Experimental Investigation of Turbine Blades Response Using Fiber Optic Strain Sensors

Mohammed Abdellatef[a], Budi Gunawan, Dongyoung Kim, and Vincent S. Neary*

Assistant Professor

[a] Presenting author: Department of Civil, Environmental and Geomatics Engineering (CEGE)

Florida Atlantic University

* Corresponding author: Marine Energy Technologies Lead, R&D Mechanical Engineer

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Outline

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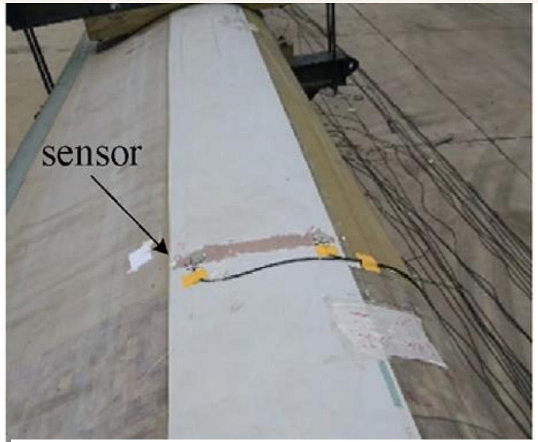
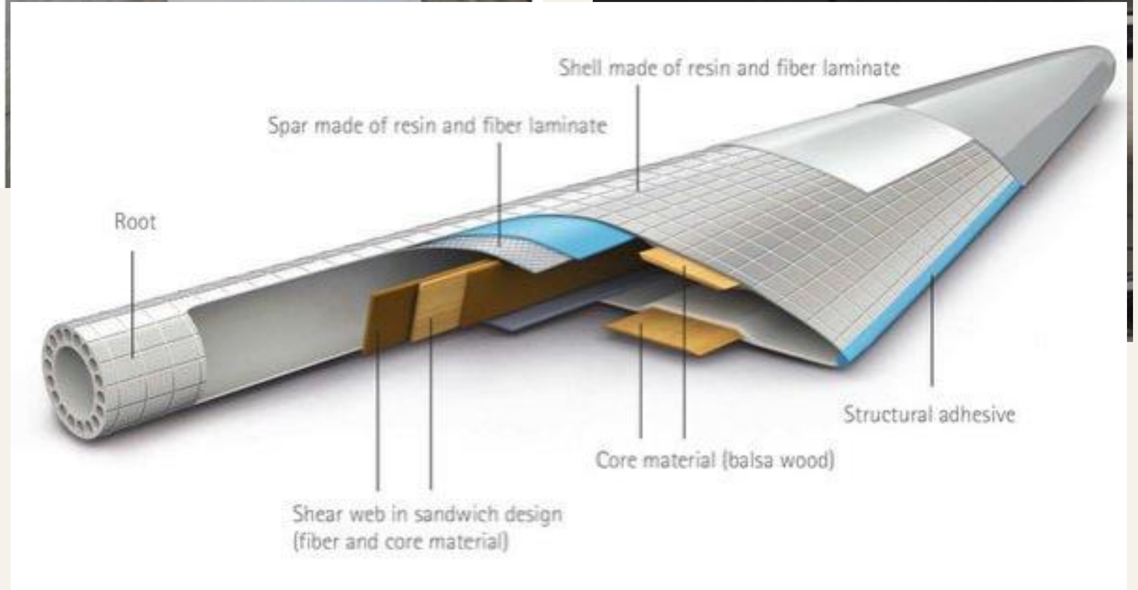
Introduction

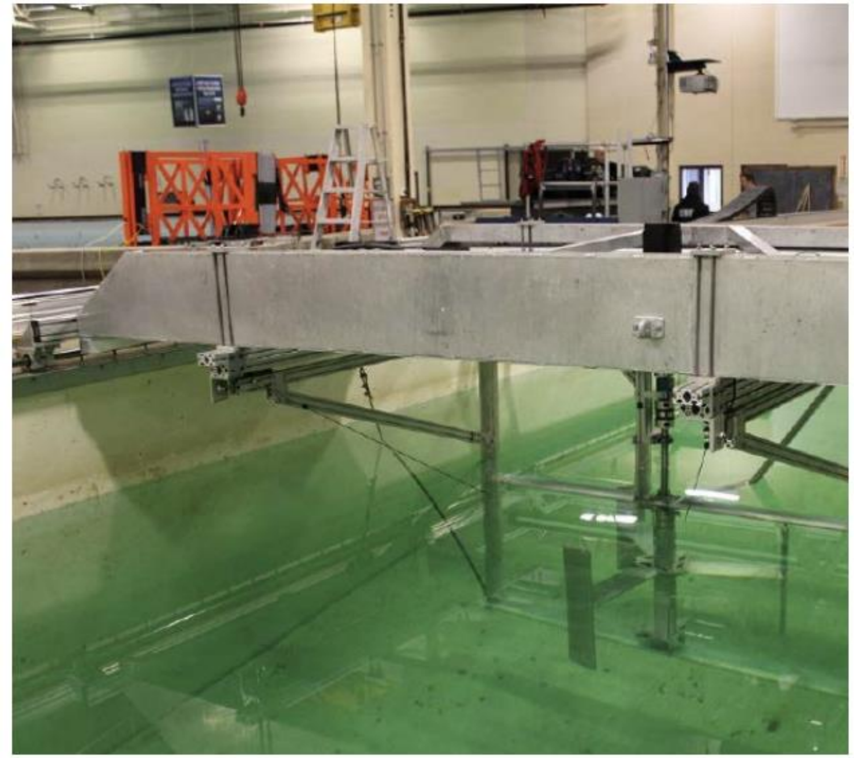




Introduction

Lockheed Martin Technology Scotland

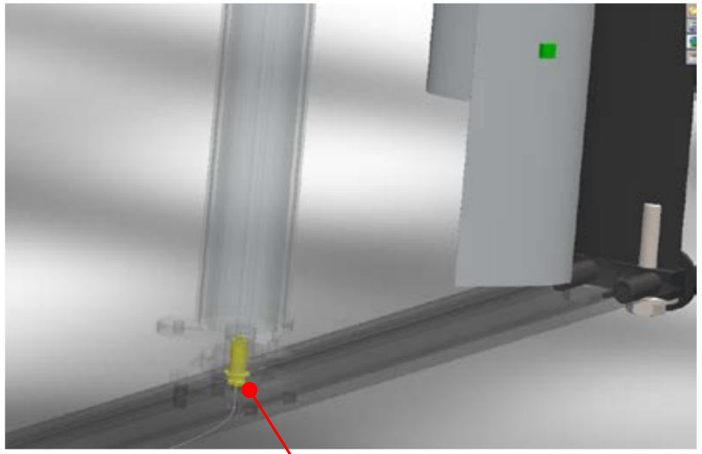
UNH-AMEC Tidal Energy Test



UNH-SNL Test

Introduction

UNH-AMEC Tidal Energy Test



Fiber Optic Sensors

UNH-AMEC Tidal Energy Test

OSTEC testbed

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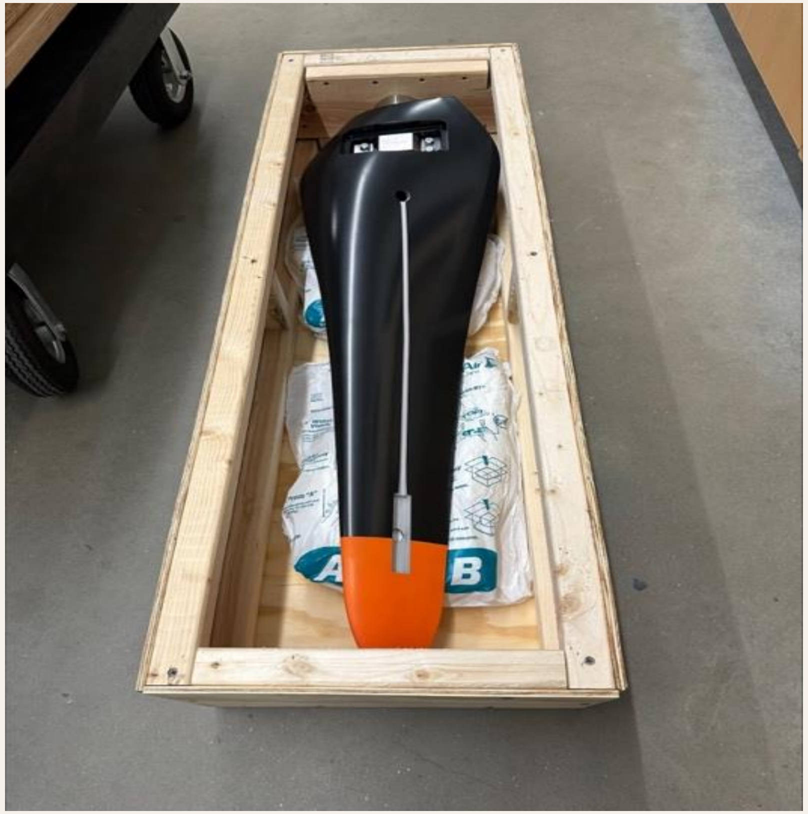
Introduction



