EPSRC Marine Wave Energy Programme

Bionic Adaptive Stretchable Materials for WEC (BASM-WEC)

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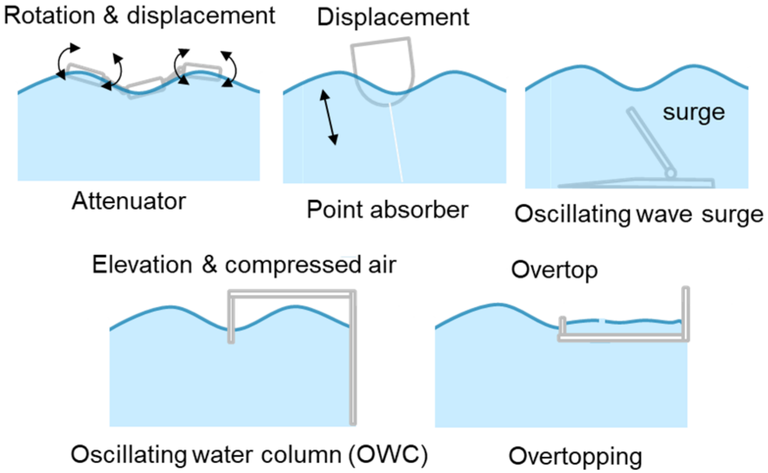
Background

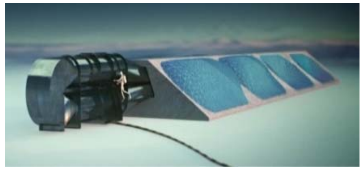
❑ Traditional WEC



- Rigid material components
- Low-performance efficiency and system vulnerability under harsh sea conditions: time-dependent variable loadings

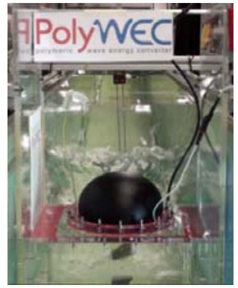
❑ Aquatic animals' flexible body & fins

❑ Flexible components WEC



Bombora mWave

Anaconda



PolyWEC OWC

- Part of WEC structures are flexible (PTO or primary mover)
- Lighter and low cost *vs* rigid WEC
- Flexible deformation adapting to time-dependent loading
- Excellent manoeuvrability, low noise, etc.

Motivation and Objectives

- **Limited materials are used**

Can we find/develop functionally driven materials, suitable for WEC structures that actively or passively change their *material characteristics* in extreme ocean environment conditions, but are stiff enough to capture the energy under normal operating conditions?

- **Analysis technique is either limited or highly case dependent**

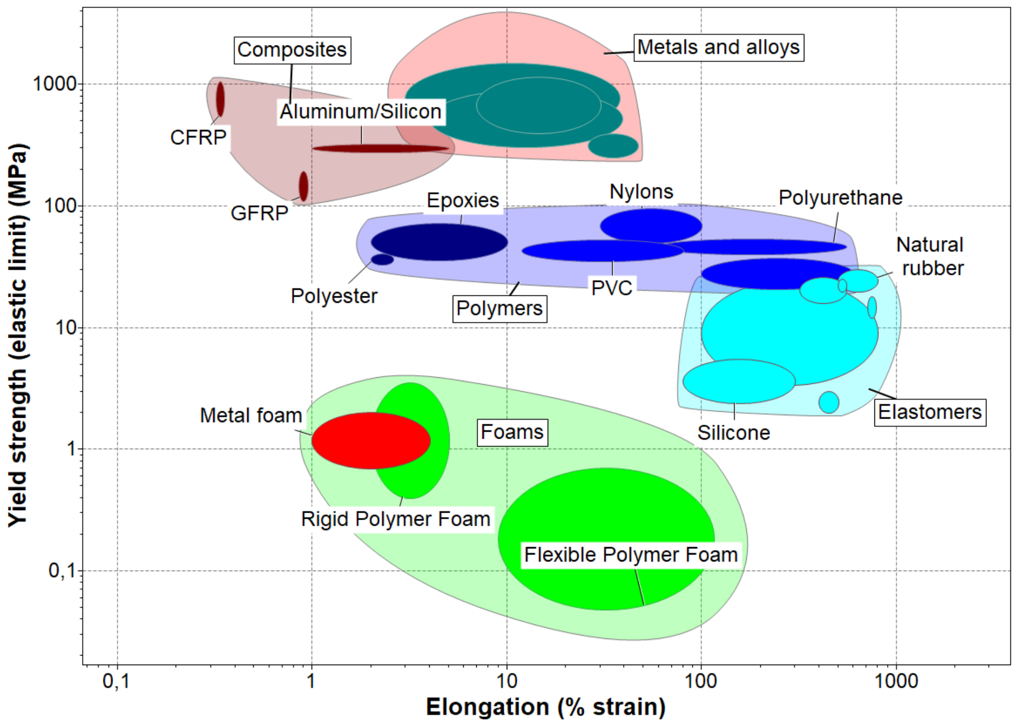
Can we perform a fully-nonlinear hydrodynamic loading estimation, to allow simulation of fluid-structure behaviour of multiple flexible bodies in a realistic environment wave conditions?

- **A life-cycle assessment for the design of functionality and new materials for more sustainable WEC is missing**

- The main ***aim*** of the project: to develop an analysis and laboratory testing integrity toolbox to reliably design, analyse, and process the state-of-the-art adaptive stretchable materials and structures applicable to WECs.

Flexible Materials in WECs

Elastomers have different benefits including high elongation, damping coefficient and fatigue life which contribute to survivability. However, elastomers suffer reduced fatigue and tensile strength and low stiffness. In BASM-WEC, selected materials will be fully characterised under dynamic and quasi-static loads considering environmental conditions.



