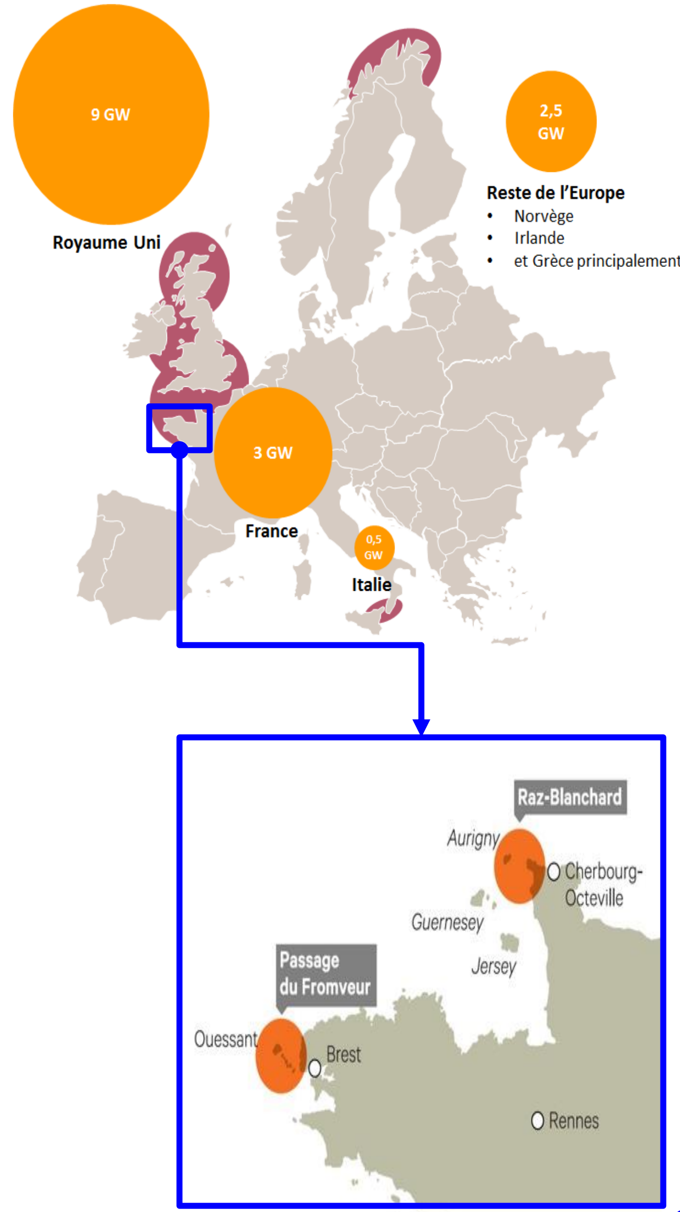
ENSTA Bretagne

Institut de Recherche Dupuy de Lôme
CNRS FRE 3744



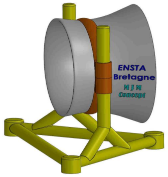
Context

- There are many areas of Europe in which extreme tidal currents are observed.
- The Celtic sea being the most dense in terms of Marine Renewable Energy potential. (Tidal energy and offshore wind)
- France has the second highest tidal energy potential the world



→ In the region of the Cherbourg peninsula in France :

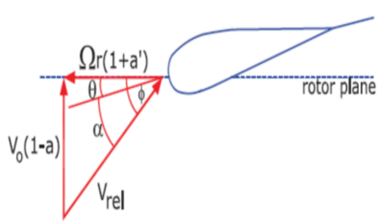
- The most attractive tidal site in France is the sea passage known as ***Le Raz Blanchard*** in French and the ***Race of Alderney*** in English.
- The water depth allows for the marine turbine systems to exceed ***20 meters diameter*** without causing any perturbation to maritime traffic and the current ***velocity peaks above 3m/s***.
- In order to present some realistic numerical results, the present study is using these data as input into.

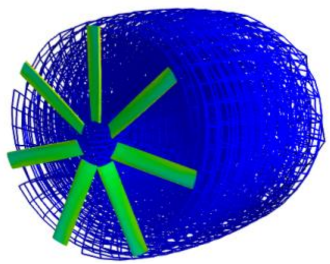


Objective

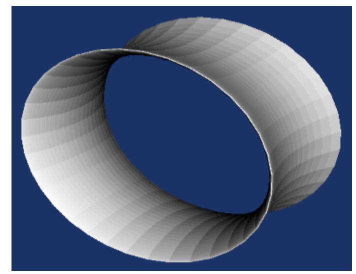
Marine propeller theory → Panel method Coupled BEM → Bare turbine design → Ducted turbine design → Hydrodynamic performance → Finite elements analysis (FEA) → Structural design composite materials → Damage induced by impact

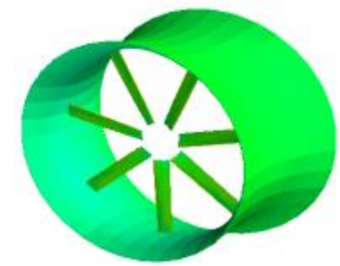
① Bare turbine design
Rotor design optimization



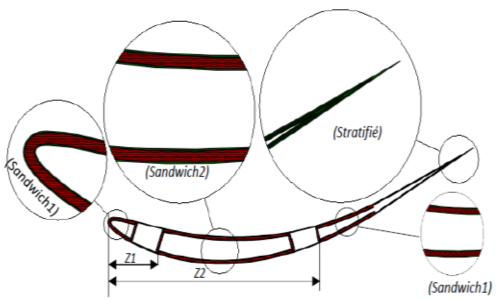


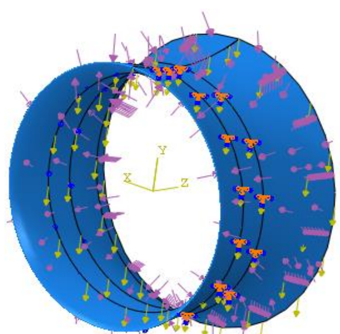
② Ducted turbine design
Geometric parameters of the duct



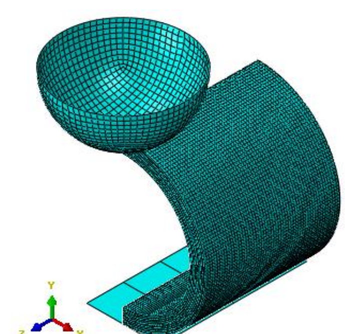


③ Structural design with composite materials
FE analysis: maximum deflexion and failure criterion



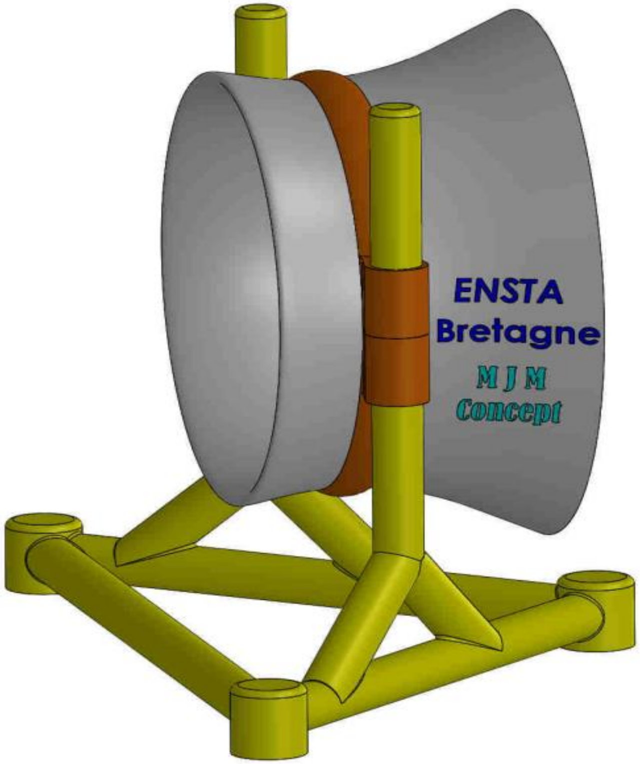


④ Impact behaviour of the composite duct
Damage modelling and certification



Presentation Overview

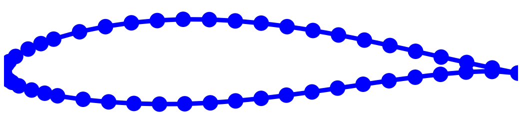
- **Hydrodynamic design**
  - Comparison between theory and data experiment
  - Rotor design procedure
  - Ducted turbine design procedure
- **Composite ducted water turbine**
  - Panel Method-FEA coupled method
  - Structural design optimization
- **Impact damage modeling**
  - Failure and damage modeling
- **Conclusion**



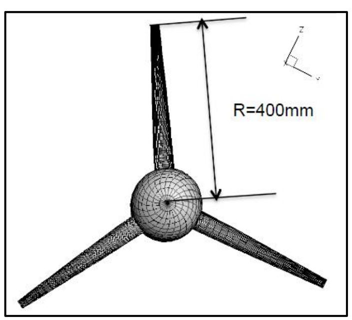
Performance comparison: theory vs. experiments

$$C_p = \frac{\omega Q}{\frac{1}{2}\rho A_r U^3}$$

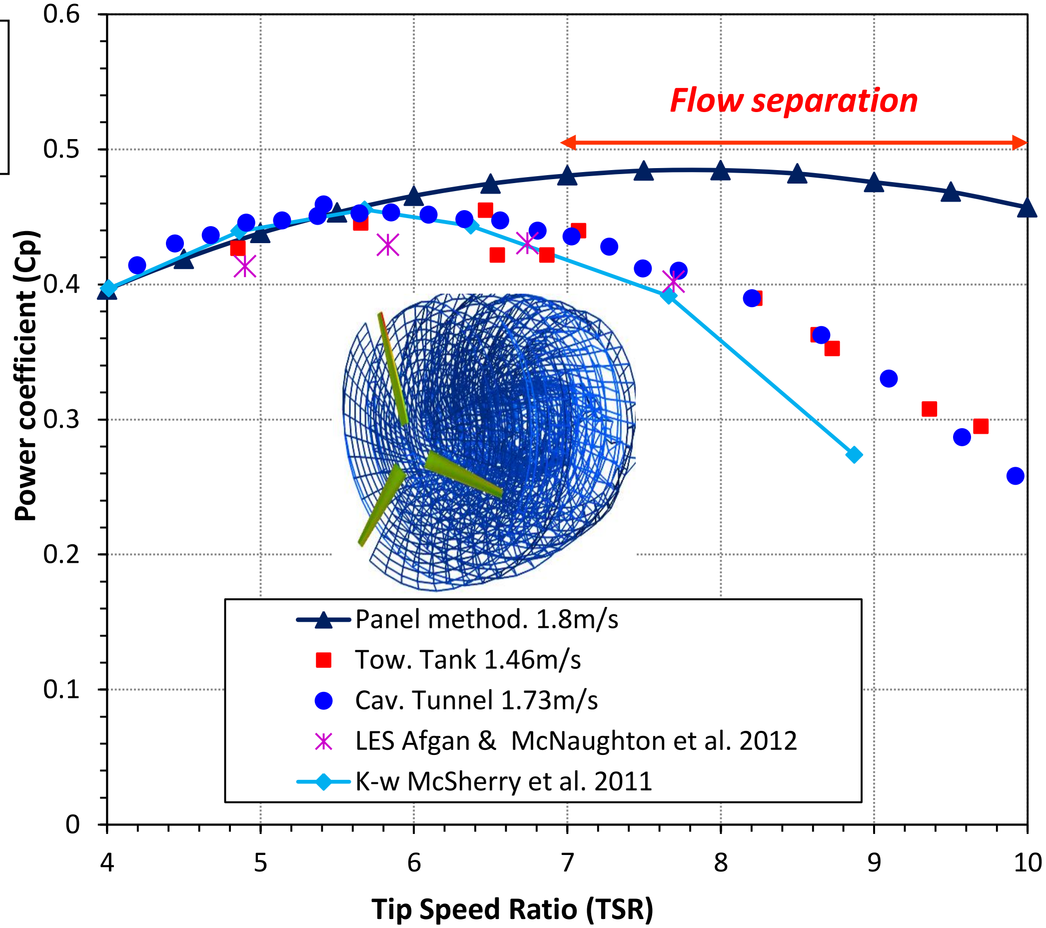
Experimental data :
Bahaj et al. 2007
(Tow. Tank 1.46m/s)
(Cav. Tunnel 1.73 m/s)