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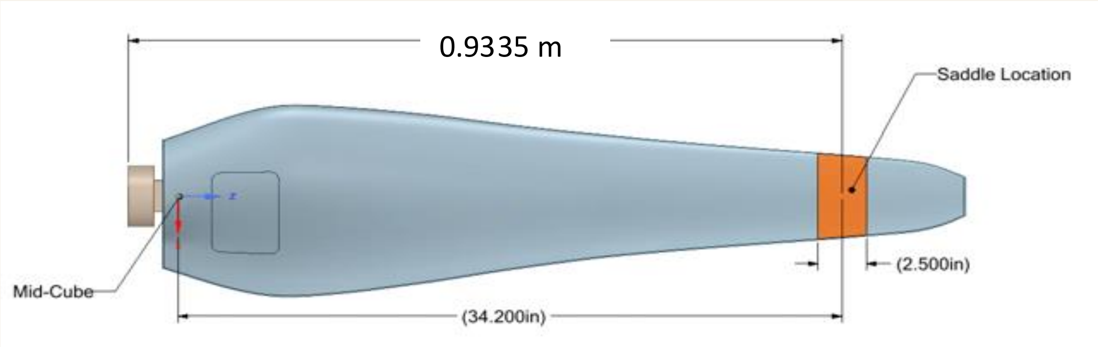
Design Loads

- OpenFAST (AeroDyn) BEM simulation identified maximum flapwise (FW), edgewise (EW) root bending and twist moments among dozens of design load cases given in IEC TS 62600-2.
  - Worst case FW, EW, DLC 1.3, Normal operation, extreme turbulence, 110 rpm
  - Worst case pitching moment (torsion), DLC 5.1, Emergency shutdown

DLC Description								Blade Loads				Rotor Loads		
DLC	Turbine State	Test #	TSR	RPM	Mean Current Speed (m/s)	TI (%)	Turbulence Model	Flapwise Bend Moment (N-m)	Edgewise Bend Moment (N-m)	Pitching Moment (N-m)	Blade Thrust (N)	Transverse Off-axis Load (N)	Vertical Off-axis Load (N)	Torque (N-m)
1.1 & 1.3	Normal Operation	1	4.11	80	2.56	7.8	NTM	3807	1050	107	5757	597	1636	3805
		2	2.73	50	2.41	8.1	NTM	2179	984	118	3604	483	1501	3650
		3	5.46	100				3927	759	96	5658	486	1509	2478
		4	Max	150				4459	445	323	5764	384	1399	1231
		5	2.73	50	2.41	11.6	ETM	2287	1099	131	3842	672	1685	4079
		6	5.46	100				4518	969	118	6593	755	1750	3124
		7	Max	150				5222	605	347	6920	598	1575	1735
		8	2.57	50	2.56	7.8	NTM	2212	1042	125	3744	506	1518	3993
		9	5.65	110				4389	791	127	6234	509	1501	2741
		10	Max	150				4968	552	311	6557	435	1415	1590
		11	2.57	50	2.56	11.7	ETM	2328	1167	139	4064	729	1736	4491
		12	5.65	110				$\boxed{5092}$	1030	$\boxed{157}$	7322	829	1756	3575
4.1	Normal shutdown	1	Rated Torque		2.56	7.8	NTM	4677	1018	121	6705	801	1890	3635
		2	Rated Torque					3095	748	67	4524	461	1481	2349
		3	Rated Torque					4125	1035	110	6109	814	1793	2919
5.1	Emergency shutdown	1	BOP		3.3	NA	Steady	4697	$\boxed{1264}$	146	6739	0	1066	4811
		2	Highest RPM		3.3	NA	Steady	5220	1264	164	6919	0	1066	4811
		3	Rated Torque		2.56	7.8	NTM	4648	1042	145	6625	801	1890	3784
		4	Rated Torque					3095	748	66	4524	461	1439	2349
		5	Rated Torque					4279	1035	98	6342	1014	1793	2780
6.1	Parked w/ 0° misalignment	1	NA	NA	3.3	NA	Steady	668	244	20	1334	0	1066	988
		2	NA	NA	2.56	7.8	NTM	598	222	20	1215	149	1201	868
	Parked w/ +30° misalignment	3	NA	NA	3.3	NA	Steady	588	371	29	1342	691	1066	1001
		4	NA	NA	2.56	7.8	NTM	565	214	37	1251	266	1234	922
	Parked w/ -30° misalignment	5	NA	NA	3.3	NA	Steady	629	393	31	1433	736	1066	1070
		6	NA	NA	2.56	7.8	NTM	561	375	33	1308	760	1164	977



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Design Loads

- The origin of the moment arm for FW and EW root bending moments is at the flange interface between the blade attachment post and the hub (moment arm length = 0.9335 m)
- Maximum predicted loads at saddle location corresponding to FW moment 5.4 kN, EW moment 1.4 kN

DLC Description								Blade Loads				Rotor Loads		
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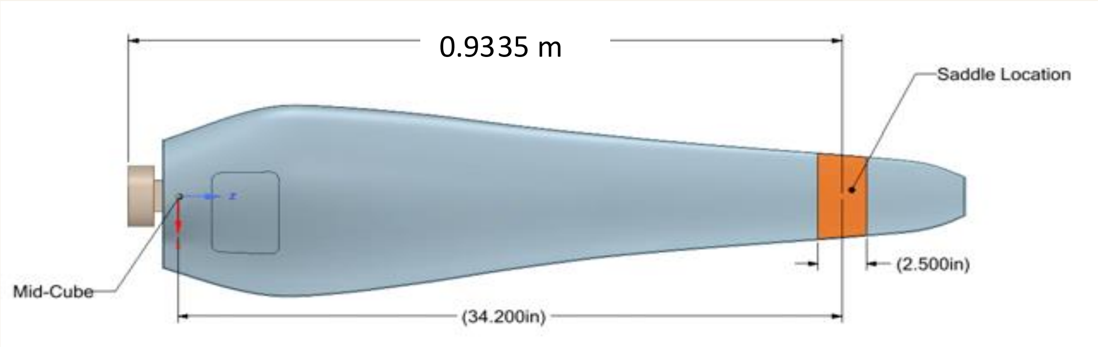