Base Material (Elastomer)

Reinforcement (Fibres or particles)

Blends

PTO (DEGs)

PROPERTIES	FACTOR
Price [GBP/kg]	2
Density [kg/m3]	4
Young's Modulus [GPa]	3
Tensile Strength [MPa]	4
Elongation [%]	5
Elastic stored energy [KJ/m3]	5
Fatigue strength at 10^7 cycles [MPa]	3
Fracture Toughness [Mpa.m^0.5]	2
Max. Service Temperature [°C]	4
Water absorption @ 24hr [%]	5
Permeability (O2) [cm3.mm/m2]	4

Ranking

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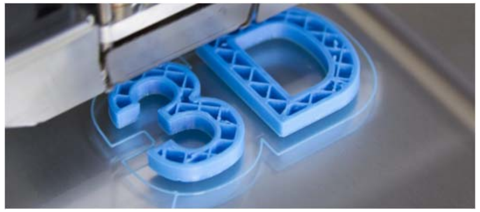
Thermosets

1. Natural rubber (NR): Car tires, seals, belts, anti-vibration mounts, tubing, rubber lining pipes and pumps.
2. Nitrile rubber (NBR): Automotive, seals, fuel and oil hose, gloves.
3. Styrene butadiene rubber (SBR): Car and truck tires, belt, hose, footwear.
4. Chlorosulfonated Polyethylene: Roofing systems, hoses, vacuum tubings, cable sheathing, roll covers, rubber boats, life-jackets, windbreakers, raincoats. Durable coatings.
5. Ethylene propylene: Roofing, seals, gaskets, hose (garden hose, steam pressure hose), cable insulation, polypropylene modification
6. Butyl / Halobutyl rubber: Inner tubes of pneumatic tires, vacuum and high-pressure applications, seals, belts, anti-vibration mounts, tubing, rubber lining pipes and pumps, chewing gum, pharmaceutical closures (halobutyl).
7. Chlorinated polyethylene:Wire & cable sheathing: shipboard and offshore. Hose, Molded goods and sealing strips. Impact modifier for rigid PVC.
8. Silicone: Automotive: seals, hose, gaskets, mounts, cable sheathing. Electrical/electronic: keypads, insulators. Food contact: Gaskets, mats. Medical: seals, syringe plungers, breast nipple protectors, catheters, baby bottle parts. Sports: swimming goggles and caps. Other: molds.
9. Polychloroprene: Wire & cable coating, hose, automotive timing belts, wet suit sponge, soles and heels, rubber coating for fabrics, roof coatings. Also, adhesives
10. Epichlorohydrin copolymer: Automotive and marine fuel hose, aircon/refrigeration hose, automotive air ducts, print rollers, seals

Thermoplastics

1. TPU (ether, aromatic, Shore A70)
2. TPU (ether, aromatic, Shore D75)
3. POE/POP (Propylene-based, Shore A80)



Tensile tests - Preliminarily results

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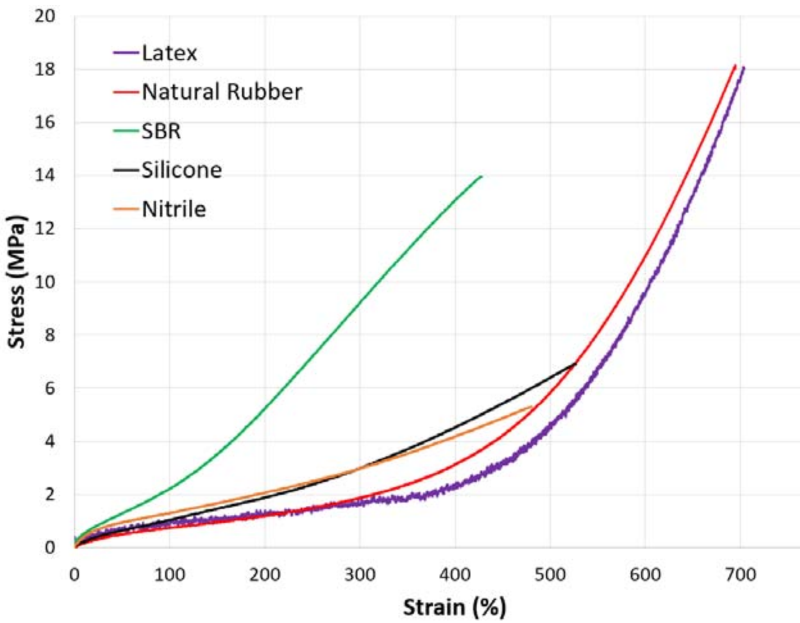

Discussion:

- Latex and NR which both are natural rubbers didn't fail during the tests providing high deformations.
- Latex and NR have a further increment of stiffness and strength in the plastic zone.
- SBR has the highest "storage elastic energy" until 300% of strain, with slight variations in the stiffness
- SBR is the material with the highest stiffness.

	Latex	NR	Nitrile	Silicone	SBR
Strength [MPa]	18.14±1.11	17.58±0.51	4.75±0.55	7.97±0.78	13.74±0.54
Y. Modulus [MPa]	1.50±0.17	1.40±0.13	4.79±0.45	5.26±0.49	6.37±0.50
Modulus @ 100% [MPa]	0.58±0.40	0.43±0.06	0.71±0.06	1.04±0.11	2.29±0.10
Energy @ 300% [MJ/m3]	3.24±0.05	3.03±0.07	4.97±0.17	5.87±0.89	12.47±0.71
Total Energy [MJ/m3]	29.14±1.80	30.14±1.26	10.48±1.76	17.70±1.80	25.59±2.73

Hyperelastic properties & models - Preliminarily results

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Mooney-Rivlin

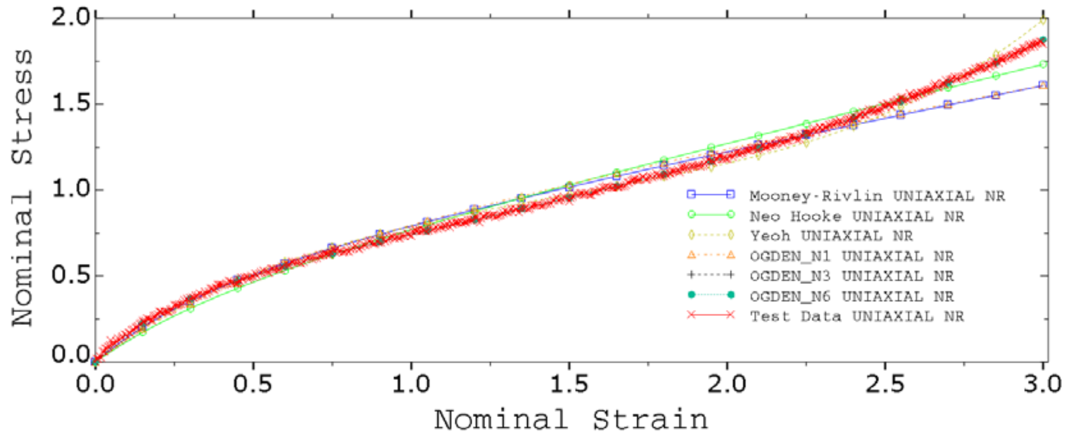
$$W = C_{10}\left(\bar{I}_1 - 3\right) + C_{01}\left(\bar{I}_2 - 3\right) + \frac{1}{D_1}\left(J_{el} - 1\right)^2$$