NACA 63-818

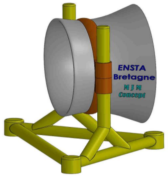


Numerical simulation
(Panel Method 1.8 m/s)



Power coefficient evolution versus TSR

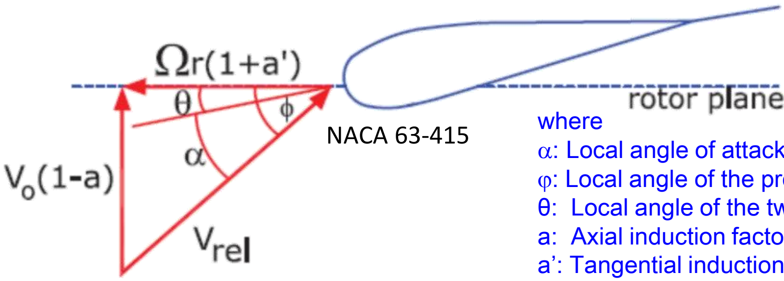
- Numerical results closer to the experimental data up to the area where there is no flow separation (TSR>7)
- The potential flow theory cannot simulate flow separation and stall



Rotor design

The design of tidal turbine is imposed by:

- ***The cavitation inception***
- ***Flow separation has to be avoided***

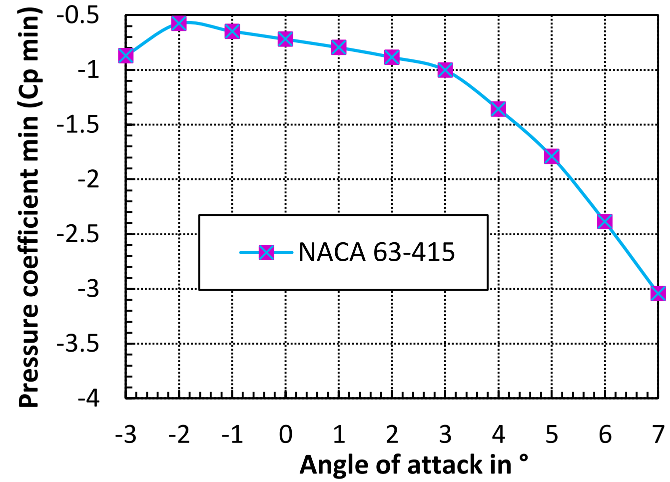


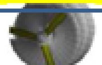
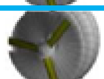
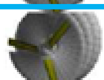
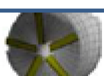
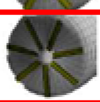
where
α: Local angle of attack
φ: Local angle of the profile
θ: Local angle of the twist
a: Axial induction factor
a': Tangential induction factor

$$tan\varphi = \frac{(1-a)V_o}{(1+a')\omega r}$$

$$a = \frac{1}{3}$$

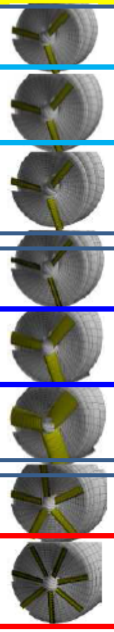
$$a' = \frac{a(1-a)}{\left(TSR\,\frac{r}{R}\right)^2}$$



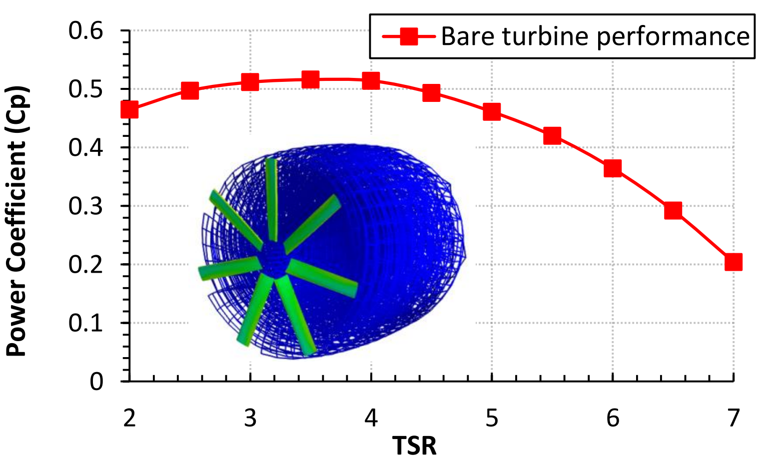
Z		P/D	c/D	AER	Kq	Cp	Cp %Betz	Power (Watt)
3		0.5	0.1	0.095	0.011	0.361	60.842	1.57E+06
3		0.4	0.1	0.095	0.013	0.431	72.790	1.88E+06
3		0.6	0.1	0.095	0.008	0.271	45.791	1.18E+06
3		0.4	0.07	0.067	0.012	0.395	66.591	1.72E+06
3		0.4	0.166	0.159	0.013	0.438	73.908	1.90E+06
3		0.4	0.25	0.239	0.012	0.398	67.144	1.73E+06
5		0.4	0.1	0.159	0.015	0.492	82.987	2.14E+06
7		0.4	0.07	0.159	0.016	0.523	88.197	2.24E+06

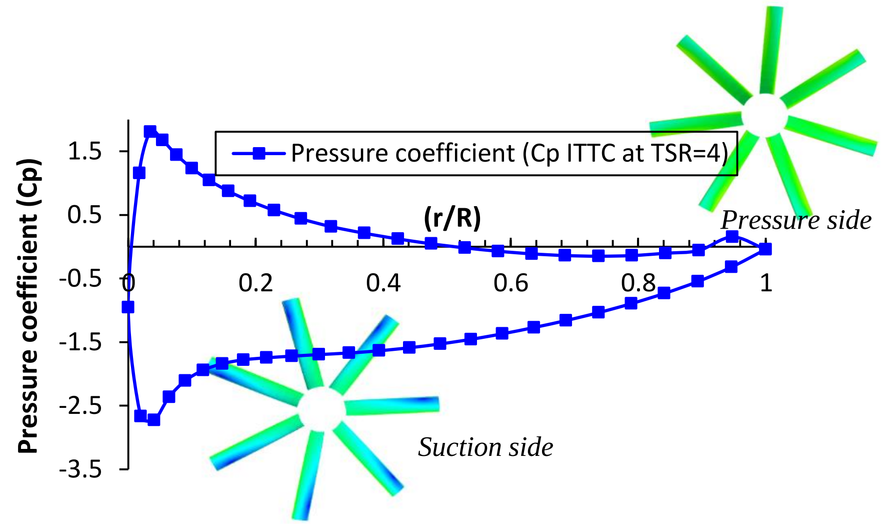
Where:
Z: Number of blades
P/D: Average pitch (propeller pitch definition)
c/D: Chord
AER: Aspect ratio
Kq: Torque coefficient
Cp: Power coefficient

Bare turbine final design

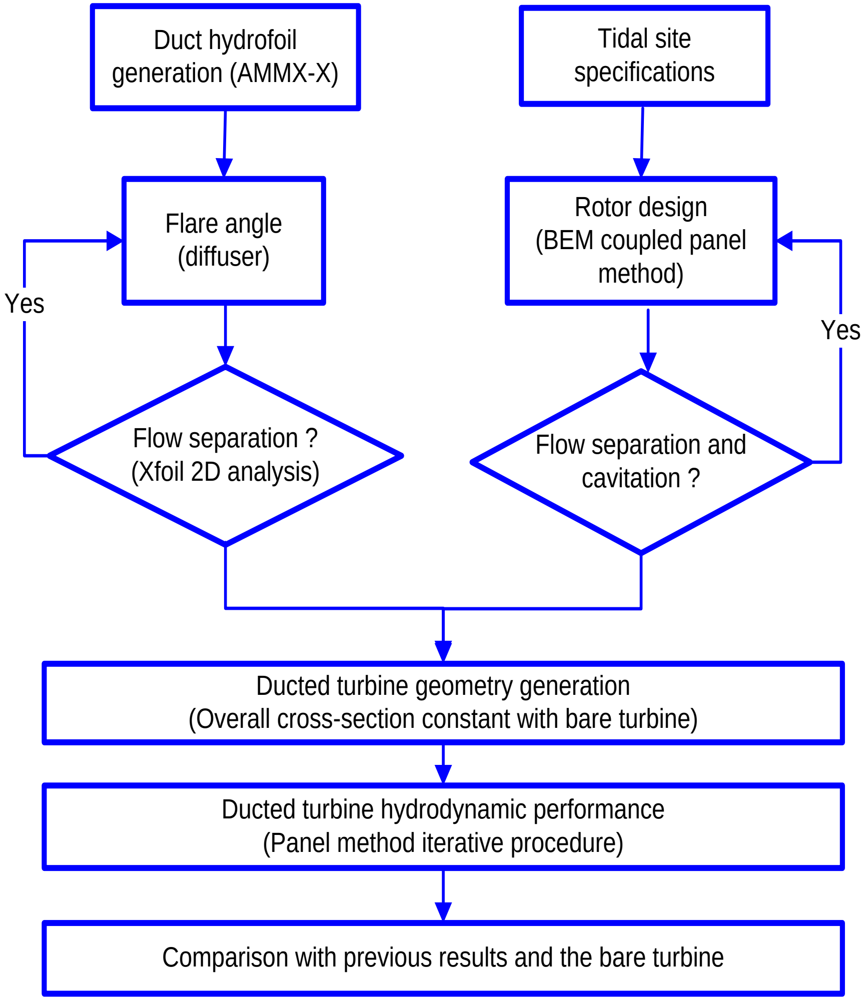


Z		P/D	c/D	AER	Kq	Cp	Cp %Betz	Power (Watt)
3		0.5	0.1	0.095	0.011	0.361	60.842	1.57E+06
3		0.4	0.1	0.095	0.013	0.431	72.790	1.88E+06
3		0.6	0.1	0.095	0.008	0.271	45.791	1.18E+06
3		0.4	0.07	0.067	0.012	0.395	66.591	1.72E+06
3		0.4	0.166	0.159	0.013	0.438	73.908	1.90E+06
3		0.4	0.25	0.239	0.012	0.398	67.144	1.73E+06
5		0.4	0.1	0.159	0.015	0.492	82.987	2.14E+06
7		0.4	0.07	0.159	0.016	0.523	88.197	2.24E+06