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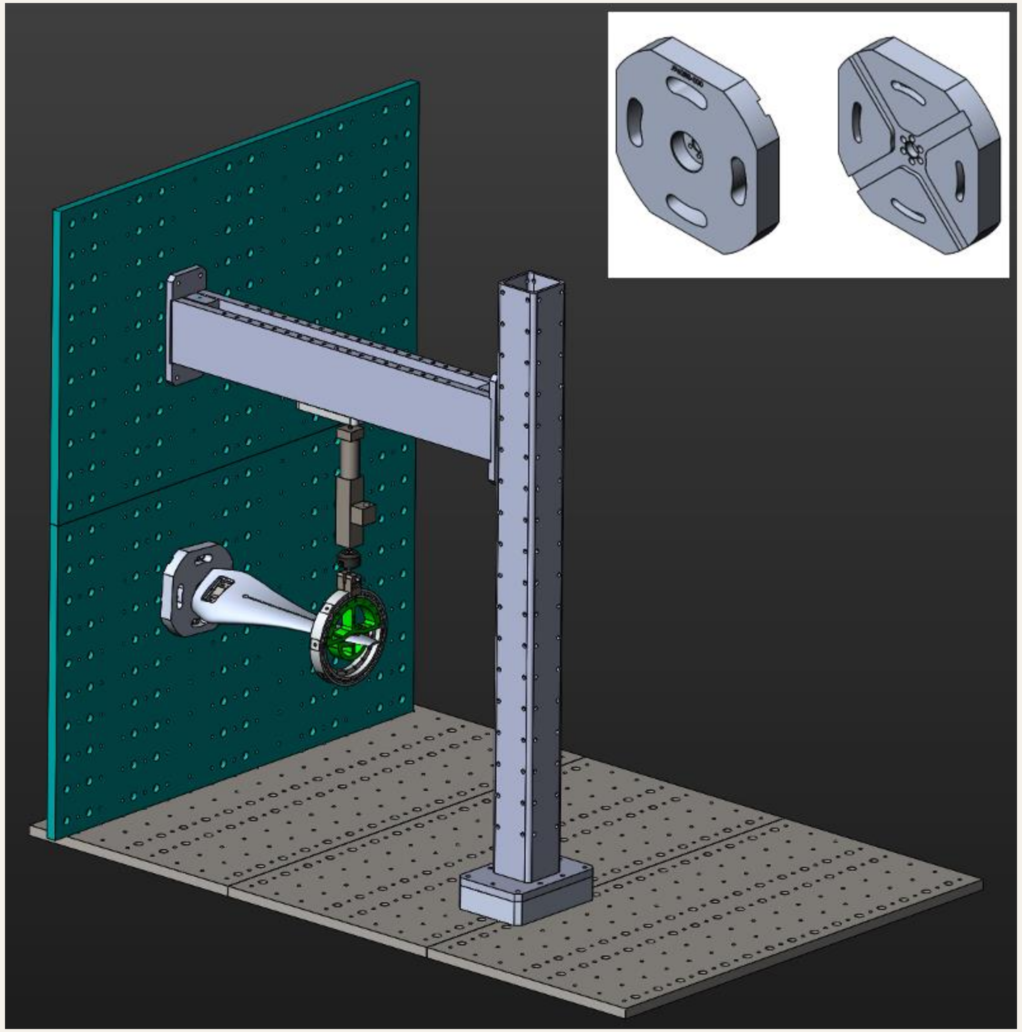
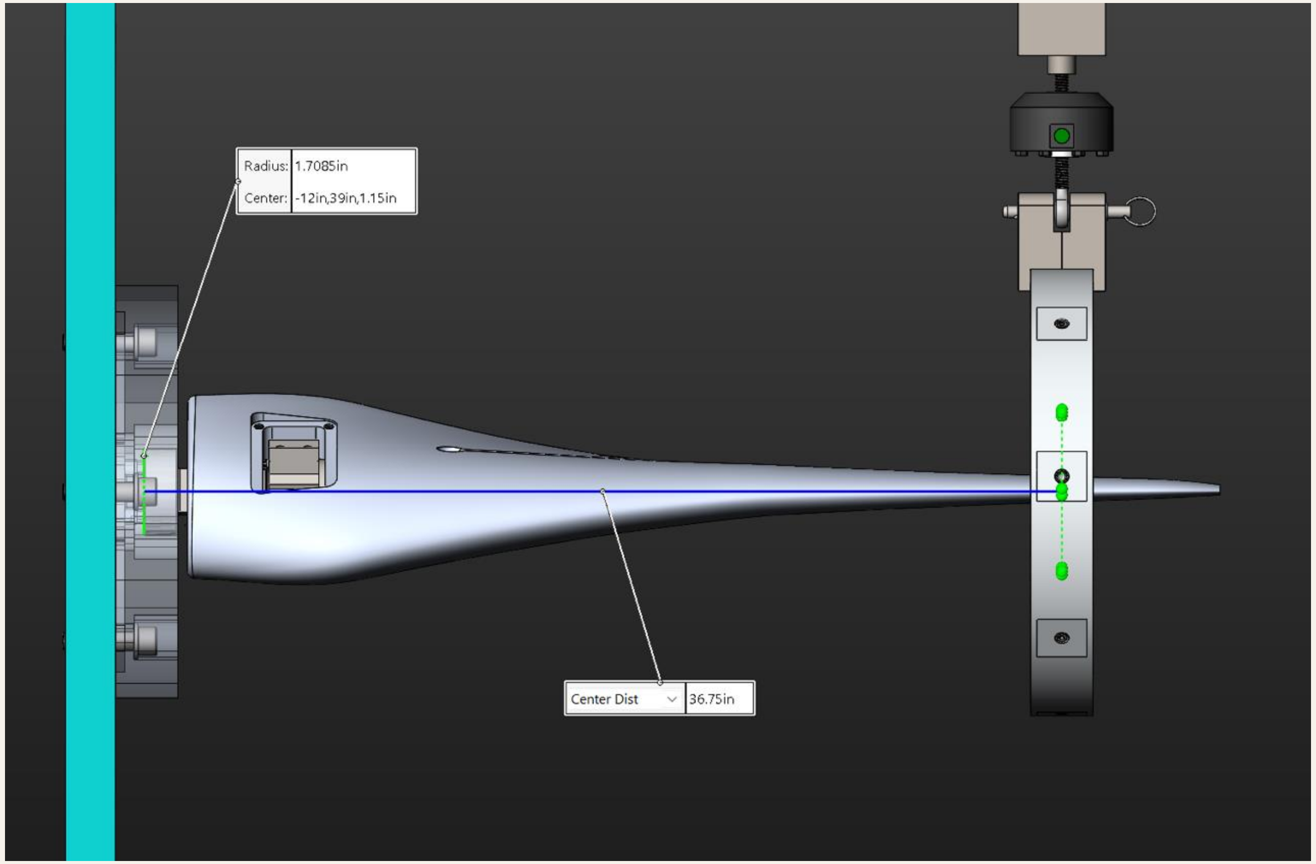
Testing Setup





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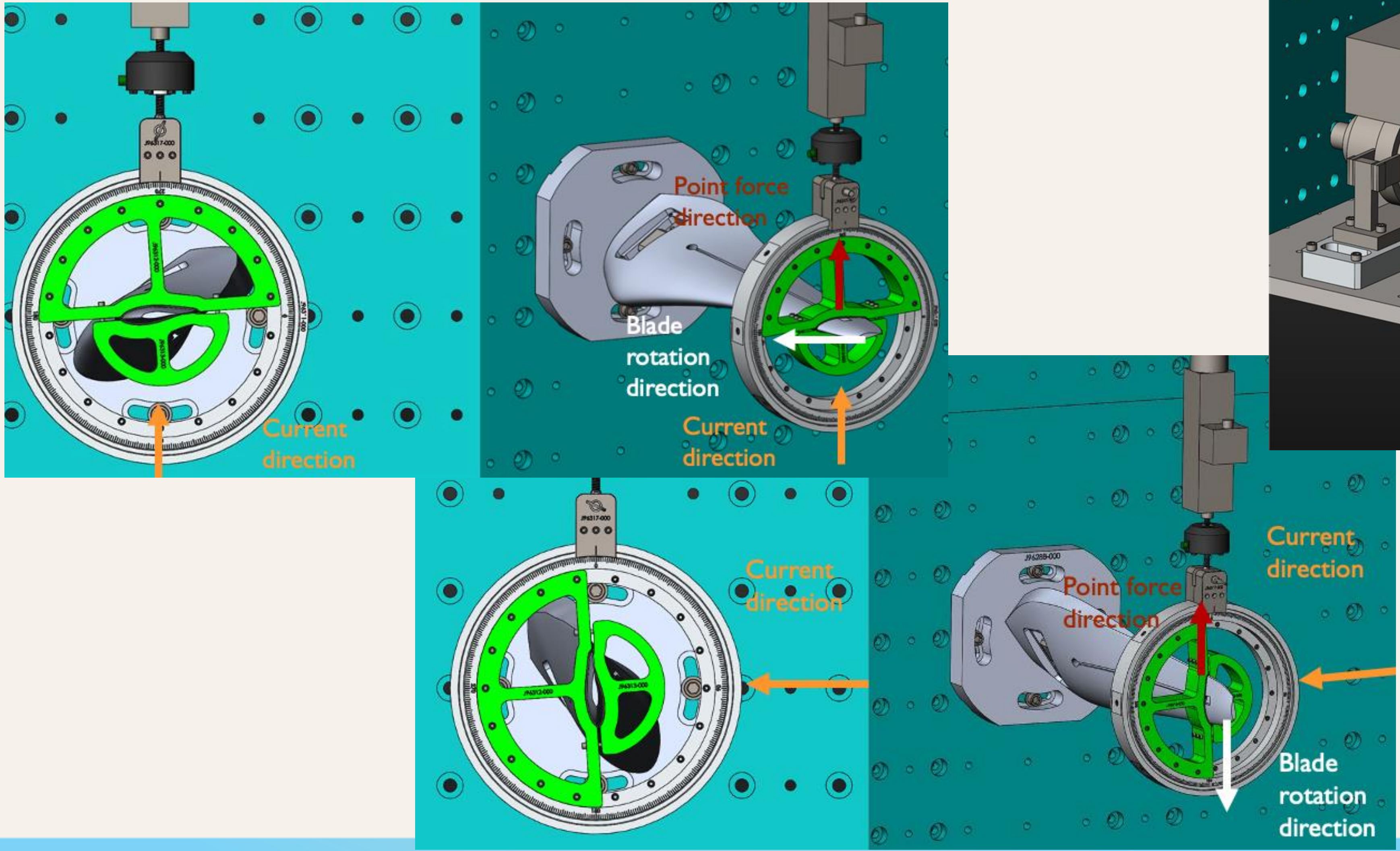