Yeoh

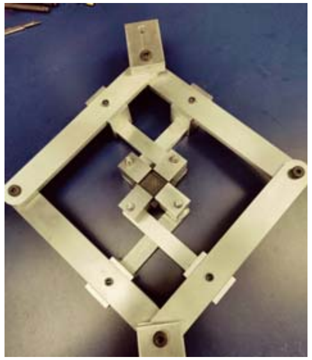
$$W = \sum_{i=1}^{3} C_{i0}\left(\bar{I}_1 - 3\right)^i + \sum_{i=1}^{3} \frac{1}{D_i}\left(J_{el} - 1\right)^{2i}$$

Ogden

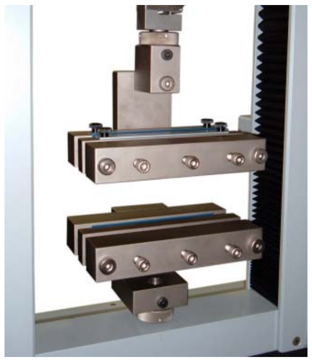
$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}\left(J_{el} - 1\right)^{2i}$$



Tensile

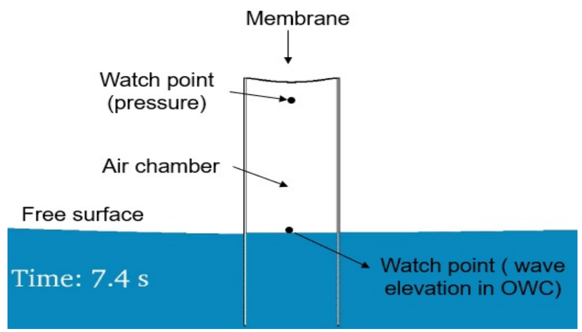


Biaxial



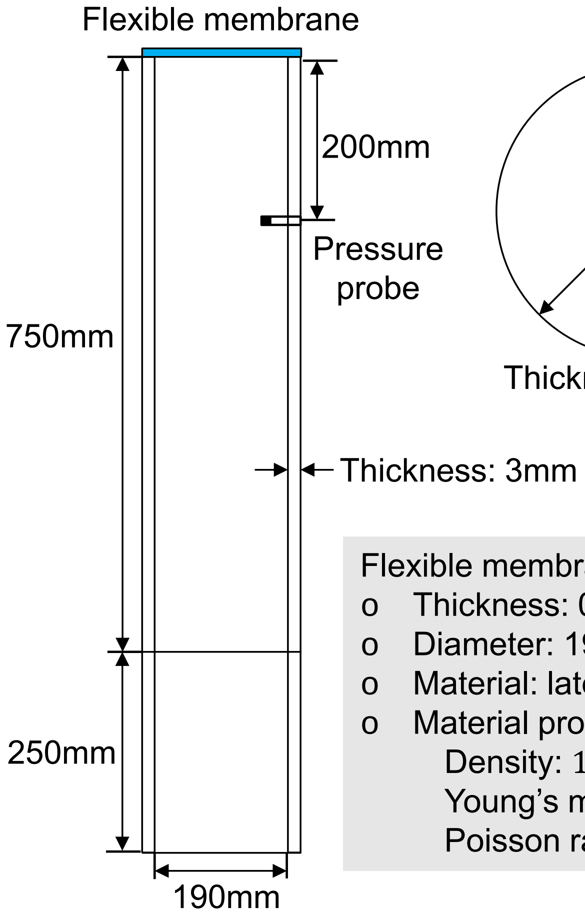
Planar

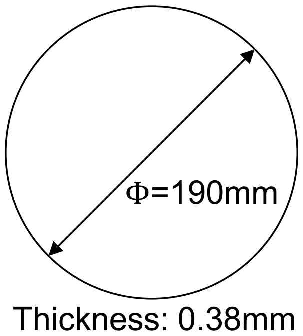
FUTURE WORK



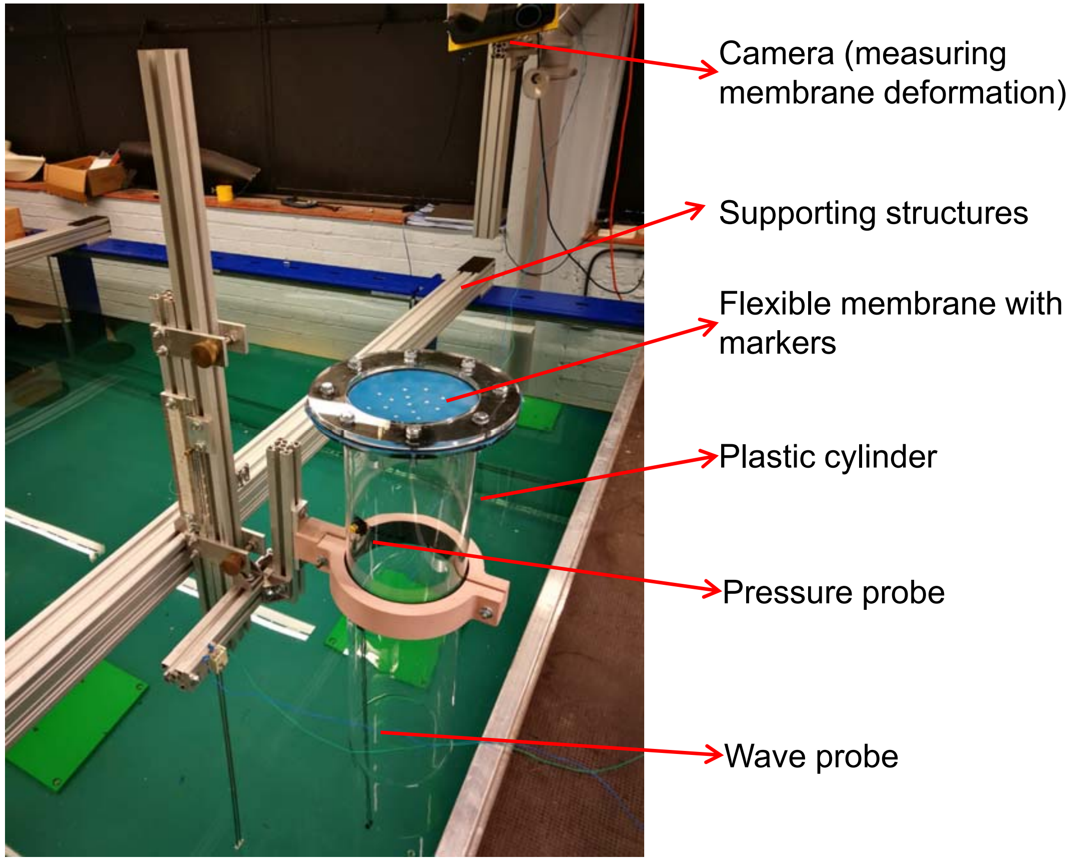
Experiment - OWC with flexible membrane (1/5)