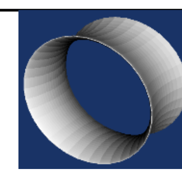
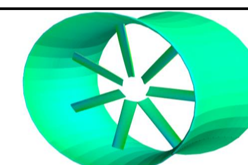
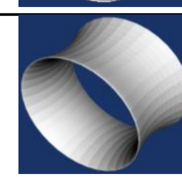
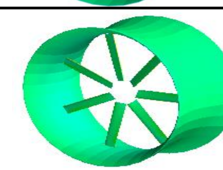
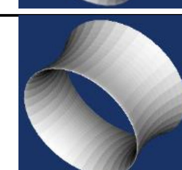
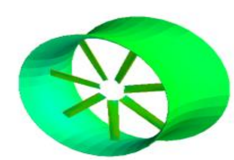


Ducted turbine design procedure

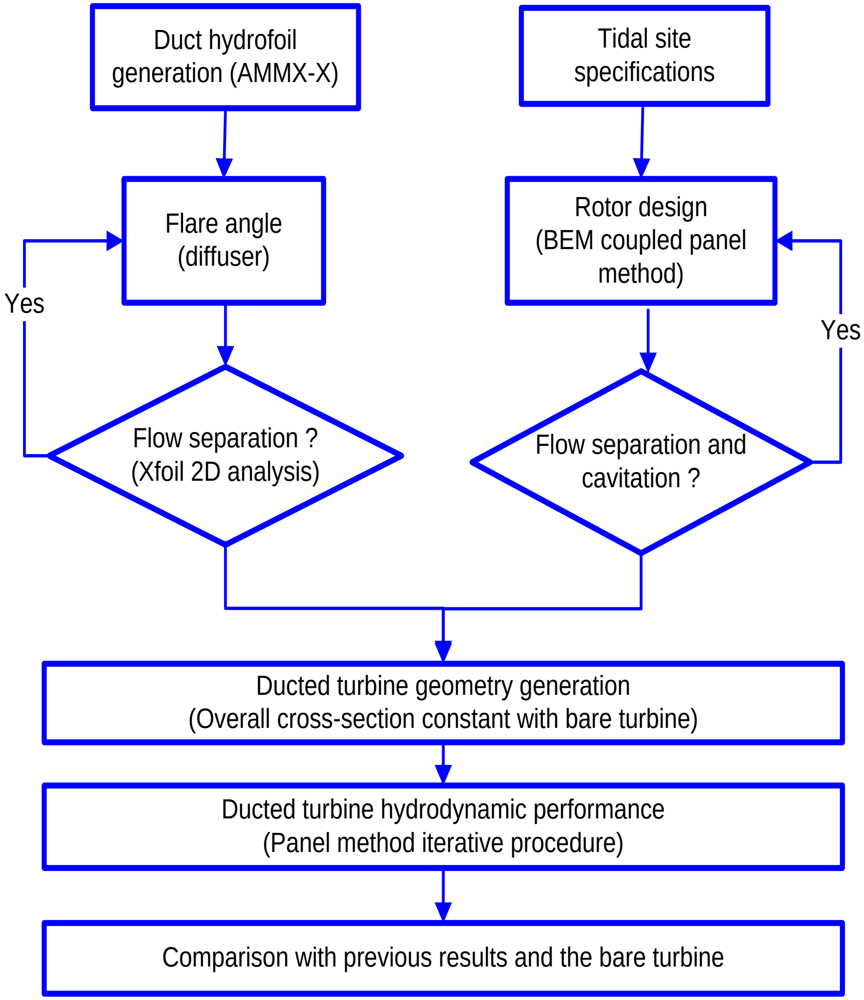


Flowchart of the hydrodynamic modelling process of the ducted turbine

Angle de diffusion Max thickness 6% Max camber 12%	**0°**	**2°**	**5°**
Rotor diameter (m)	**17.08**	**16.87**	**16.32**
Cp max	0.73	0.76	0.81
Cp* max	**0.53**	**0.54**	**0.55**
TSR	5.5	5	6
Power(M Watt)	2.32	2.35	2.36
Real benefit relative to bare turbine at the same overall diameter (20m)	+3.67 %	+5.20 %	+5.30 %

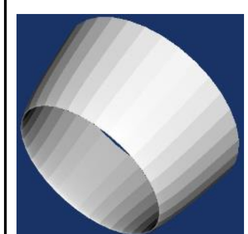
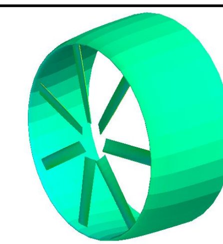
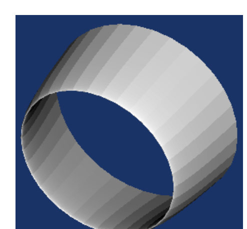
Flare angle	***Duct geometry***	***Ducted configuration***
0°		
2°		
5°		

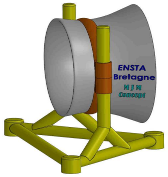
Ducted turbine design procedure



Flowchart of the hydrodynamic modelling process of the ducted turbine

Flare angle Max thickness 6% Symmetrical profile	9°	11°
Rotor diameter (m)	16.83	16.24
Cp max	0.84	0.96
Cp* max	0.60	0.63
TSR	5.5	6
Puissance(M Watt)	2.60	2.77
Real benefit relative to bare turbine at the same overall diameter (20m)	+14.12 %	+19.18%

Flare angle	*Duct geometry*	*Ducted configuration*
9°		
11°		



Discussion

- ❑ Before designing the water turbine, the site characteristics must be well defined (dimension, current velocity, depth)

➡ BARE TURBINE CONFIGURATION

- ❑ Adapting numerical tools for marine propellers to water turbines design
- ❑ Blade element method is used to estimate the pitch distribution
- ❑ The potential flow is computed using panels method
- ❑ The bare turbine reaches 88% of the Betz limit

➡ DUCTED TURBINE CONFIGURATION

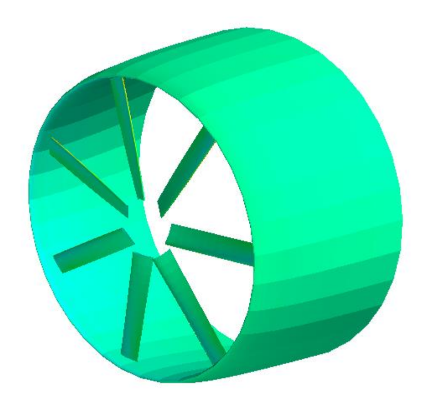
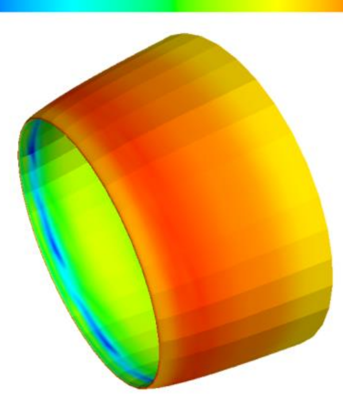
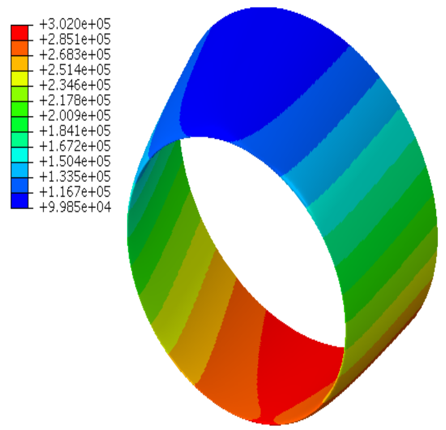
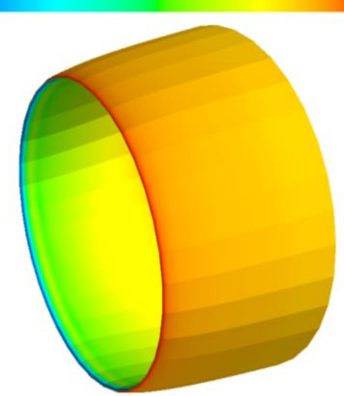
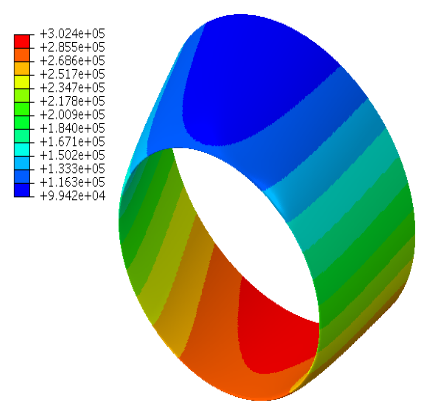
- ❑ The duct induced circulation accelerates the inner flow
- ❑ The rotor and duct system is solved using an iterative method
- ❑ The addition of the duct must be made with a constant overall cross-section. The Cp definition is modified to Cp* to be defined as a function of the overall section and not the rotor section only. We obtained up to 20% gain in power.

Presentation Overview – Structural design

- ❑ Structural design
  - ✓ Composite ducted turbine
  - ✓ Structural optimization
- ❑ Composite material under dynamic load
  - ✓ Impact damage modelling : Numerical model (VUMAT-CZM)
  - ✓ Model validation (VUMAT-CZM *vs* Experimental)
- ❑ Impact on ducted turbine
- ❑ Conclusion

Structural design

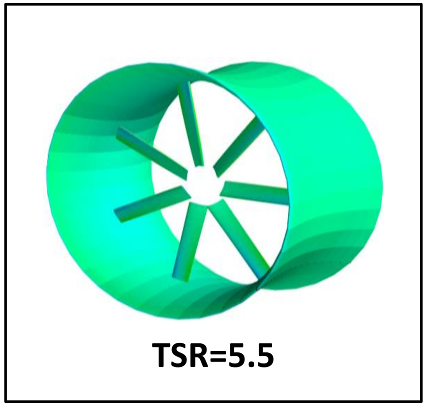
- The Panel Method-Finite Element Analysis (PM-FEA) coupled method allows to use the hydrodynamic pressure obtained with the panel method program as input into the FEA code.
- The DLOAD user subroutine is computed into the FEA (ABAQUS) code to project the hydrodynamic pressure on the duct panel structural mesh.