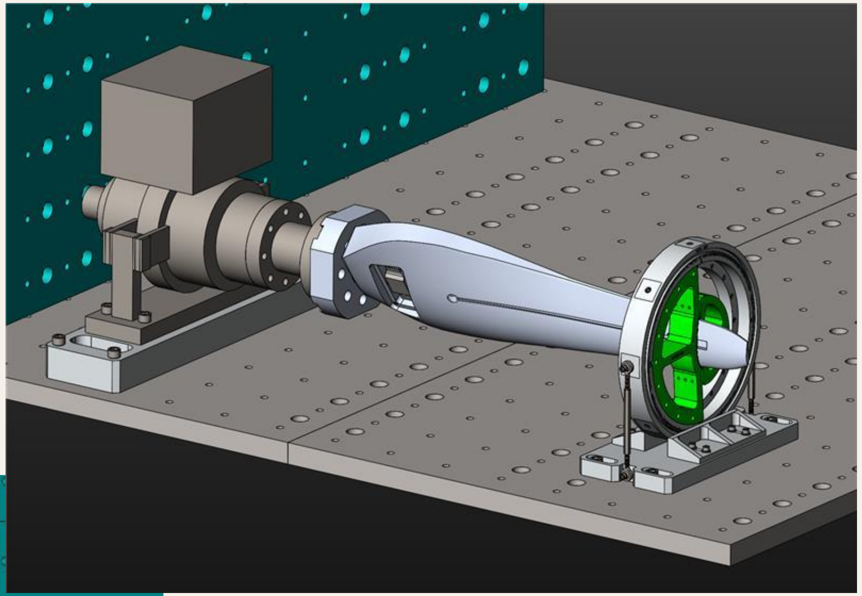

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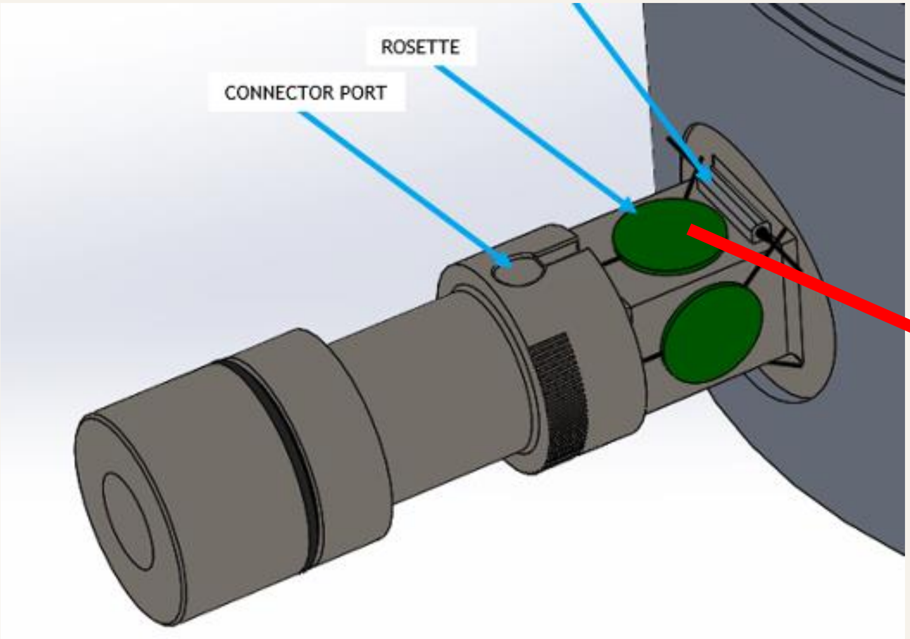
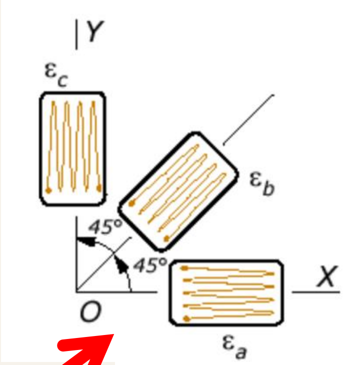
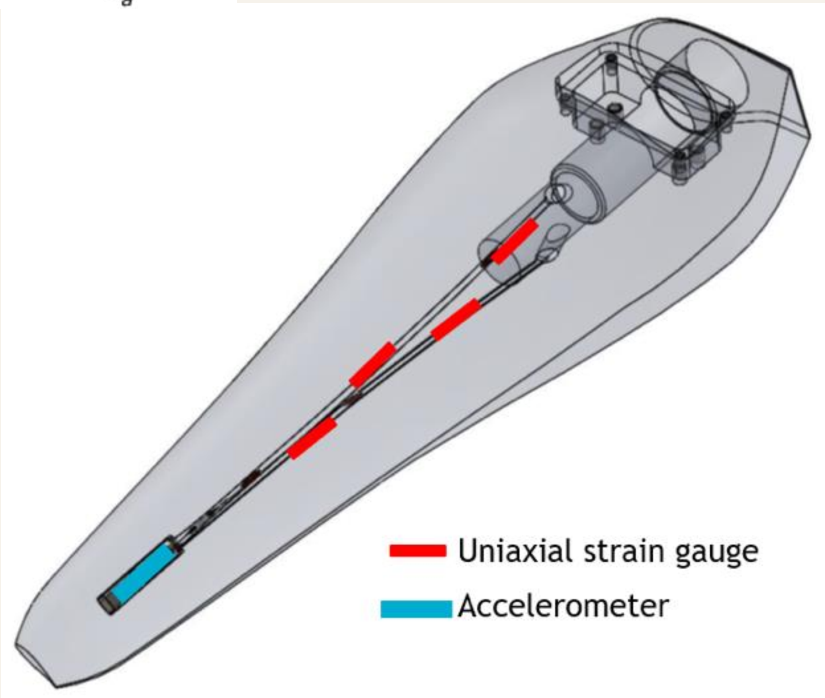
Testing Instrumentation







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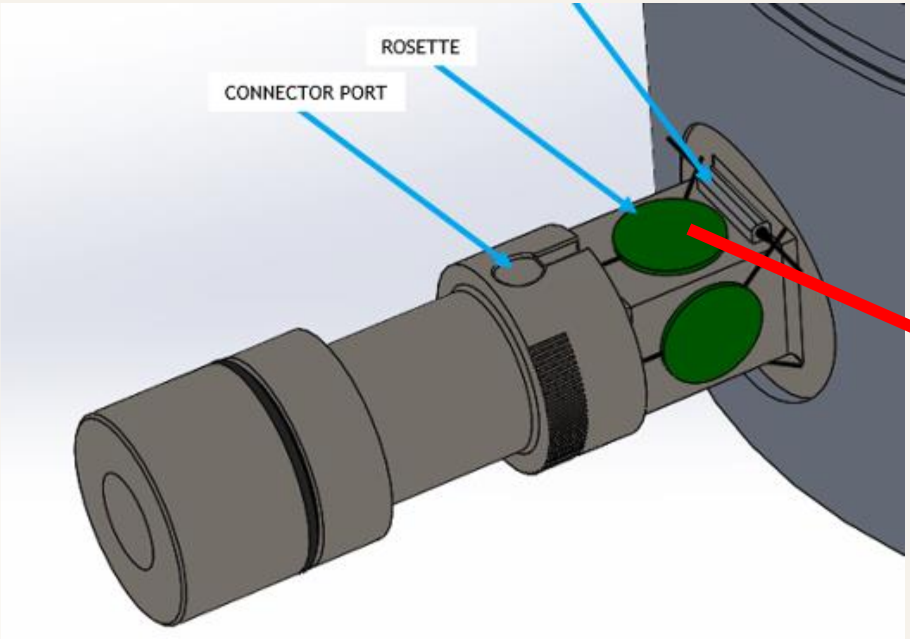