- **OWC model and configuration**





Flexible membrane
- Thickness: 0.38mm
- Diameter: 190mm
- Material: latex
- Material properties:
  - Density: $1.1 \times 10^3 \mathrm{kg/m^3}$
  - Young's module: $0.98 \times 10^6 \mathrm{Pa}$
  - Poisson ratio: 0.4995



Experiment – testing configuration and conditions (2/5)

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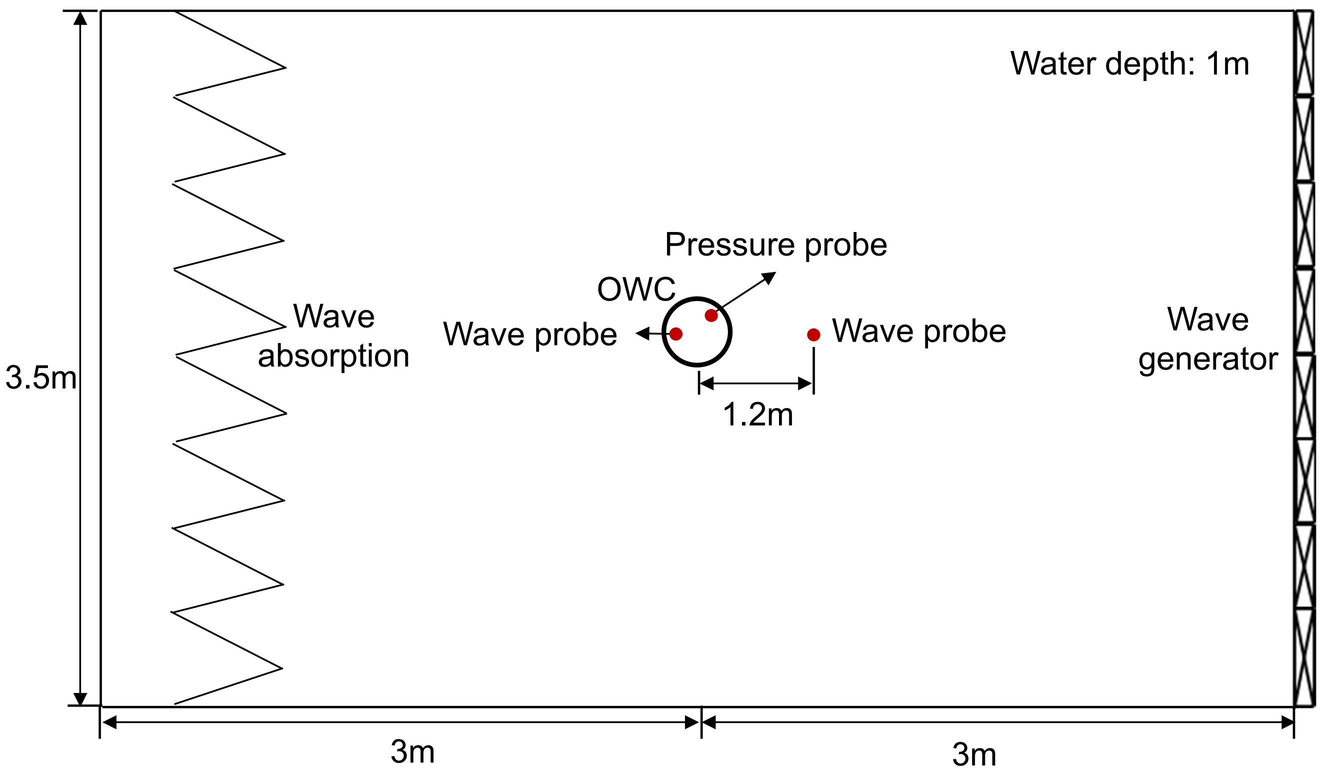
- **OWC model and configuration**



Schematic diagram of OWC model and configuration

Overview of *small* wave tank in KHL

Wave conditions

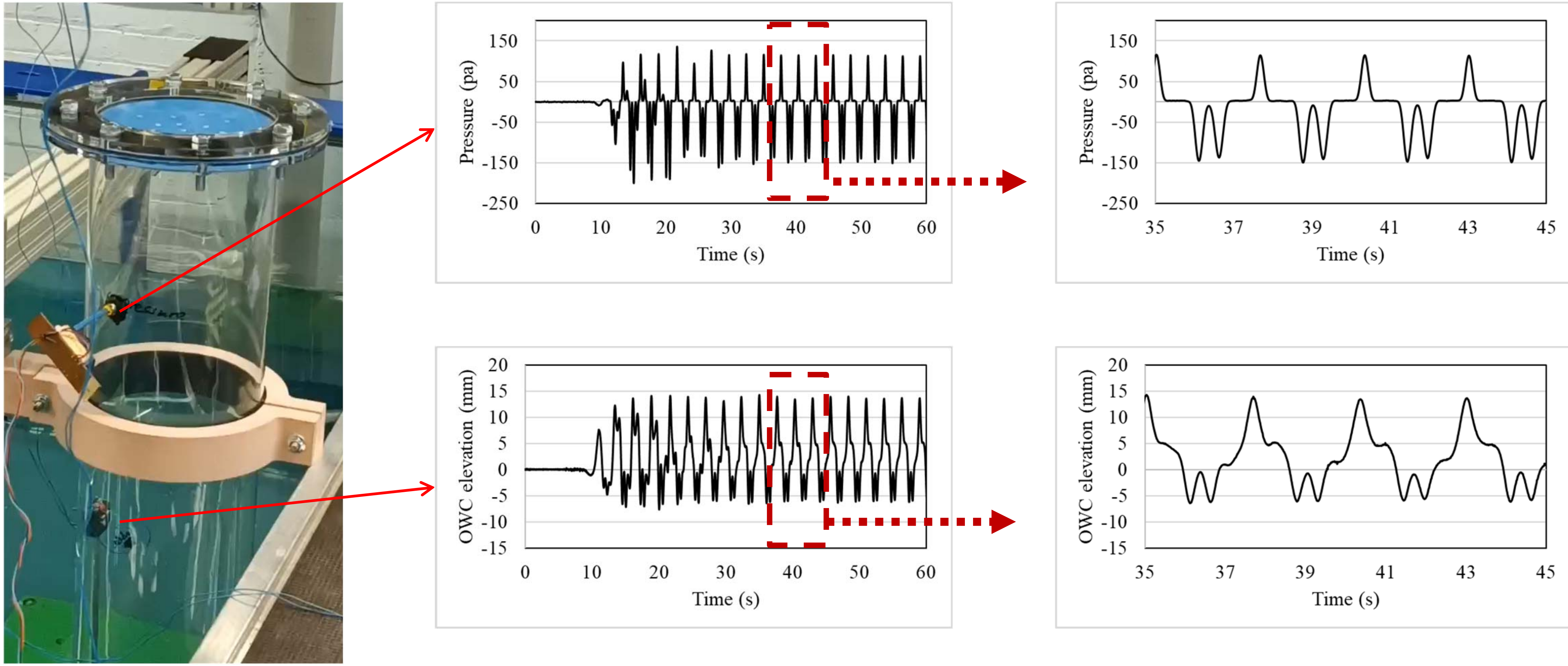
✓ Fixed wave amplitude (H_{wave} =10mm), vary wave frequency: f_{wave} = 0.3~1.3Hz