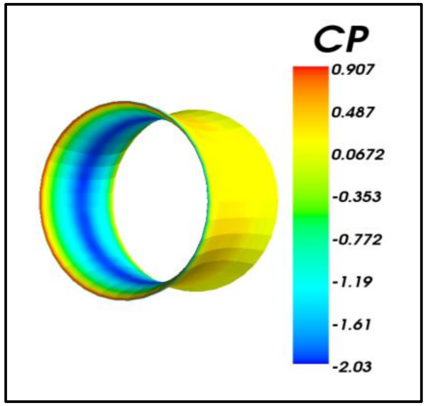
	Ducted turbine design	Hydrodynamic pressure	Hydrostatic pressure (Pa)
AMM0-6 – 9°flare angle Symmetrical profile 6% maximum thickness Cp*=0.60 De/Ds=0.85	 TSR=5.5	 	
AMM0-6 –11°flare angle Symmetrical profile 6% maximum thickness Cp*=0.63 De/Ds=0.82	 TSR=6	 	

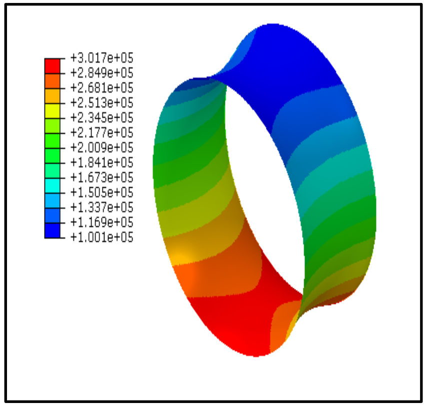
Structural design

Ducted turbine design | **Hydrodynamic pressure** | **Hydrostatic pressure (Pa)**

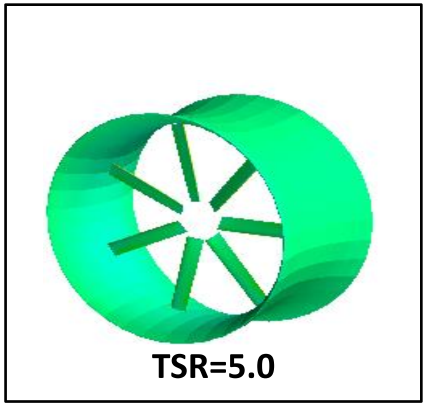
AMM12-6 –Diffuseur à 0°
12% de cambrure max
6% d'épaisseur max
Cp*=0.53
De/Ds=1

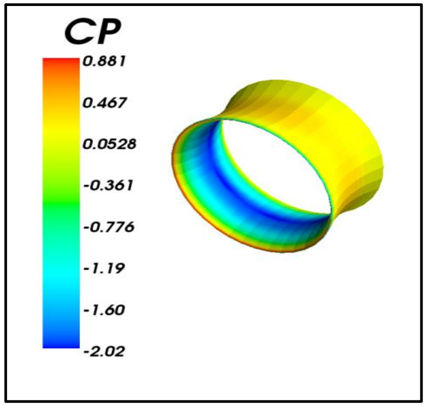


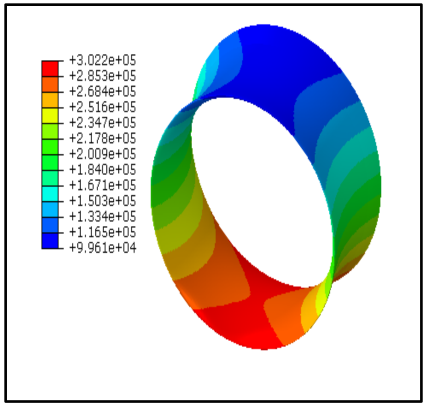




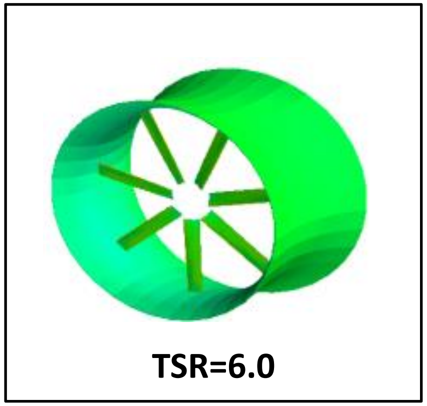
AMM12-6 –Diffuseur à 2°
12% max camber
6% max thickness
Cp*=0.54
De/Ds=0.975

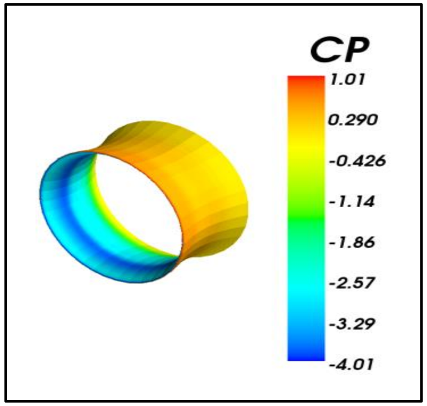


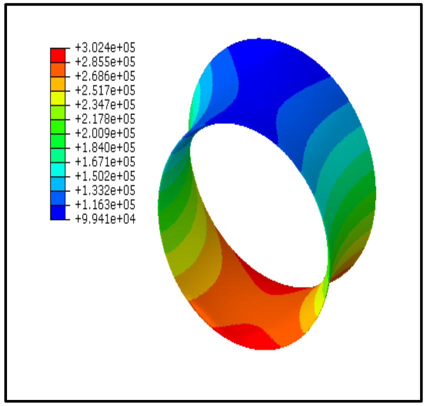


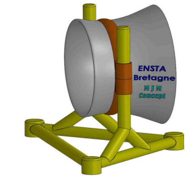


AMM12-6 –Diffuseur à 5°
12% max camber
6% max thickness
Cp*=0.55
De/Ds=0.925



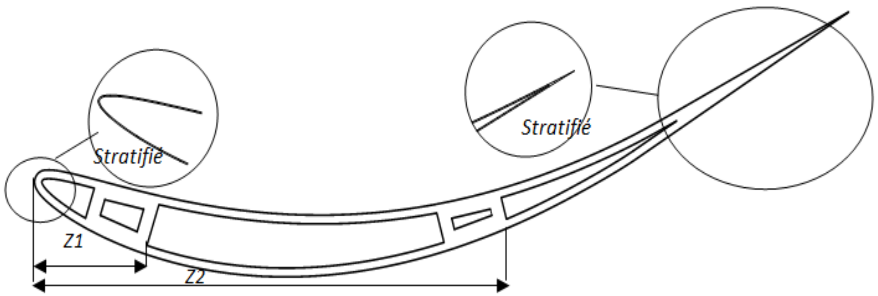




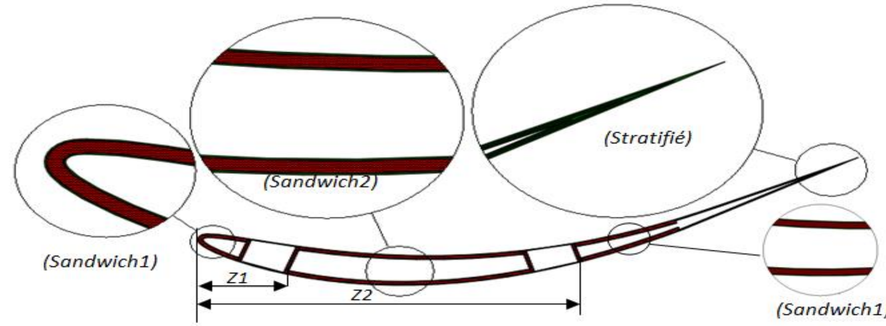


Structural optimization

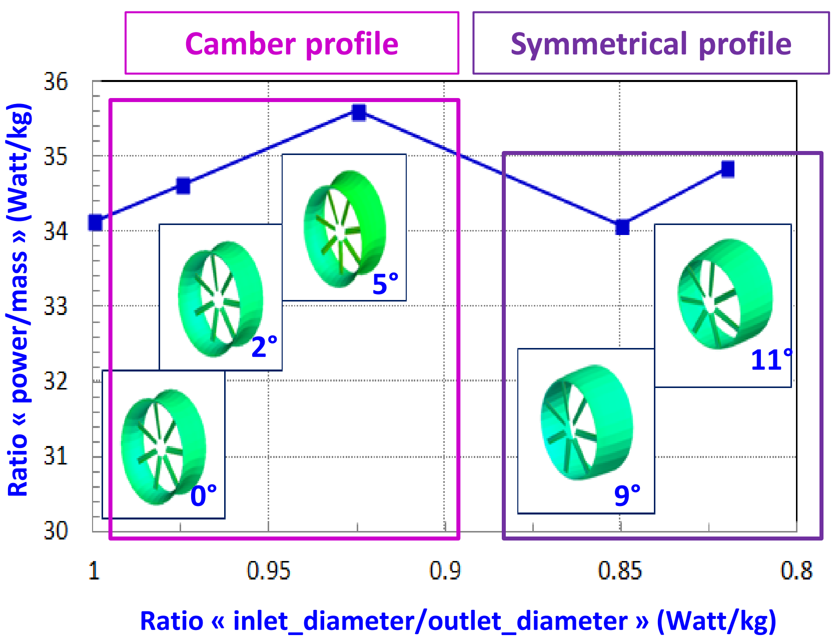
- Iterative procedure with 3 criteria: max. deflexion, failure (Hashin criterion) and max. «power/mass»
- With the only Hashin criterion, the convergence is obtained at the first iteration



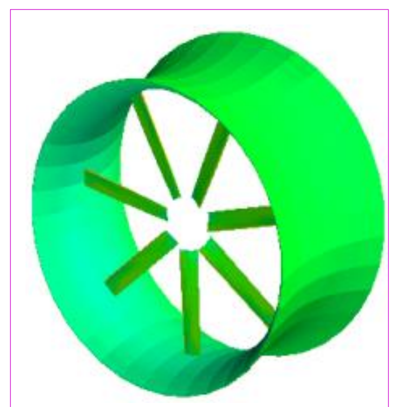
First iteration (profile AMM 12-6- à 5°)



Final iteration (profile AMM 12-6 à 5°)



Ratio «power/masse» versus Rapport «D_inlet/D_outlet»



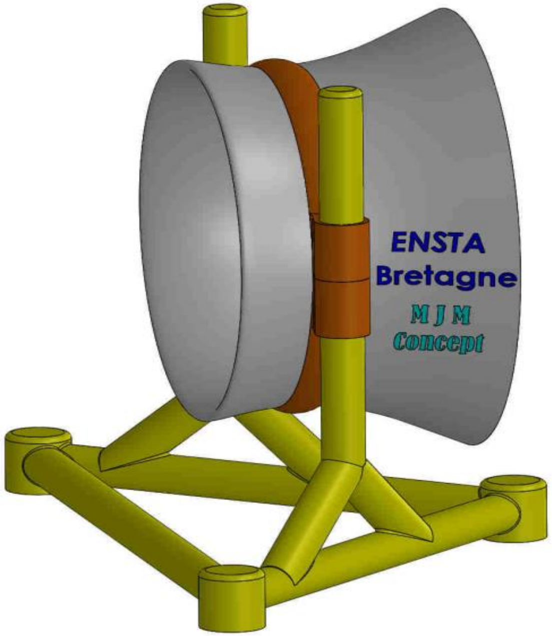
AMM 12-6 –Diffuser 5°

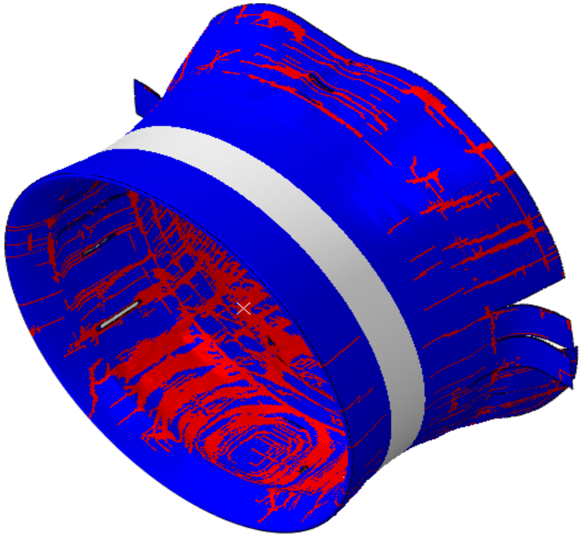
- ✓ **Structural integrity**
- ✓ **Minimizing the mass**
- ✓ **Best ratio power/mass**
- ✓ **Camber profile rather incidence**