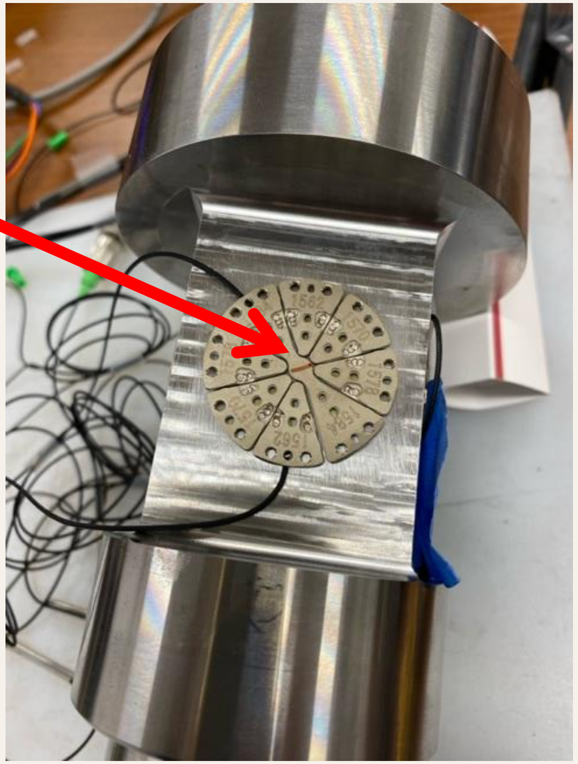

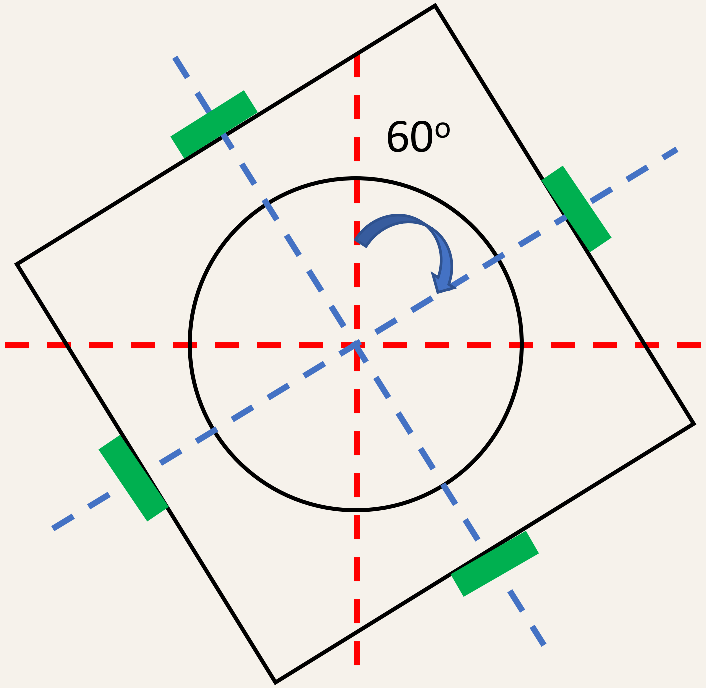

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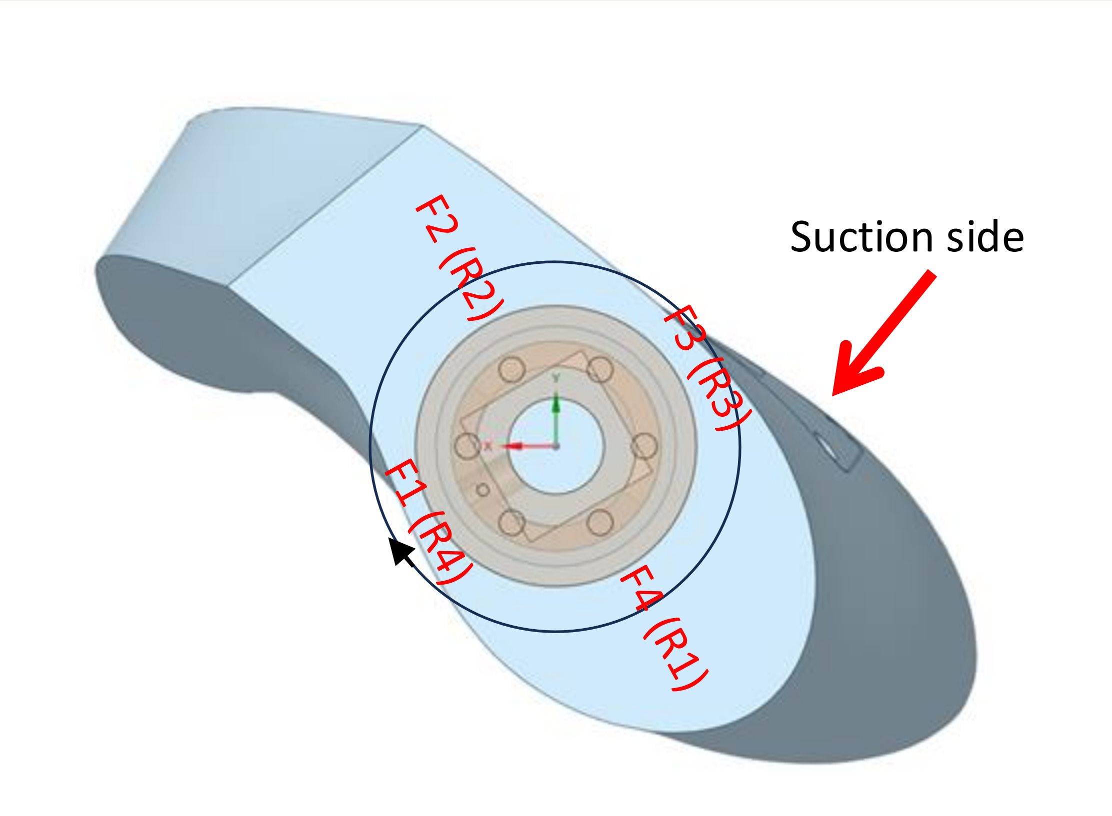
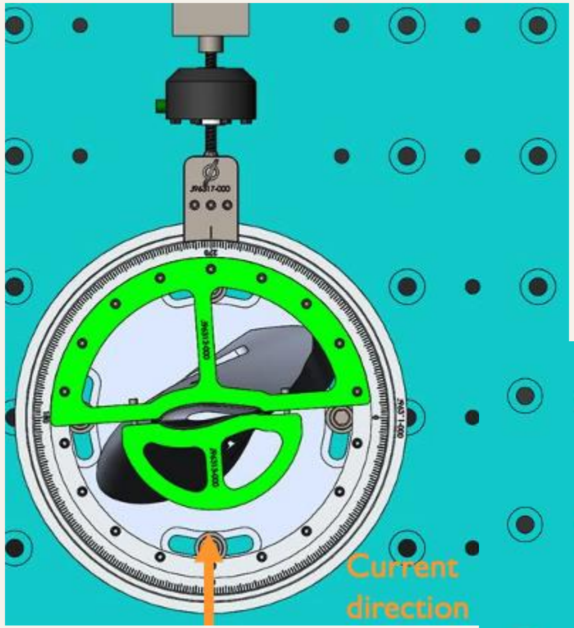
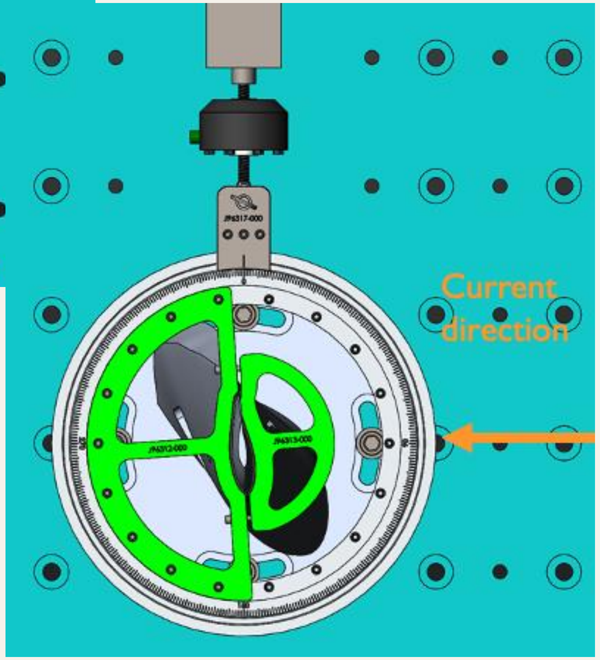
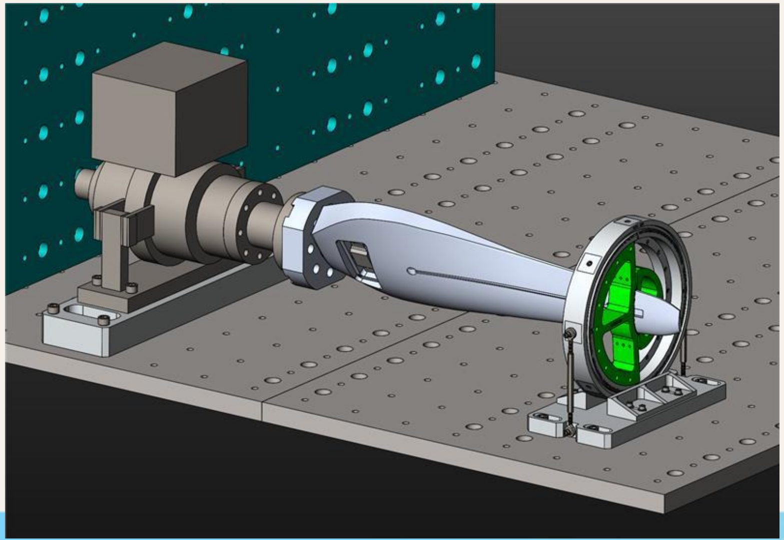