✓ Fixed wave frequency (f_{wave} =0.375Hz), vary wave amplitude: H_{wave} = 3~22 mm

Experiment – preliminary results (3/5)

- **Preliminary results**

Wave conditions: wave frequency f=0.375Hz, wave amplitude H=10mm

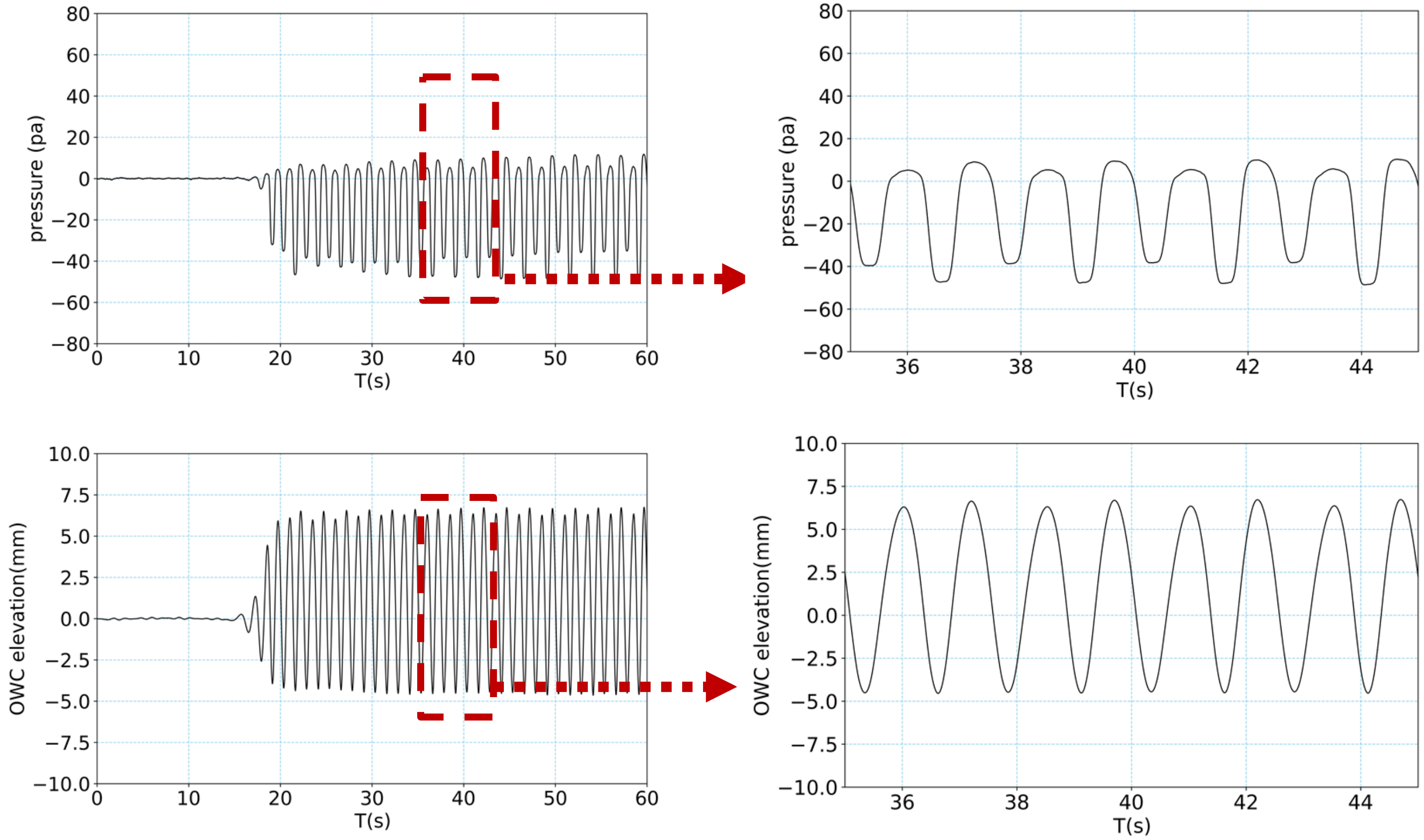


Time history of pressure and wave elevation in OWC

Experiment (4/5)

- **Preliminary results**

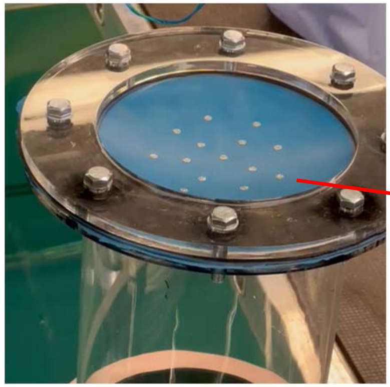
Wave conditions: wave frequency f=0.8Hz, wave amplitude H=10mm



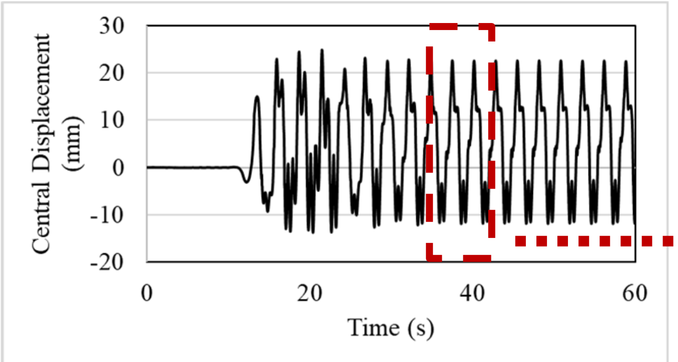
Time history of pressure and wave elevation in OWC