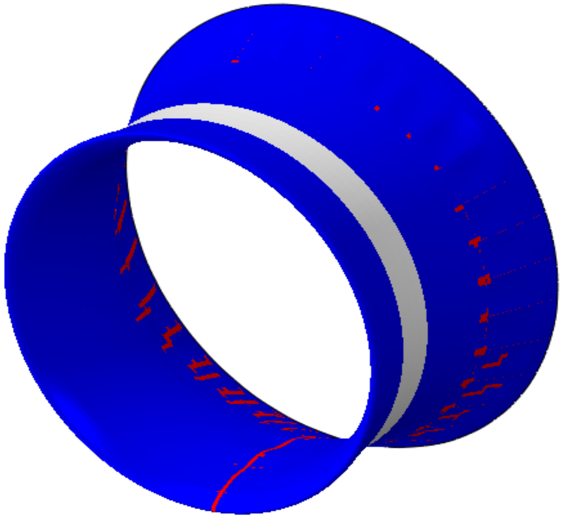
✓ **Final turbine design :**
- **Effective power coefficient 55%**
- **Ratio «D_inlet/D_outlet»= 0.925**
- **Ratio « power/mass » = 35.7 Watt/Kg**

Presentation Overview

- ❑ Structural design
  - ✓ Composite ducted turbine
  - ✓ Structural optimization
- ❑ **Composite material under dynamic load**
  - ✓ **Impact damage modelling: Numerical model (VUMAT-CZM)**
  - ✓ **Model validation (VUMAT-CZM vs Experiment)**
- ❑ Impact on ducted tidal turbine
- ❑ Conclusion





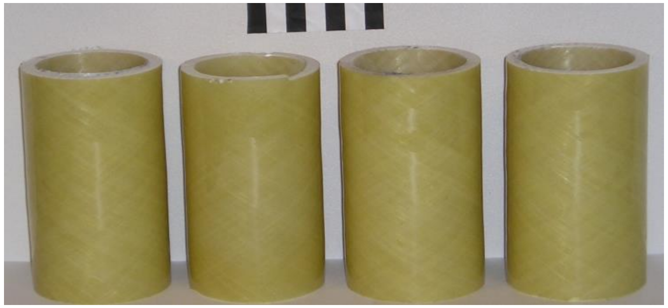


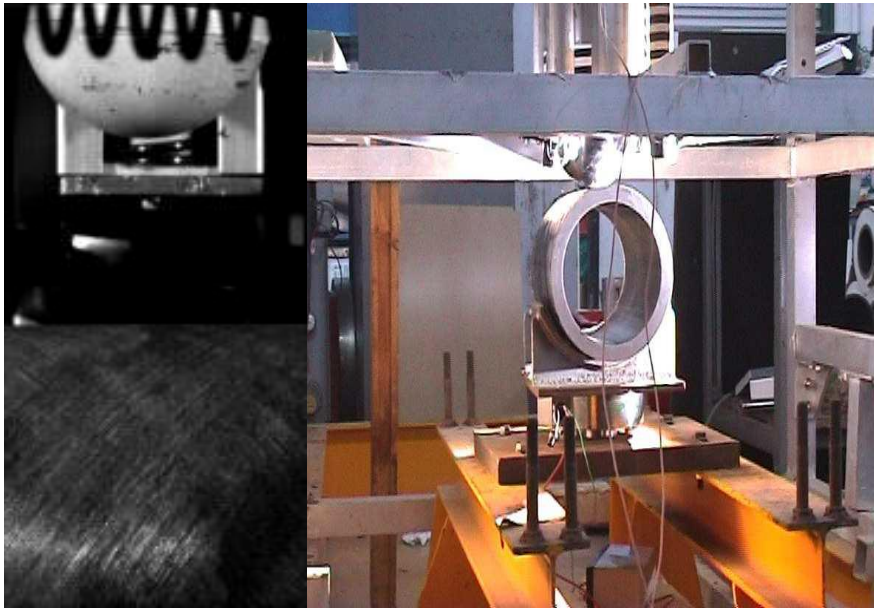
Impact damage modelling

- Low velocity impact investigation on tubular structure
- Damage model (VUMAT)

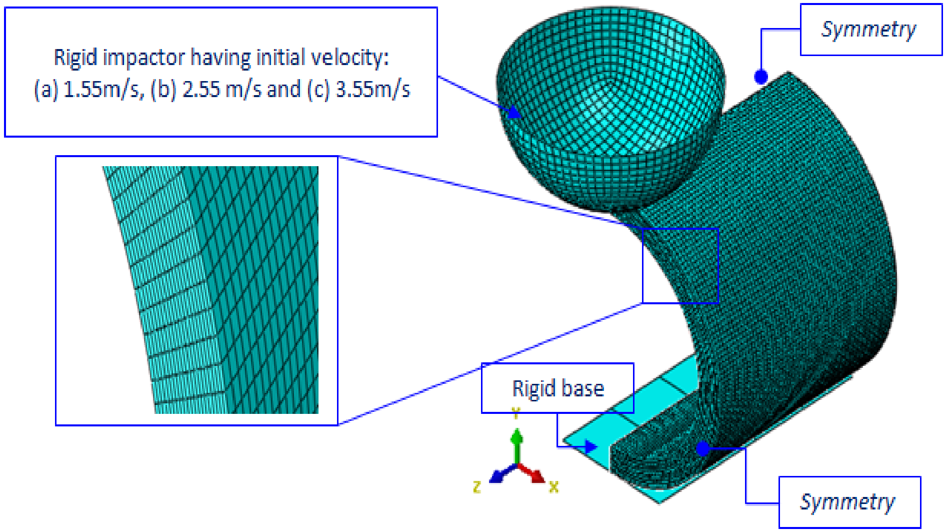
Numerical model:

Glass/Epoxy tube [± 55°]$_{10}$
Internal diameter : 55 mm
Thickness : 6 mm
Impact velocities: 1.55, 2.55 and3.55 m/s.
Mesh using C3D8R elements





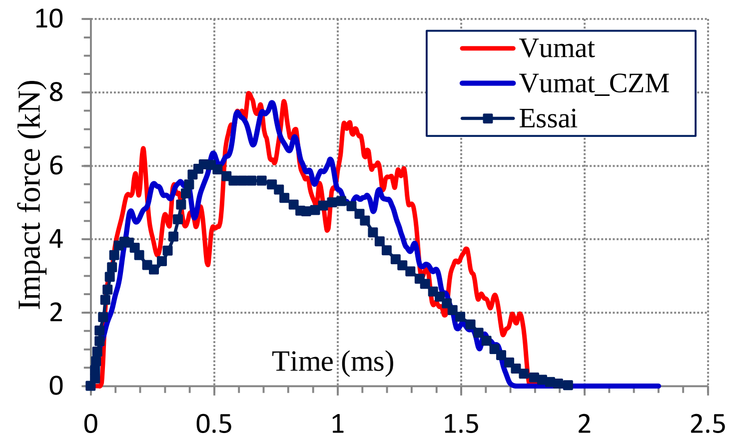
Experimental set-up of impact investigation



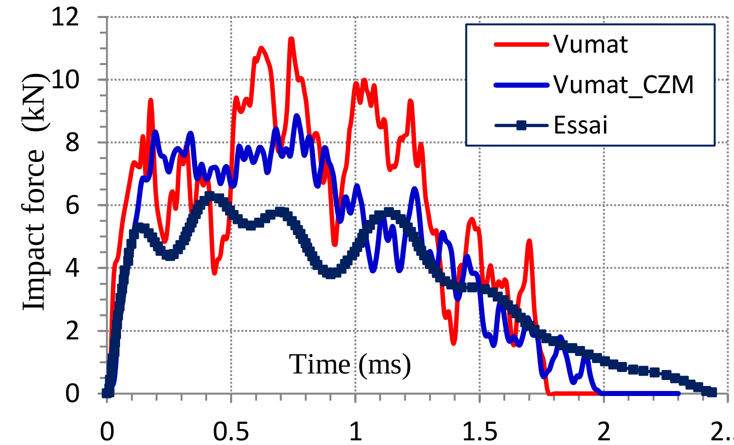
1/4 Finite element model of the composite cylinder

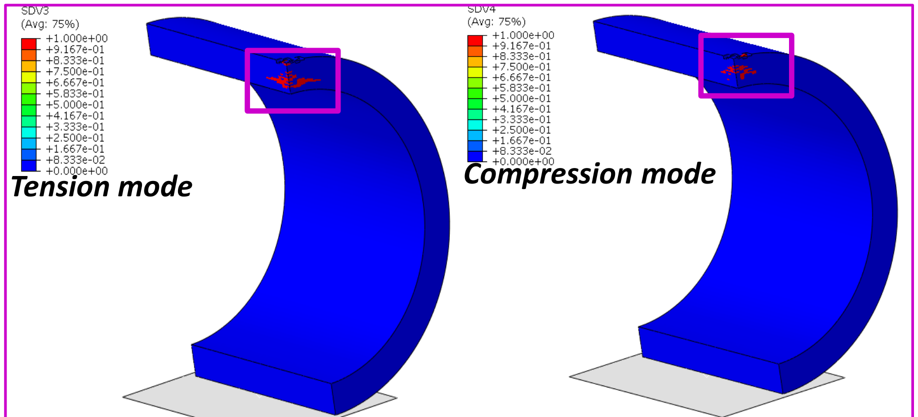
Damage model validation

- **Impact energy of 5.202 Joules (V=2.55 m/s)**

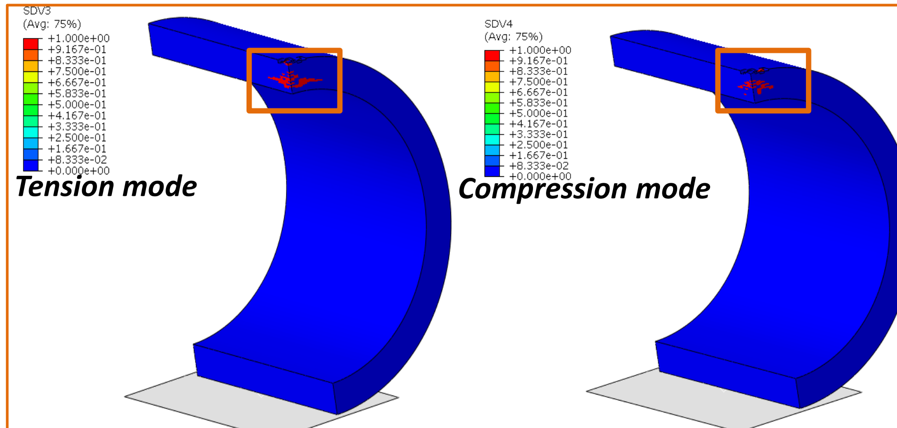


- **Impact energy of 10.082 Joules (V=3.55 m/s)**



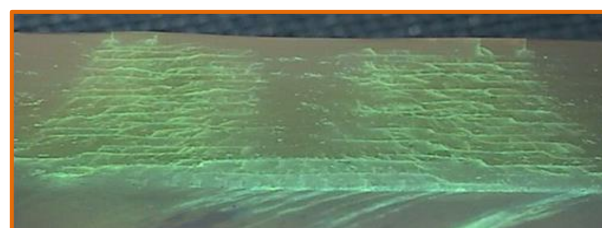


Matrix damage prediction



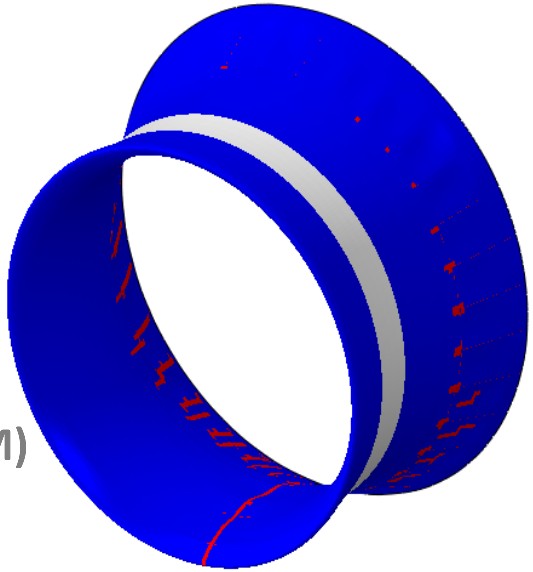
Matrix damage prediction

Axial section through damaged cylinder wall using UV lighting

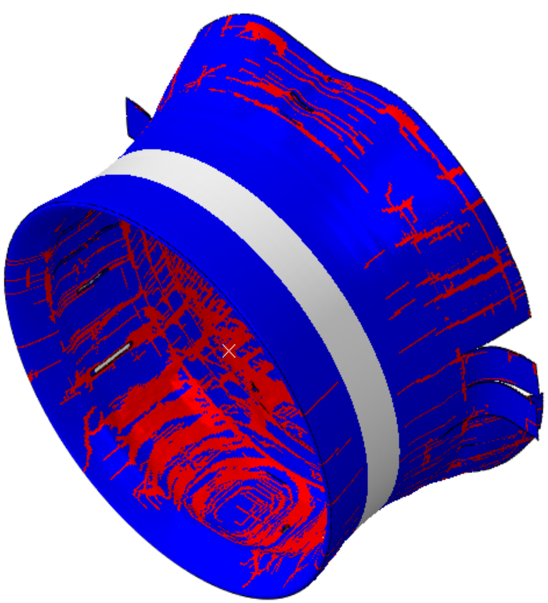


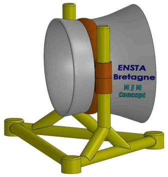
Axial section through damaged cylinder wall using UV lighting