Loading Configuration

Blade/Root	Applied Load	Load Direction	Blade Pitch Angle
B3R3	5.25-5.27 kN	Push/Pull	0 (flapwise)
	2.38 kN		-90^o (edgewise)
	4-5.27 kN		-30^o
	0.19 kN.m	Torque	-
B4R1	5.44 kN	Push/Pull	0 (flapwise)
	5.27 kN		-90^o (edgewise)
	4 kN		-30^o
B2R2	5.44 kN	Push/Pull	0 (flapwise)
	4.23-5.27 kN		-90^o (edgewise)
	4 kN		-30^o







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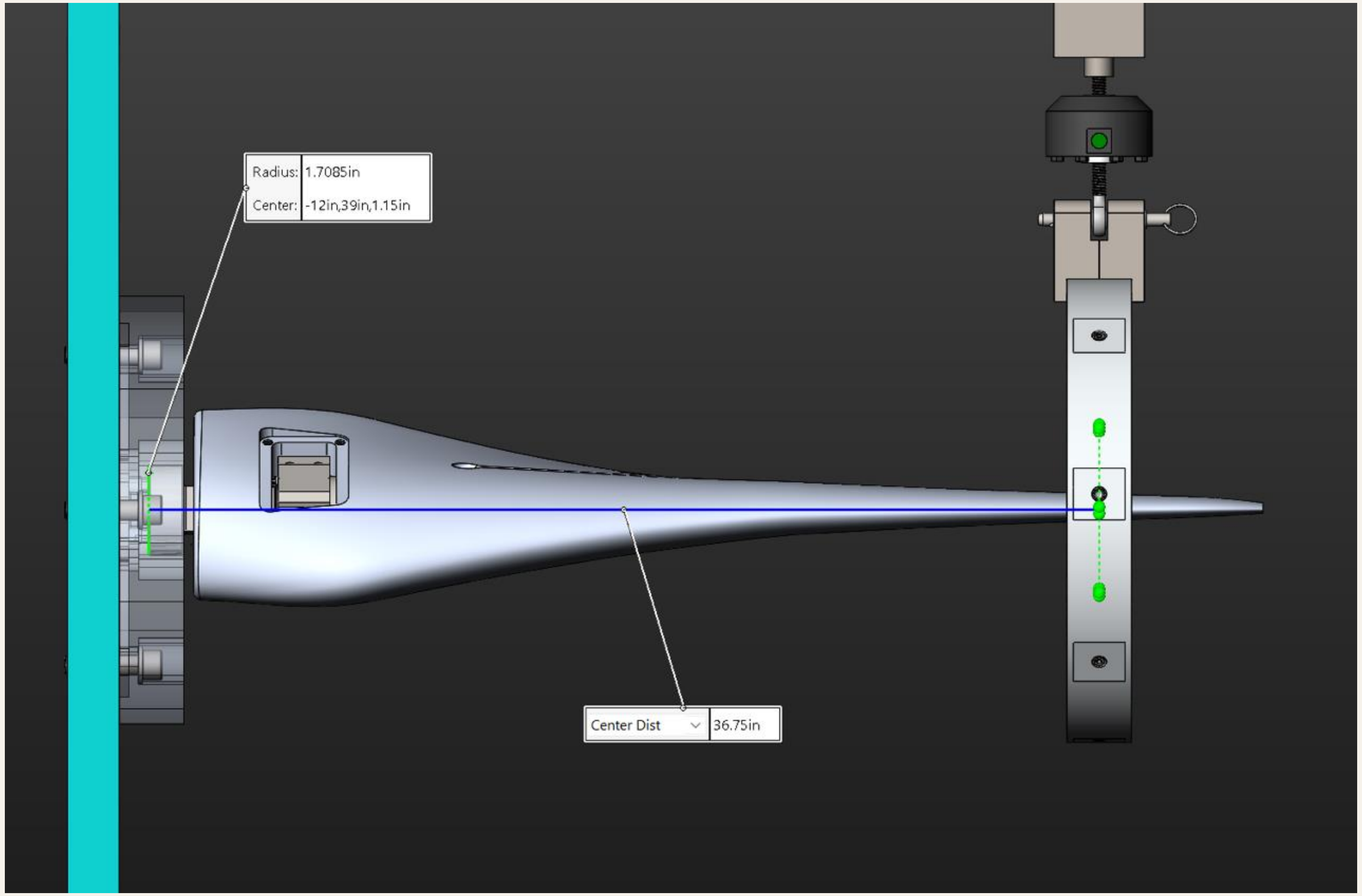
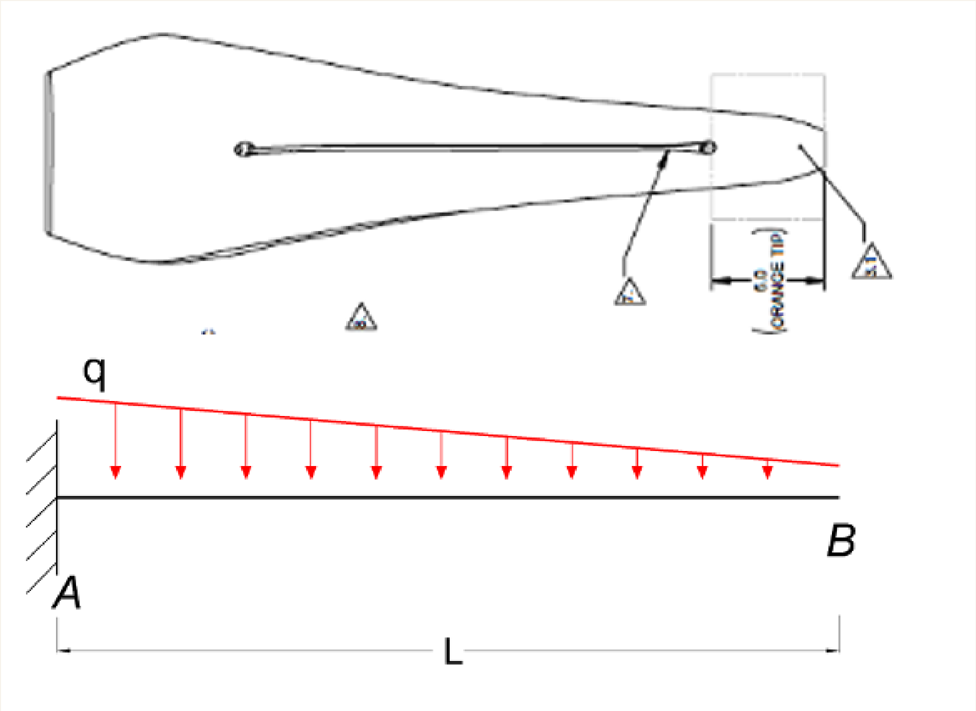
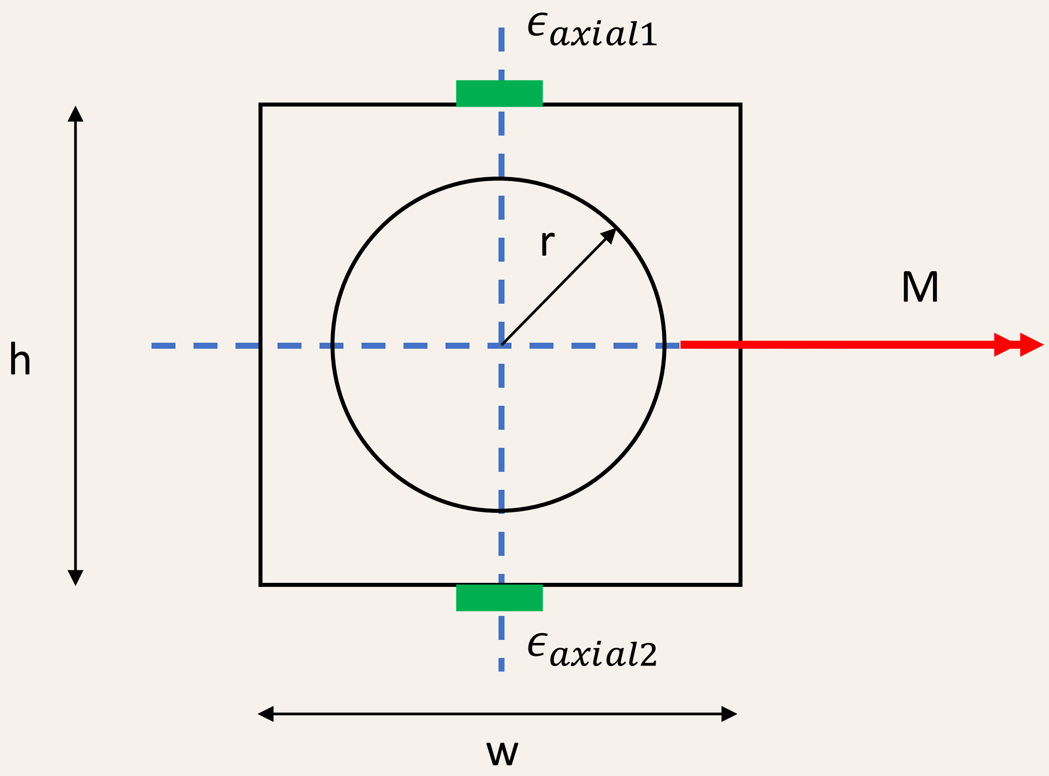
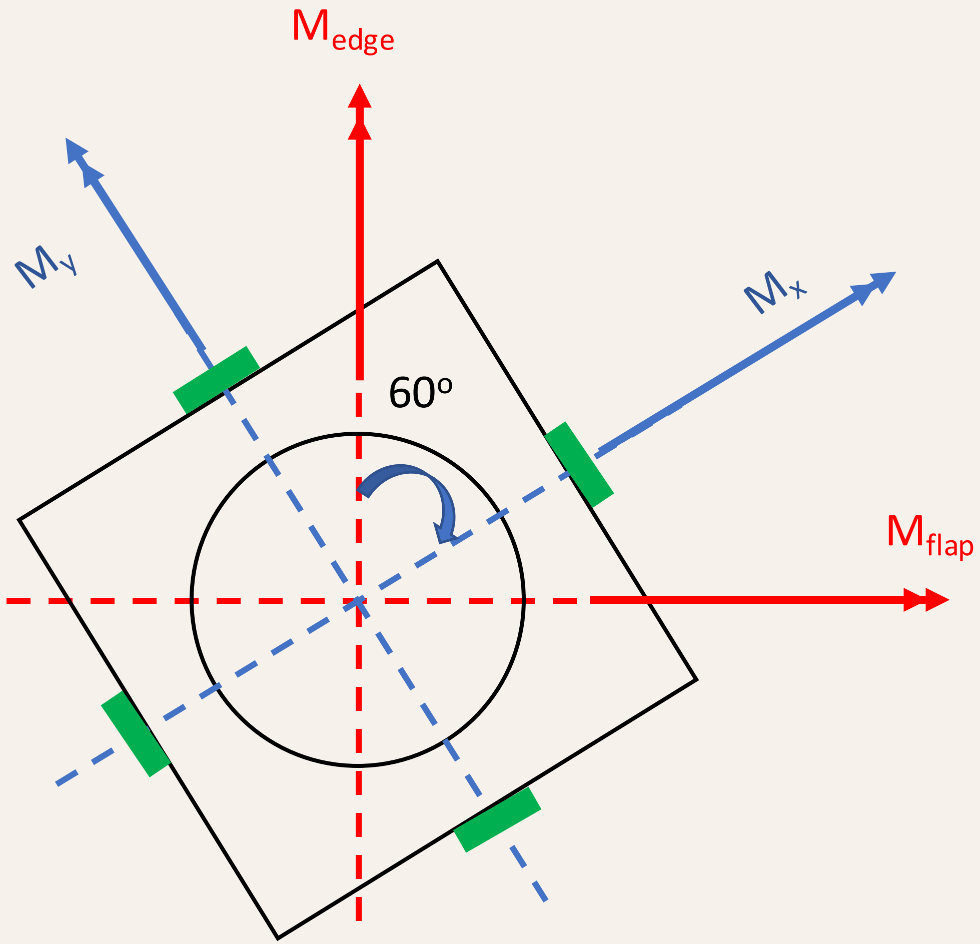
Analytical Model





Analytical Model





$$M = \frac{\epsilon_{axial1} - \epsilon_{axial2}}{h} * E * (\frac{wh^3}{12} - \frac{\pi r^4}{4})$$