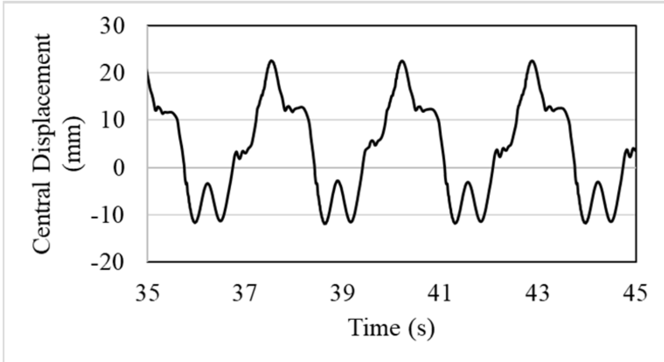
Experiment (5/5)

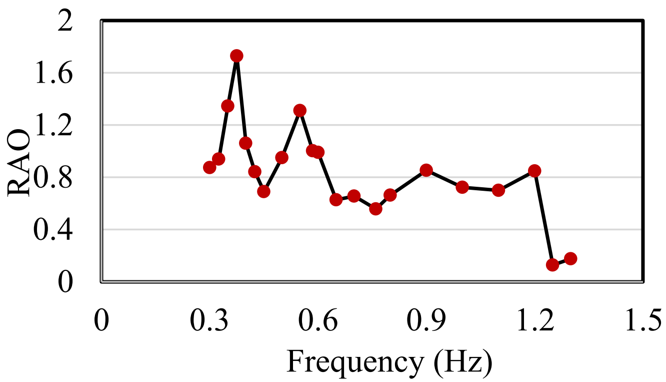
Time history of ***membrane deformation*** wave amplitude of 10mm and frequency of 0.375Hz



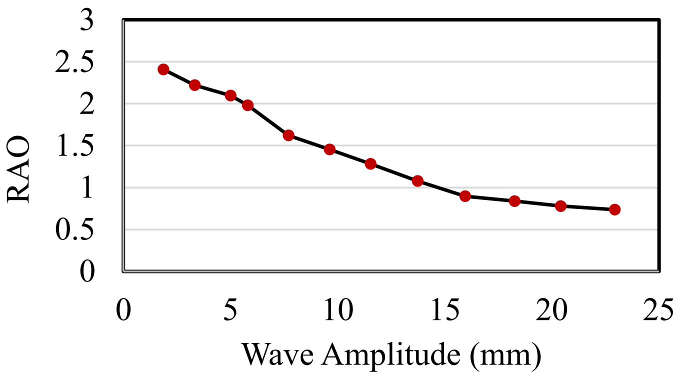
f_{wave} = 0.6 Hz, H_{wave} =20mm







Wave frequency impact on RAO (wave amplitude of10mm)

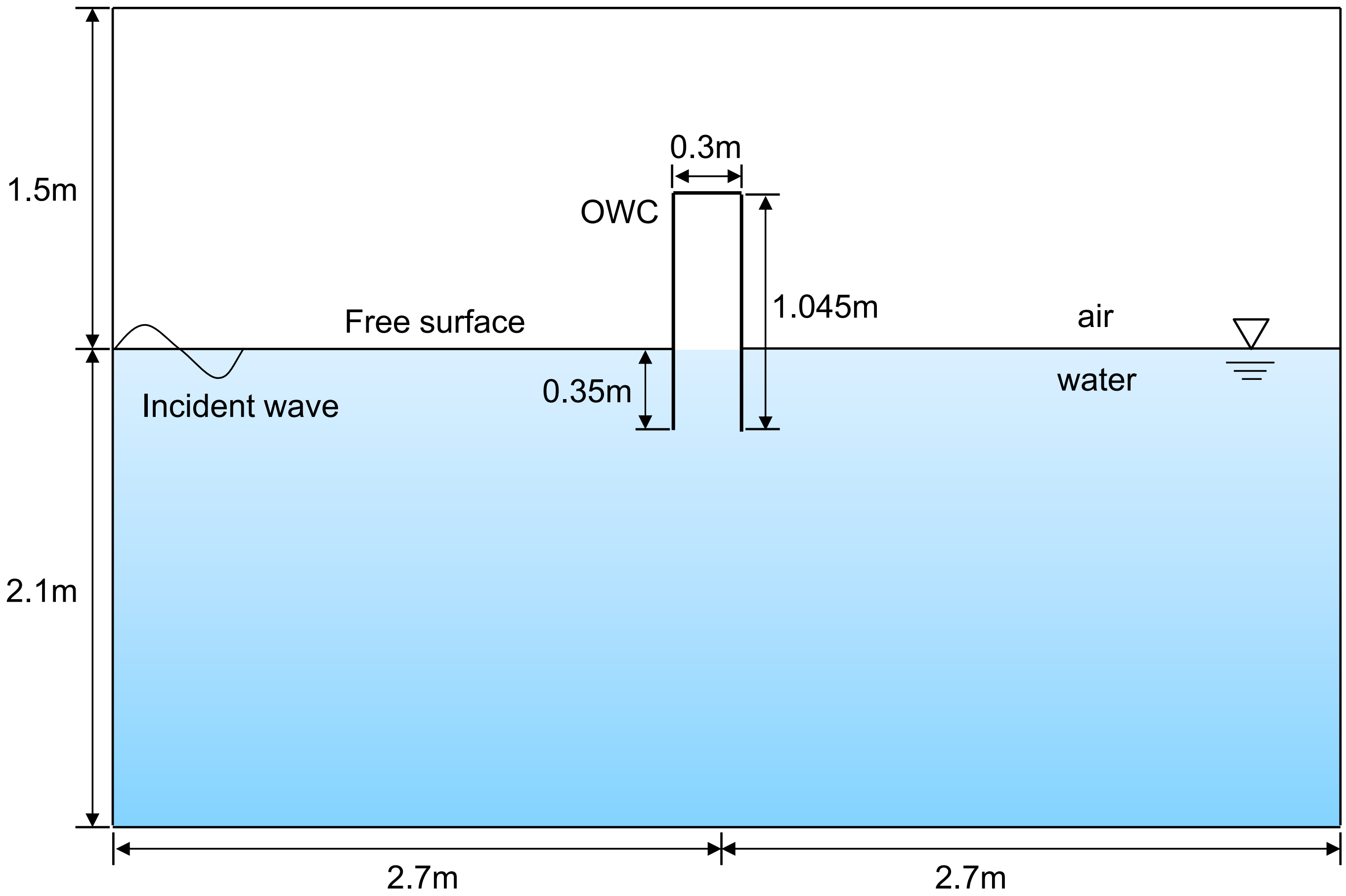


Wave amplitude impact on RAO (wave frequency of 0.375Hz)