Presentation Overview



- ❑ **Structural design**
  - ✓ **Composite ducted turbine**
  - ✓ **Structural optimization**
- ❑ **Composite material under dynamic load**
  - ✓ **Impact damage modelling: Numerical model (VUMAT-CZM)**
  - ✓ **Model validation (VUMAT-CZM vs Experiment)**
- ❑ **Impact on ducted tidal turbine**
- ❑ **Conclusion**

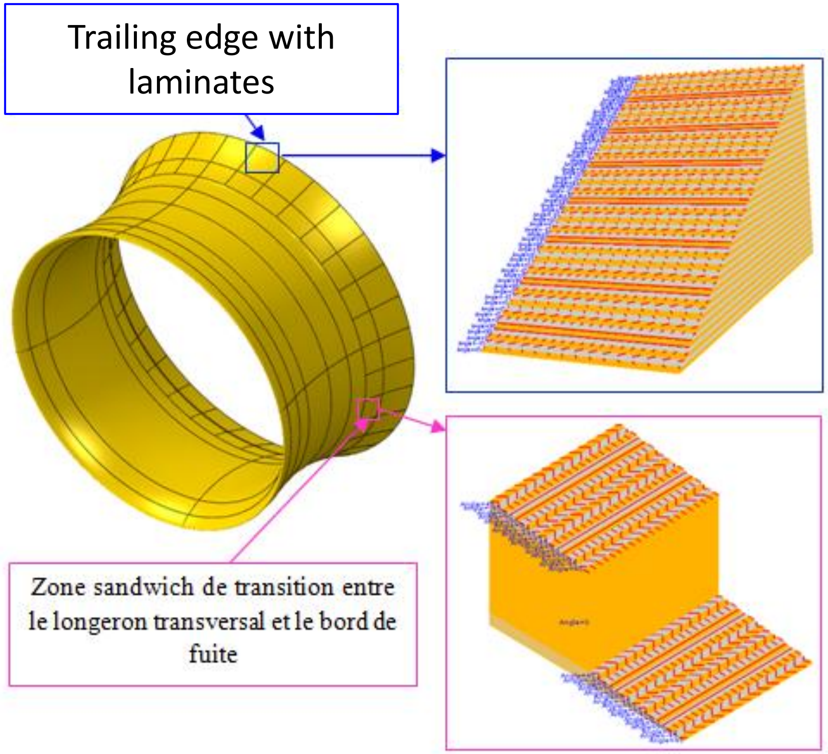


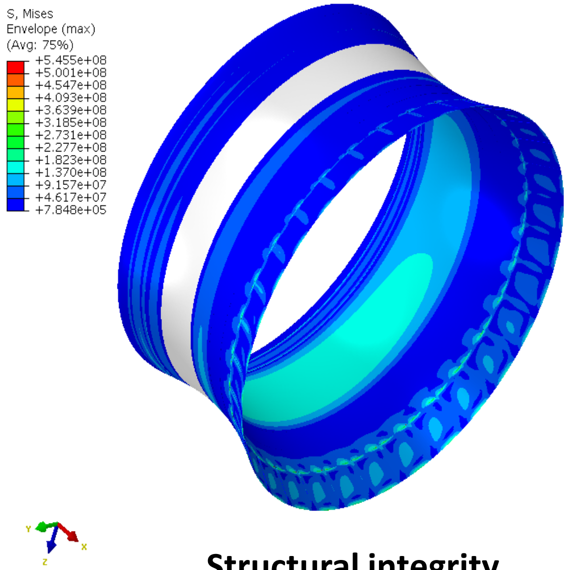


Impact on ducted tidal turbine

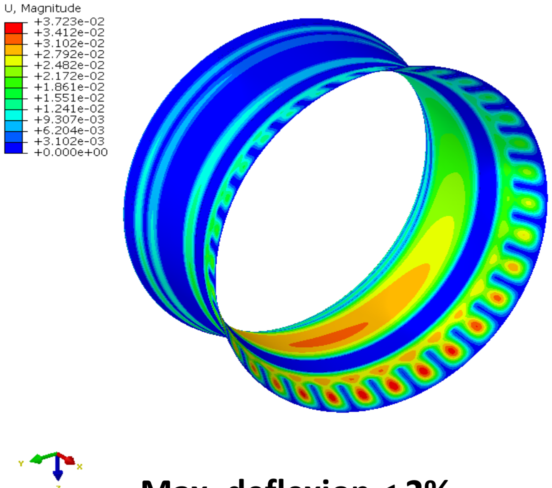
Step 1: Complete duct model

- Stacking layup
- Shel elements (S4R)
- Structural integrity and max. deflexion criteria
- Ratio « power/mass »





Structural integrity

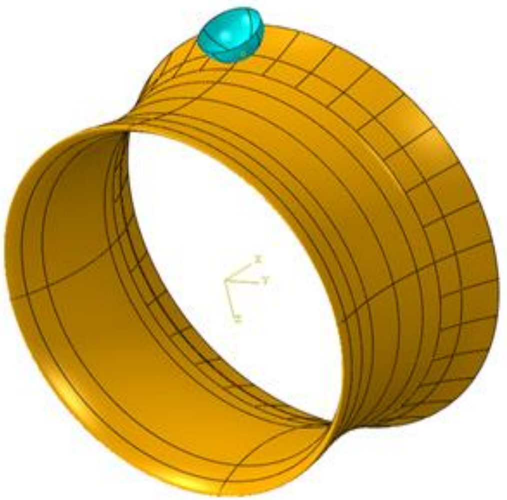


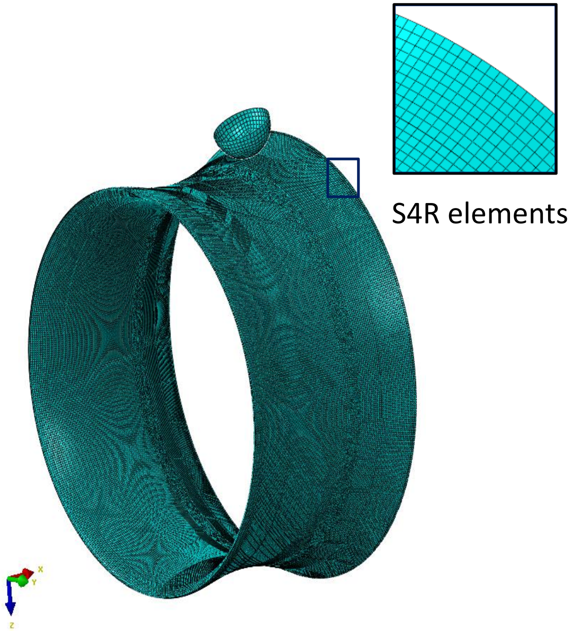
Max. deflexion < 2%

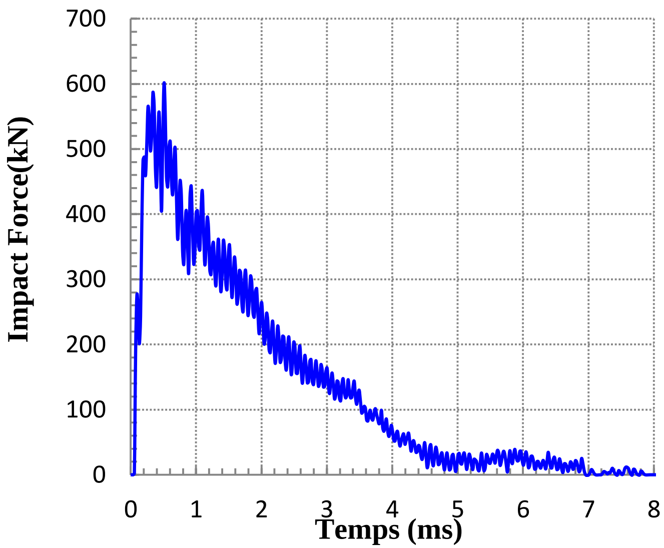
Impact on ducted tidal turbine

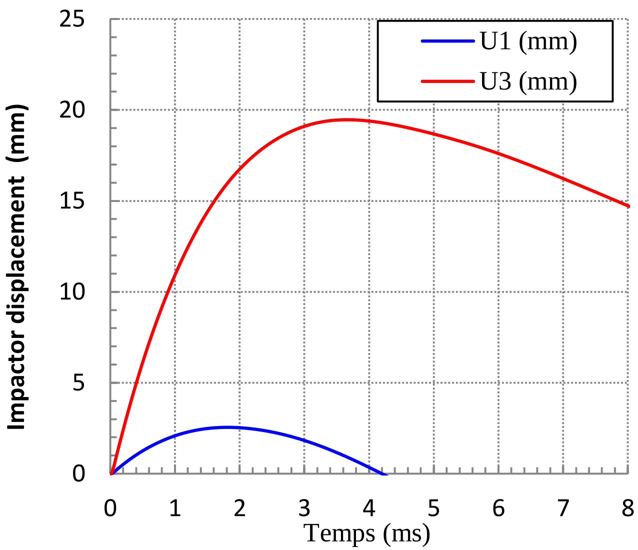
Step 2: Impact model

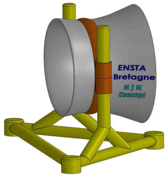
- Impact zone (trailing edge)
- Hemispherical impactor shape
- Impactor : D=3m et M=70Kg
- Normal incidence
- Shel elements (S4R)
- Impact energy 7,18 kJ







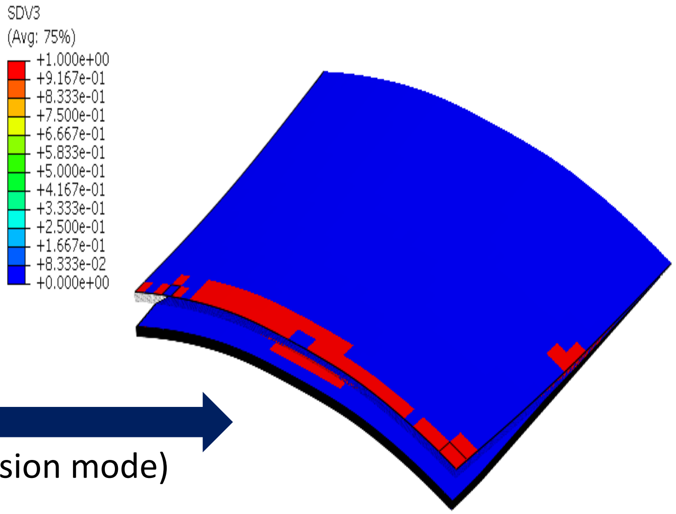




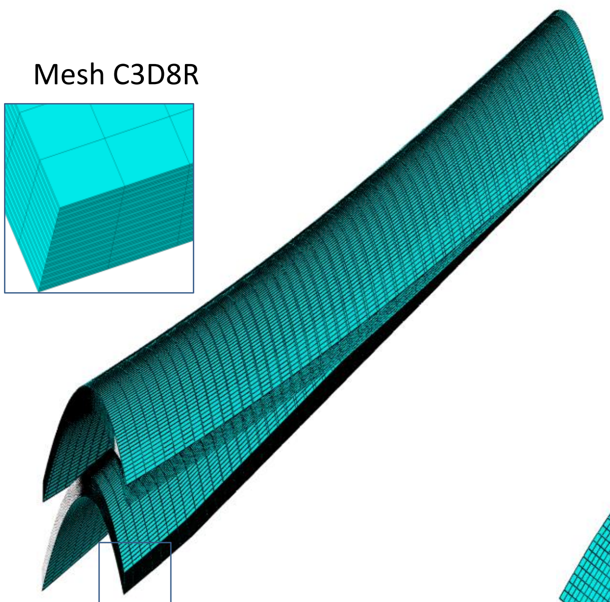
Impact on ducted tidal turbine

Step 3: Submodel containing intralaminar damage model

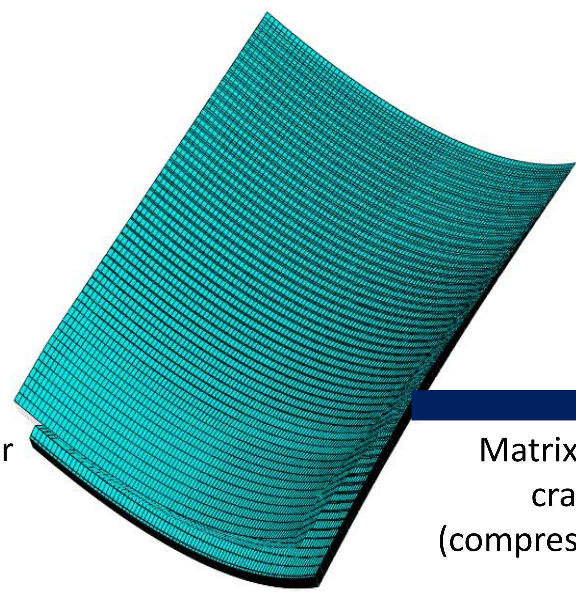
- Numerical zoom in critical zones
- Solid model (C3D8R)
- Results from previous step (global impact model) are considered as input
- The impact scenario is controlled from the previous step
- Damage assessment : Vumat

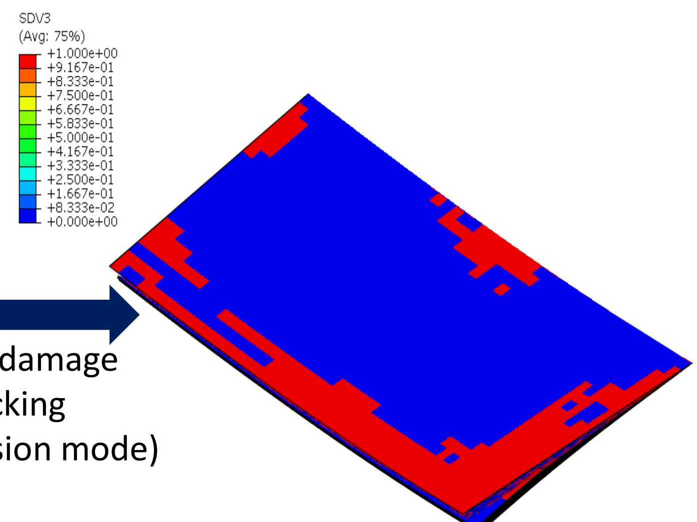


Mesh C3D8R



Matrix damage cracking (tension mode)



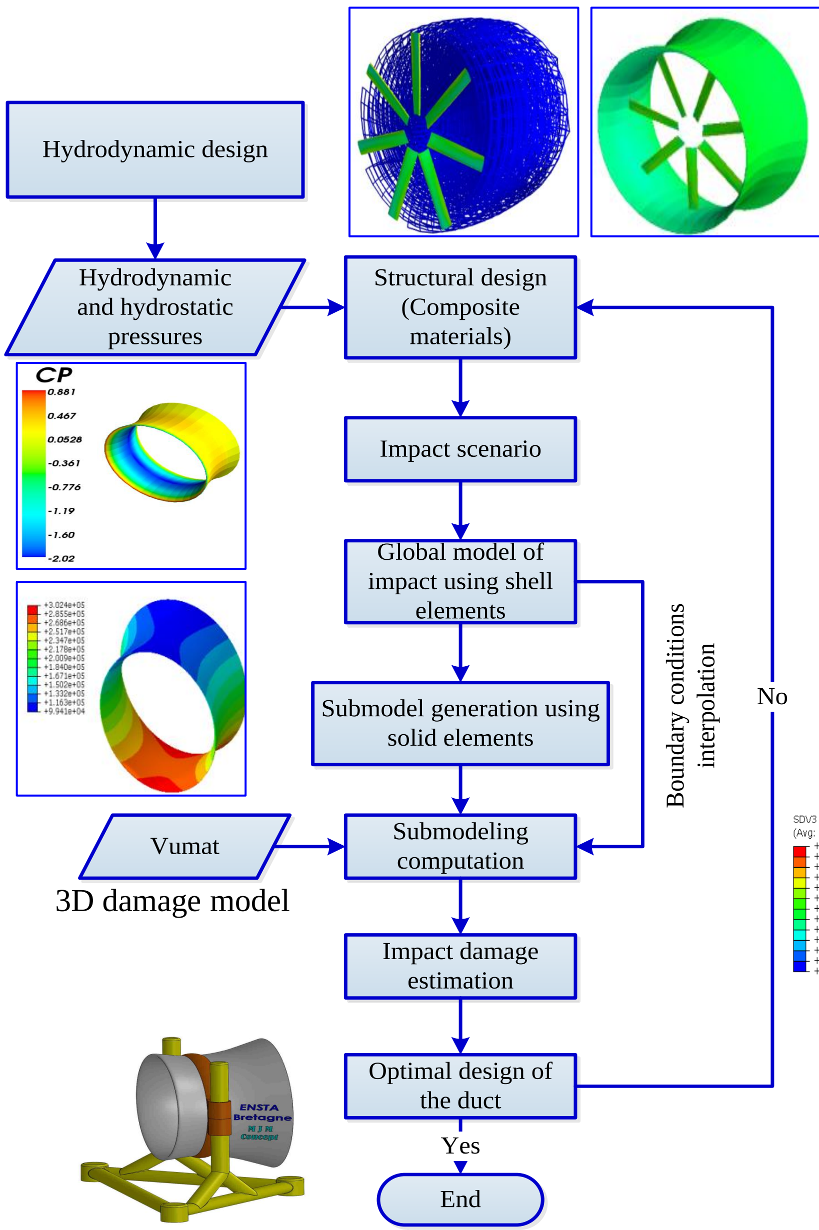


- Zone in contact with the impactor

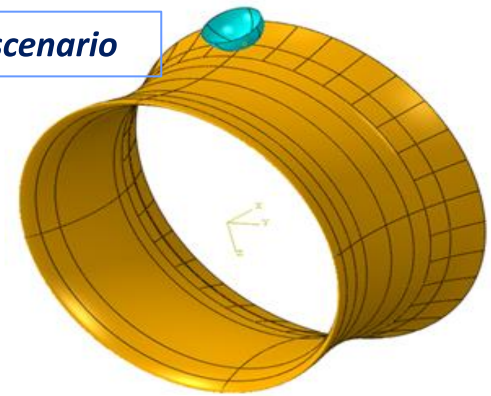
Matrix damage cracking (compression mode)

- Zone in front of the impactor contact zone

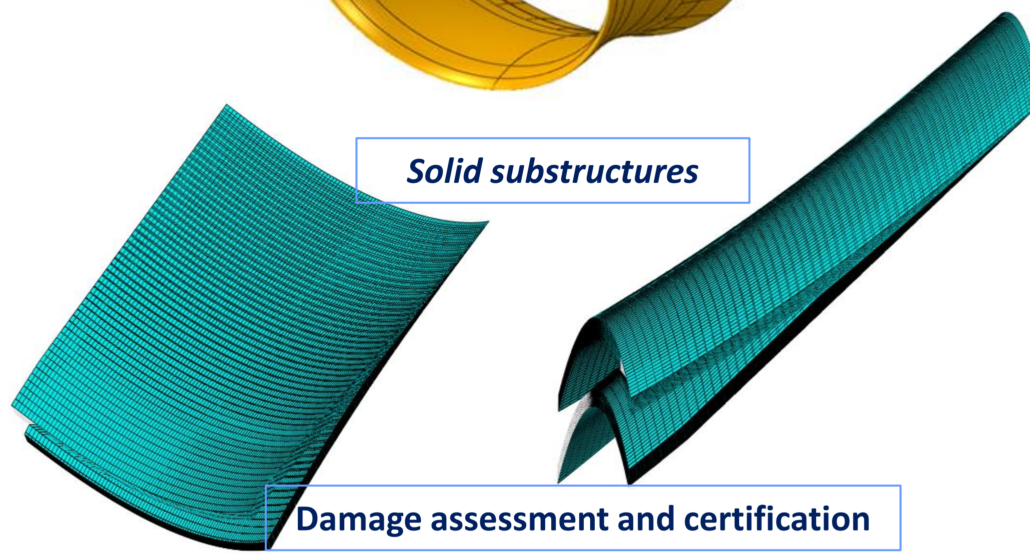
Impact on ducted tidal turbine



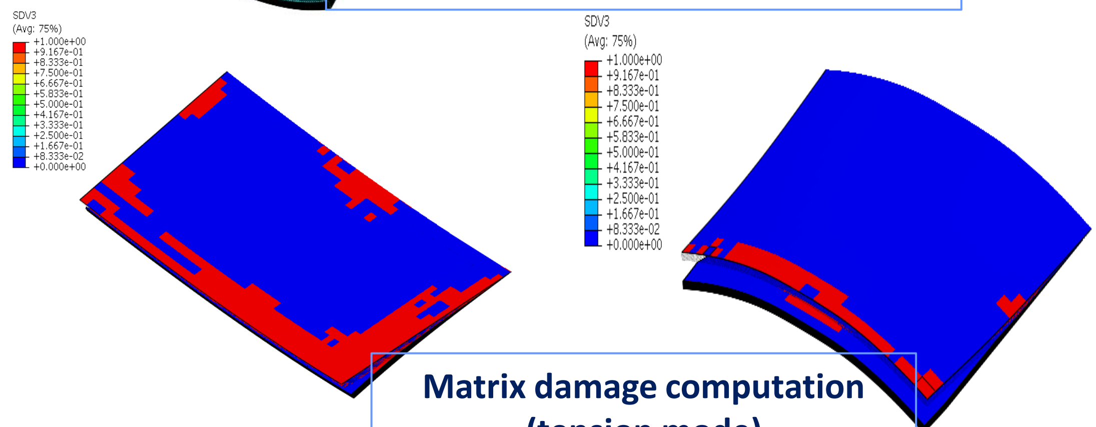
Impact scenario



Solid substructures

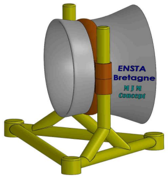


Damage assessment and certification



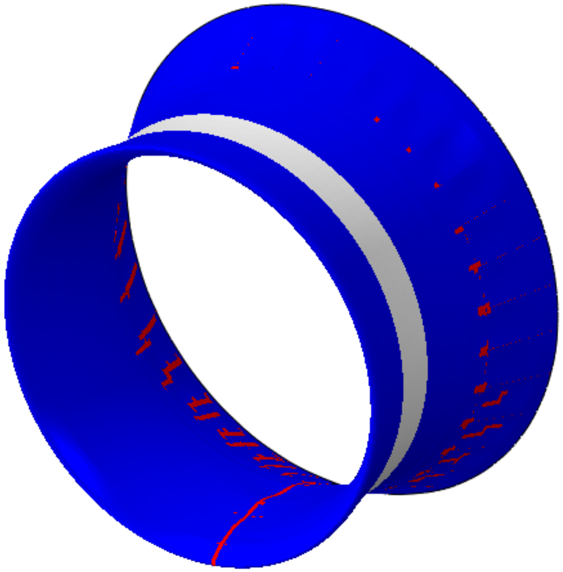
Matrix damage computation (tension mode)