- Multiple peaks can be observed in RAO vs. frequency plot – indicators of
  - ✓ strong non-linearity of material;
  - ✓ Increased WEC capture band width;
  - ✓ 1st peak – OWC hydrodynamic stiffness; 2nd peak – structure natural frequency
- RAO decreases with wave amplitude due to increased damping

CFD numerical modelling - 2D OWC model (1/3)

- **Computational model set-up**



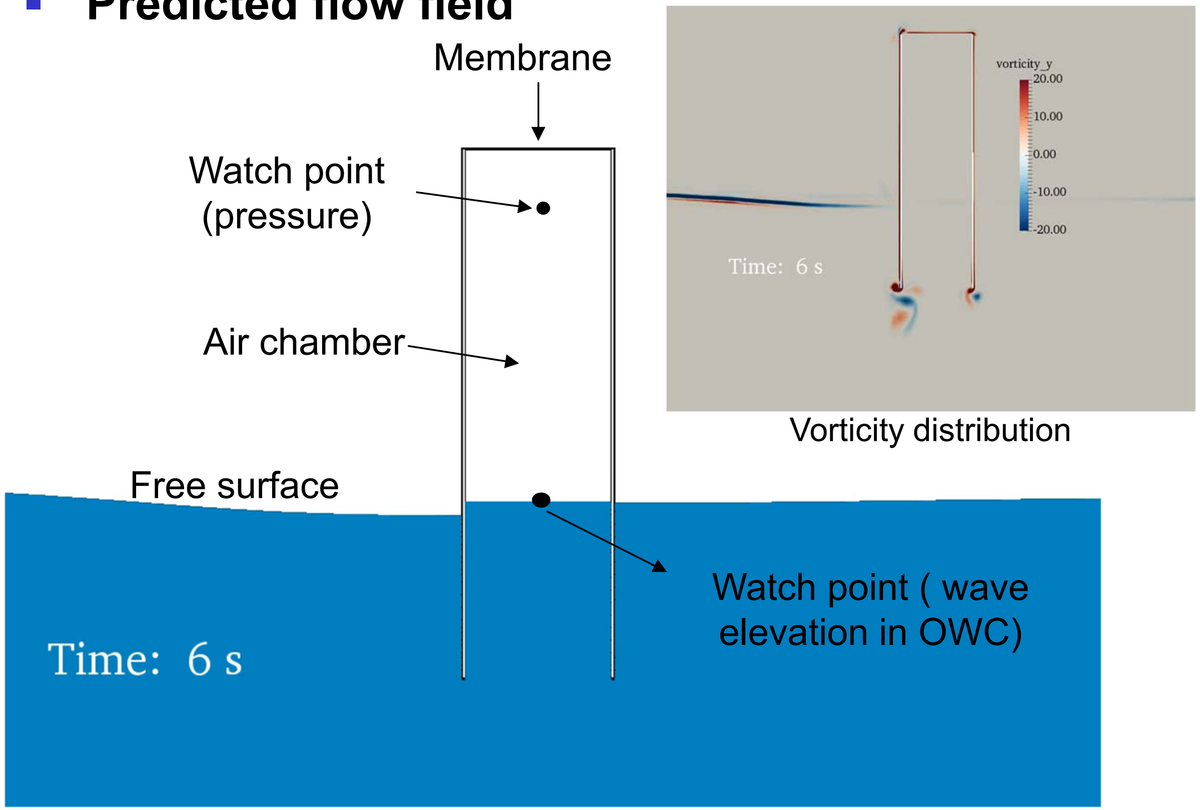
OWC geometry dimensions
- Length: 300mm
- Thickness: 1mm

Material properties
- Name: natural rubber
- Density: $1.1 \times 10^3 \mathrm{kg/m^3}$
- Young's module: $5.25 \times 10^6 \mathrm{Pa}$
- Poisson ratio: 0.4995

Incident Wave
- Stocks 2nd wave
- Wave amplitude (H_{wave}): 60mm
- Wave period (T_{wave}): 1.313 s
- Wave length: 2.7m

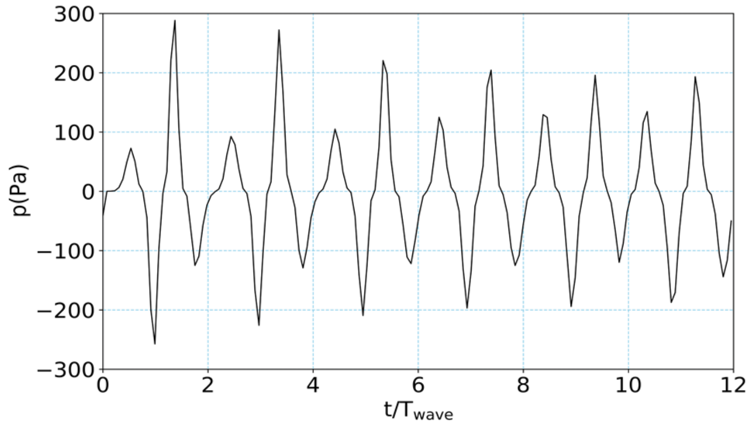
CFD numerical results (2/3)