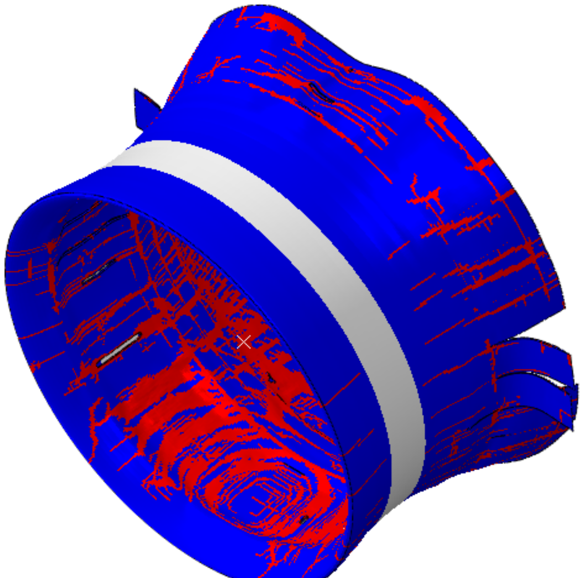
Modeling strategy for studying the damage certification of the MJM concept



Presentation Overview

- ❑ **Structural design**
  - ✓ **Composite ducted turbine**
  - ✓ **Structural optimization**
- ❑ **Composite material under dynamic load**
  - ✓ **Impact damage modelling: Numerical model (VUMAT)**
  - ✓ **Model validation (VUMAT vs Experiment)**
- ❑ **Impact on ducted tidal turbine**
- ❑ **Conclusion**



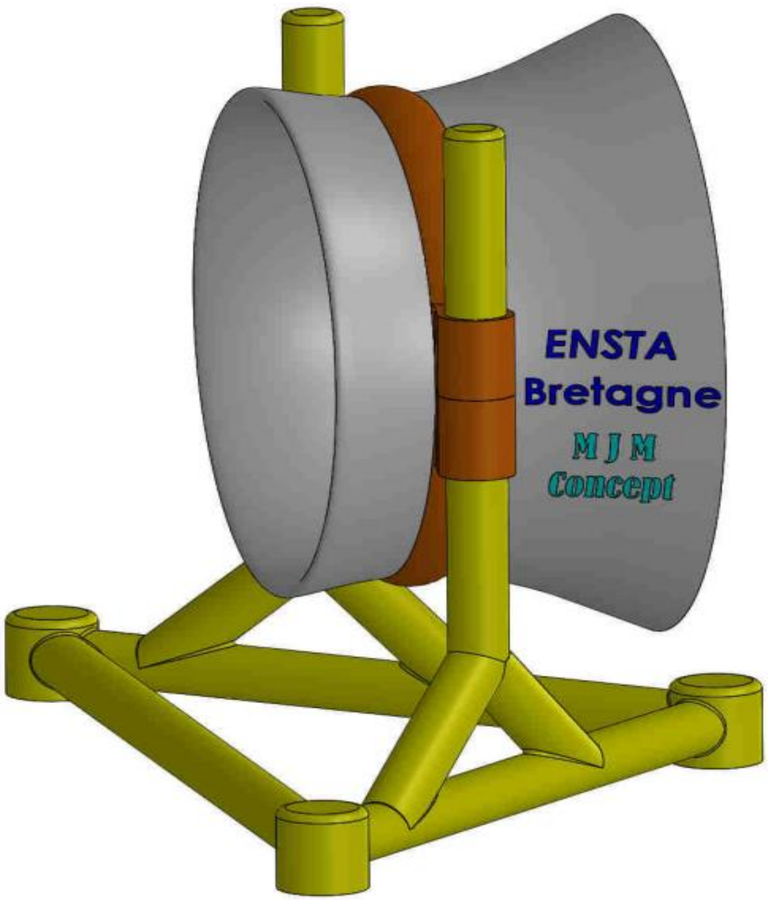


Conclusion

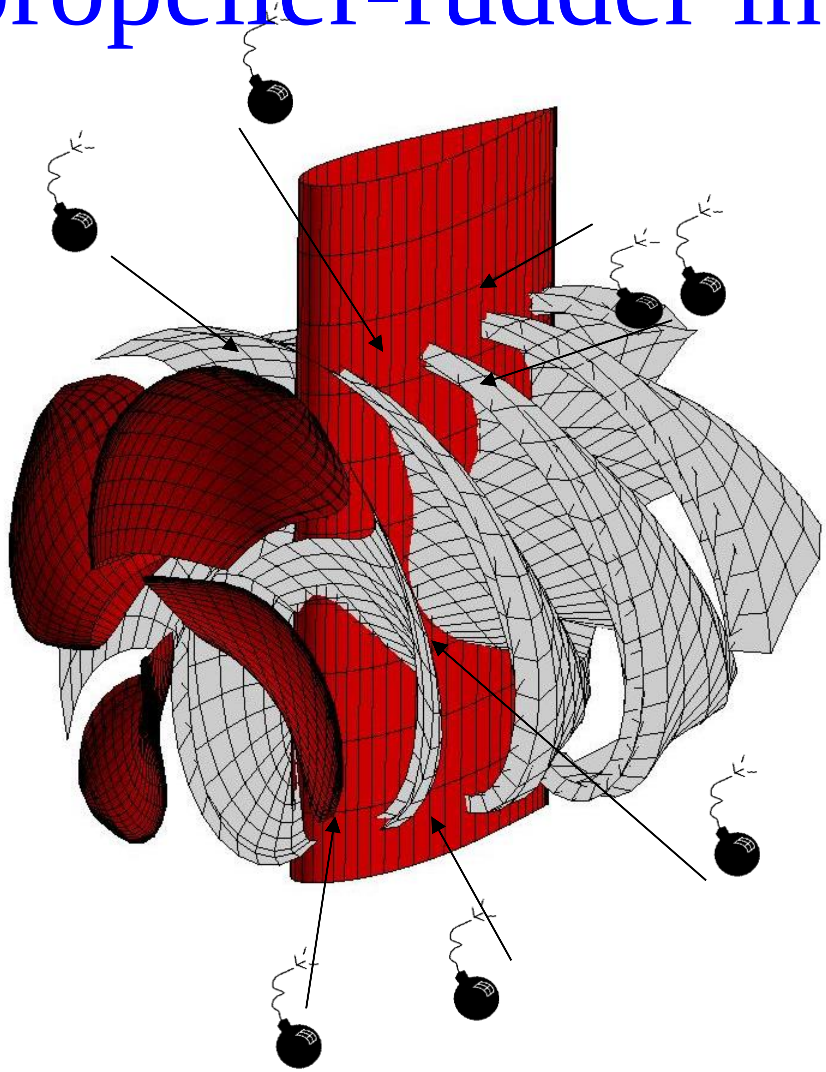
- A design method involving Blade Element Momentum (BEM) and the Panel method code was developed and used to obtain the geometry of an horizontal axis marine current turbine for the Race of Alderney.
- A bare turbine was designed which can attain up to 90% of the Betz limit.
- The addition of an accelerating duct at the same overall diameter with the bare turbine was investigated.
- It was found that, to obtain a sufficient acceleration capable to compensate the loss of blade diameter, the section of the duct has to be seriously cambered, presenting a flare angle or both combination.
- Structural design optimization for optimum ratio <power/mass> leads to a camber duct profile rather than incidence.
- Composite damage model has been developed and validated with experimental measurements.
- The damage model is then used to the certification of the MJM composite ducted tidal turbine concept.
- The developed procedure allow the damage assessment for a better design efficiency of the MJM concept.

Questions

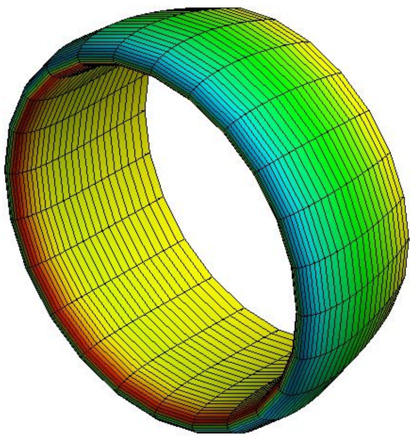
THANK YOU FOR YOUR ATTENTION



Annexe1 : rotor-duct interaction from propeller-rudder interaction

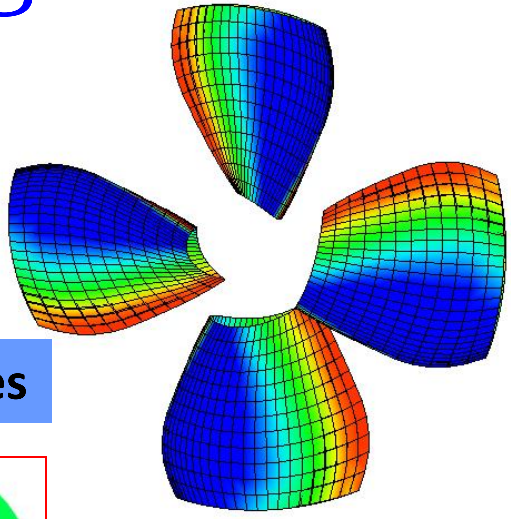


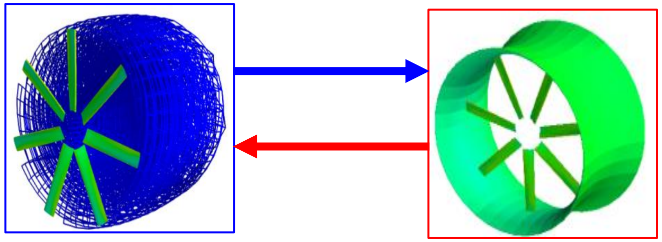
Annexe 2 : Induced velocities method Ducted configuration



Duct induced velocities

Propeller induced velocities





mahrez.ait@ensta-bretagne.org
mostapha.tarfaoui@ensta-bretagne.fr

ENSTA Bretagne

iRDL Institut de Recherche Dupuy de Lôme CNRS FRE 3744

Région Bretagne

Brest Métropole