- **Predicted flow field**

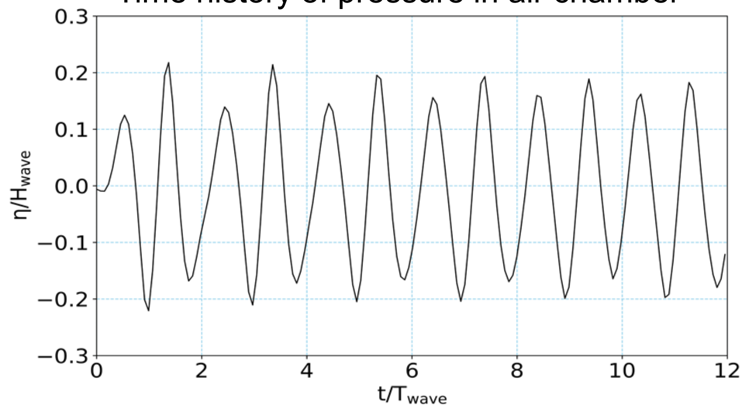


Vorticity distribution

Overview of OWC under regular wave



Time history of pressure in air chamber

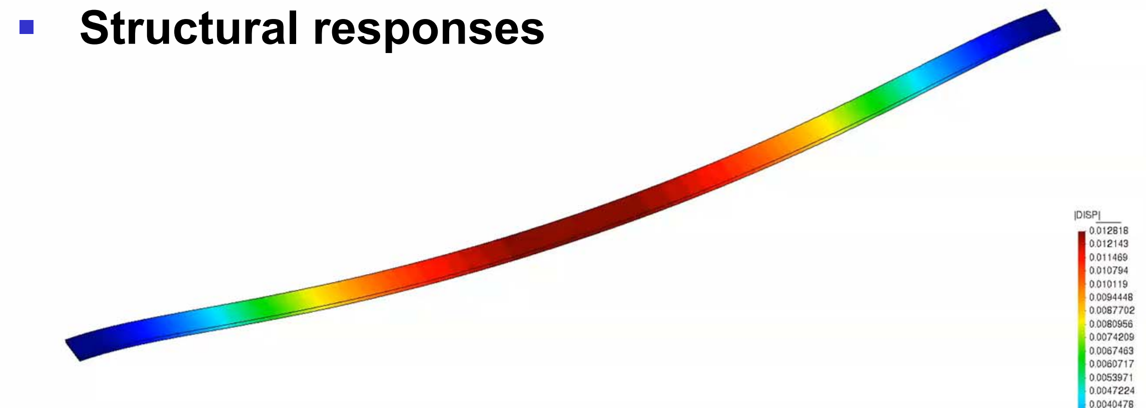


Time history of wave elevation in OWC

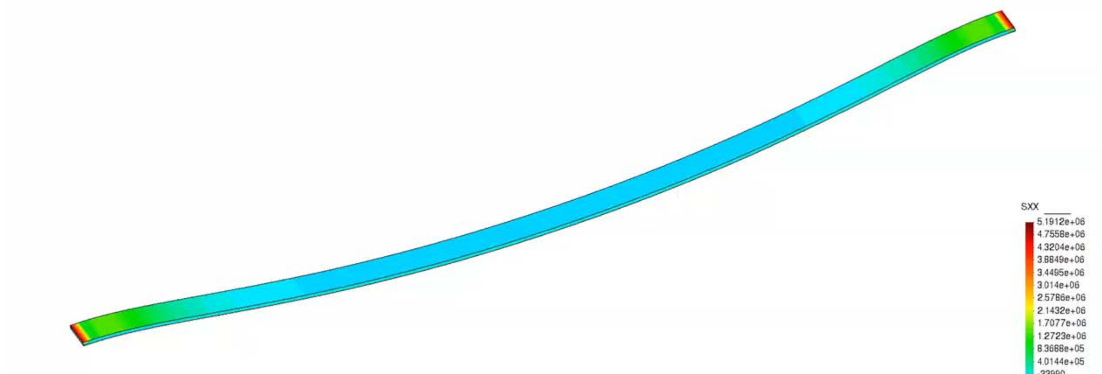
- Time history plots for pressure and wave elevation indicate dominant frequency – incident wave frequency

CFD numerical results (3/3)

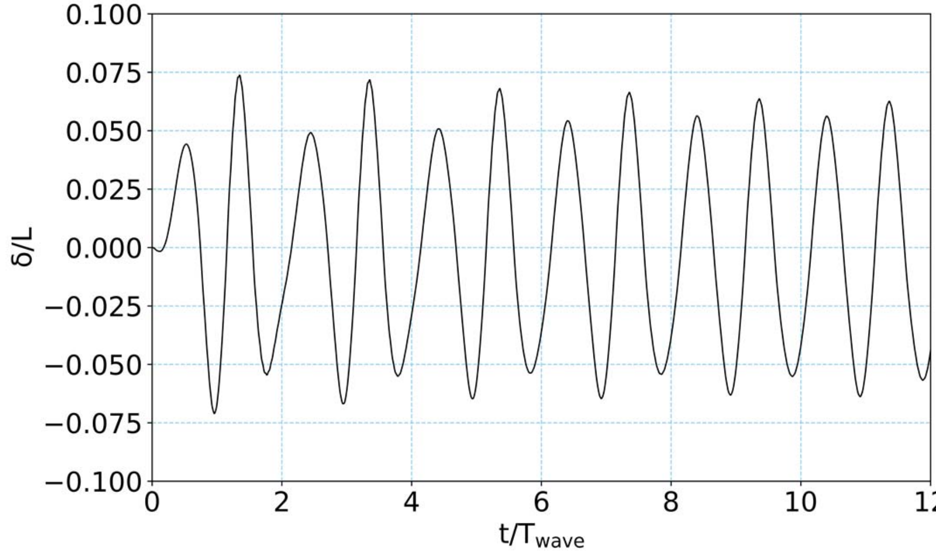
- **Structural responses**



Structural deformation



Stress (σ_x) distribution



Time history of displacement at the mid-point of membrane

δ : displacement of middle point
L: length of membrane 300 mm
T_{wave} : wave period 1.313 s

Near Future Work

- Characterization on hyper-elastic properties and models covering a wide range of material
- Completion physical testing with other wave conditions and material properties
- Scale up model testing in KHL large wave tank
- Identify/find non-dimensional law for flexible-WEC testing in addition to Fr number
- CFD analysis for physical model testing and verification
- Other types of flex-WEC

Thank You !

Website:
http://personal.strath.ac.uk/qing.xiao/
https://basm-wec.org/

Summary of model test and numerical simulation

	Model test	**Numerical simulation**
Model type	Three dimension	Two dimension
Flexible Material	Latex	Natural rubber
Material properties	Hyper-elastic model **Data from datasheet of NR** Density: $1.1 \times 10^3 \mathrm{kg} \cdot \mathrm{m}^3$ Young's module: $5.25 \times 10^6 \mathrm{Pa}$ Poisson ratio: 0.4995	Linear model **Data from datasheet of NR** Density: $1.1 \times 10^3 \mathrm{kg} \cdot \mathrm{m}^3$ Young's module: $5.25 \times 10^6 \mathrm{Pa}$ Poisson ratio: 0.4995
Incident wave	Regular wave	Regular wave
Wave frequency	0.3~0.9Hz	0.76Hz
Wave amplitude	10mm	60mm
Wave length (λ)	1.93~17.3m	2.70m
Water depth	1m	2.1m
OWC diameter (D)	200mm	300mm
λ/D	9.6~86	9.0