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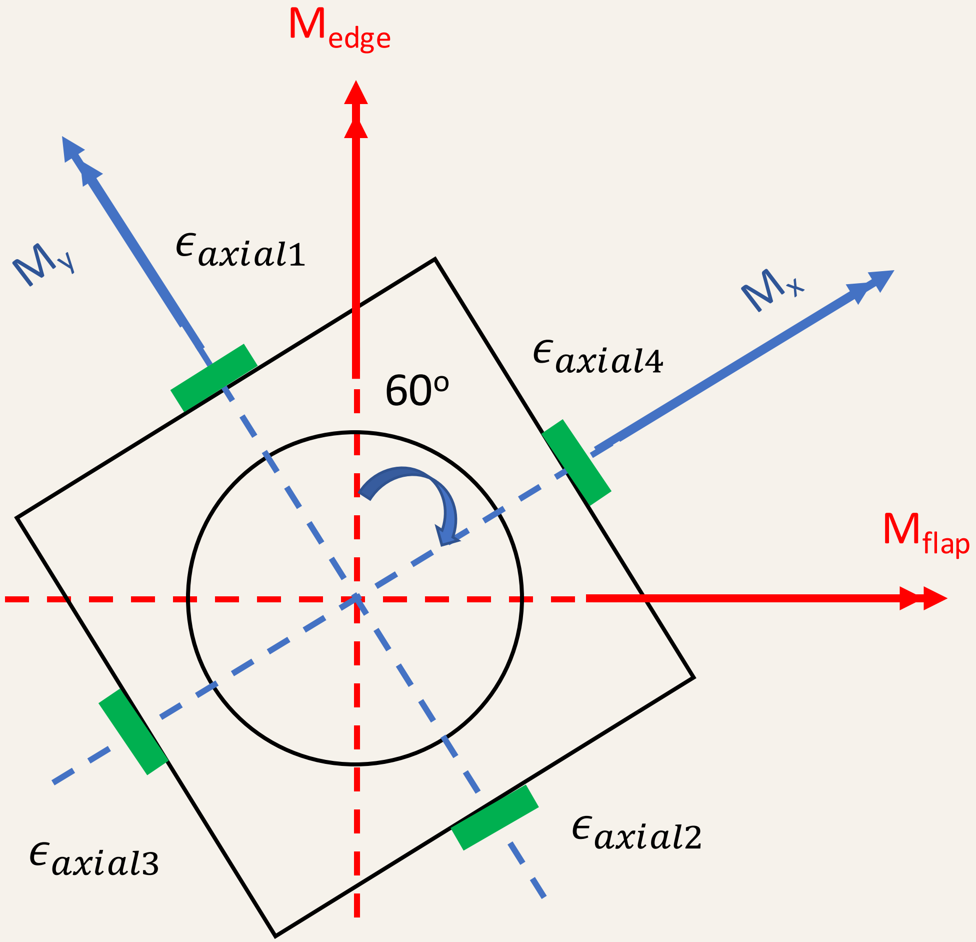
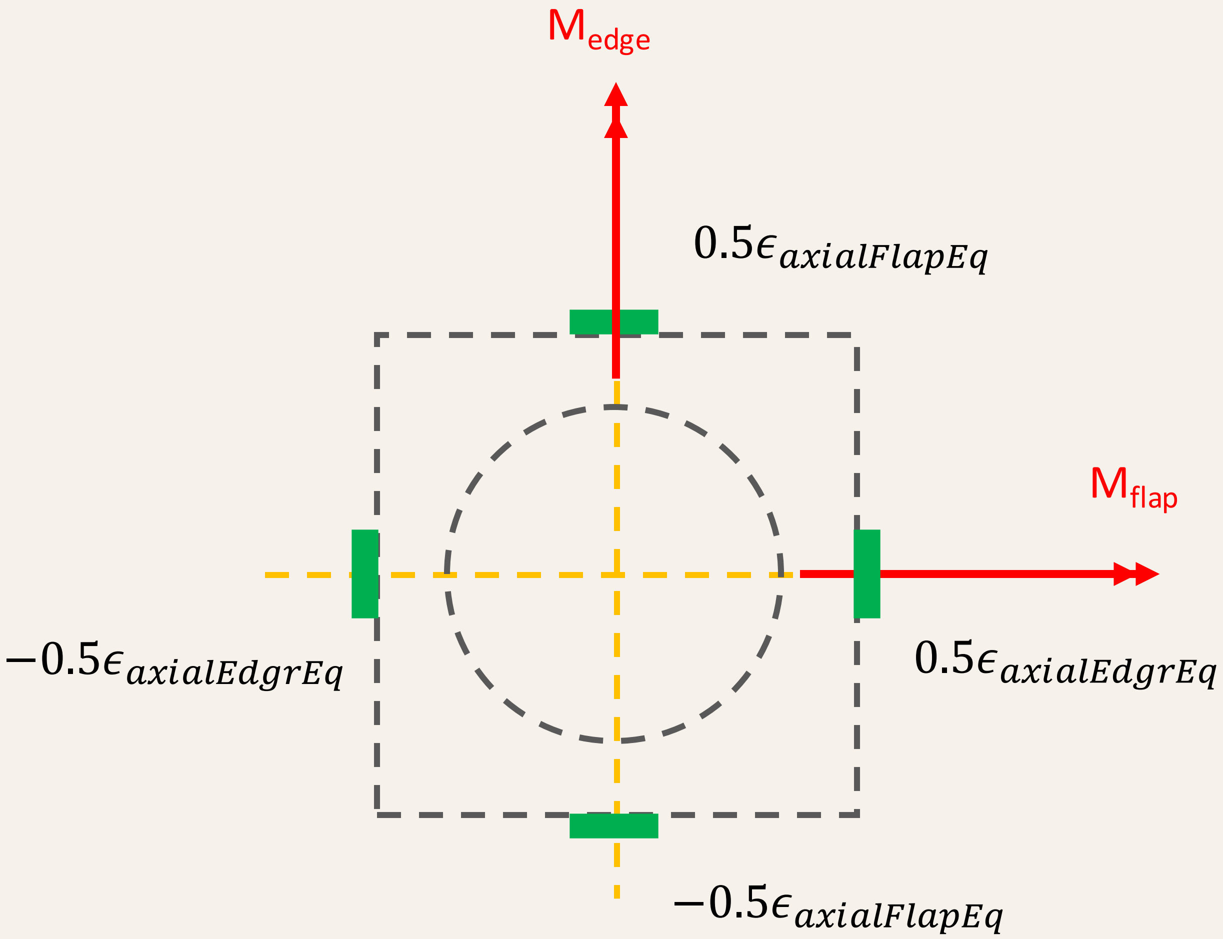
Equivalent Strain Measure

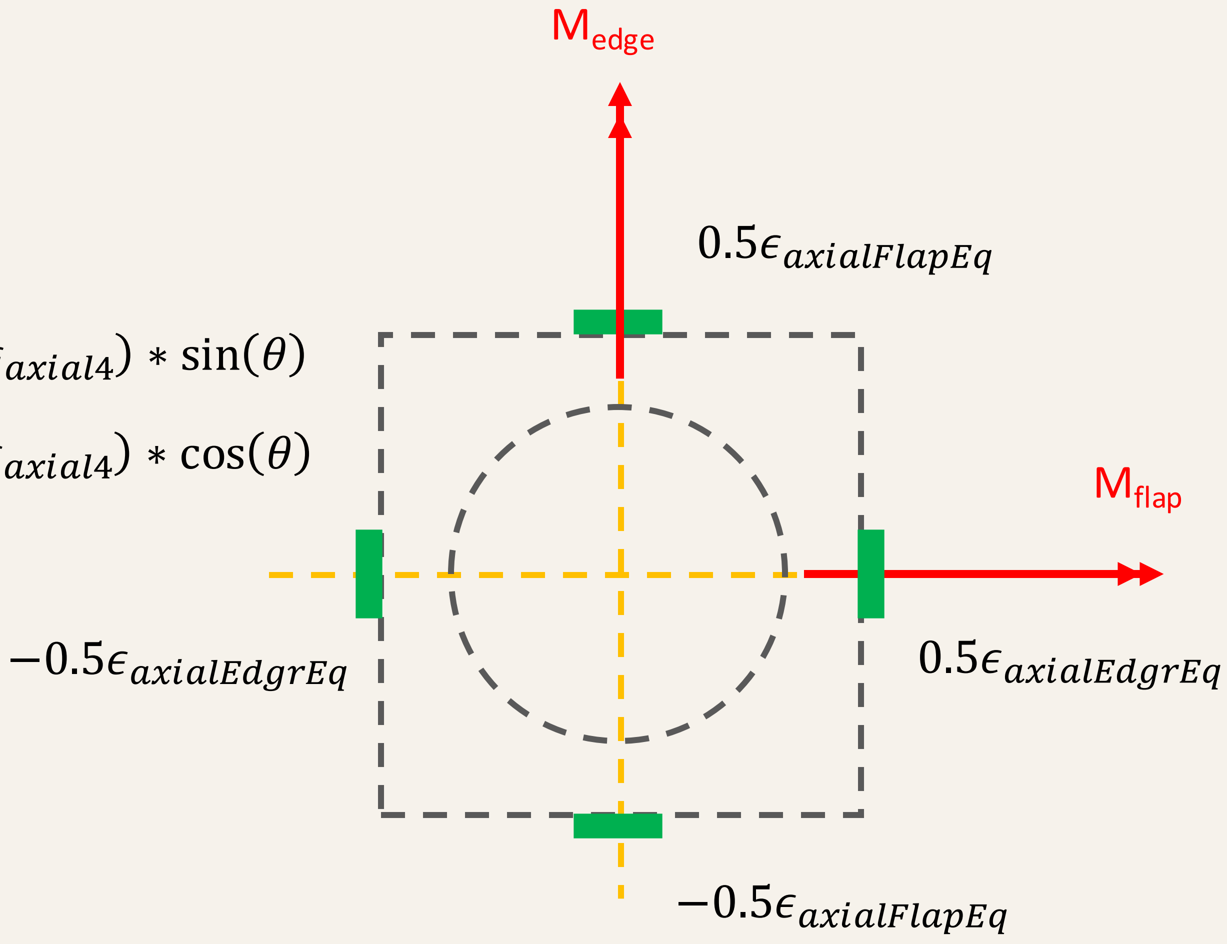




Equivalent Strain Measure

$$\epsilon_{axialFlapEq} = (\epsilon_{axial1} - \epsilon_{axial2}) * \cos(\theta) - (\epsilon_{axial3} - \epsilon_{axial4}) * \sin(\theta)$$

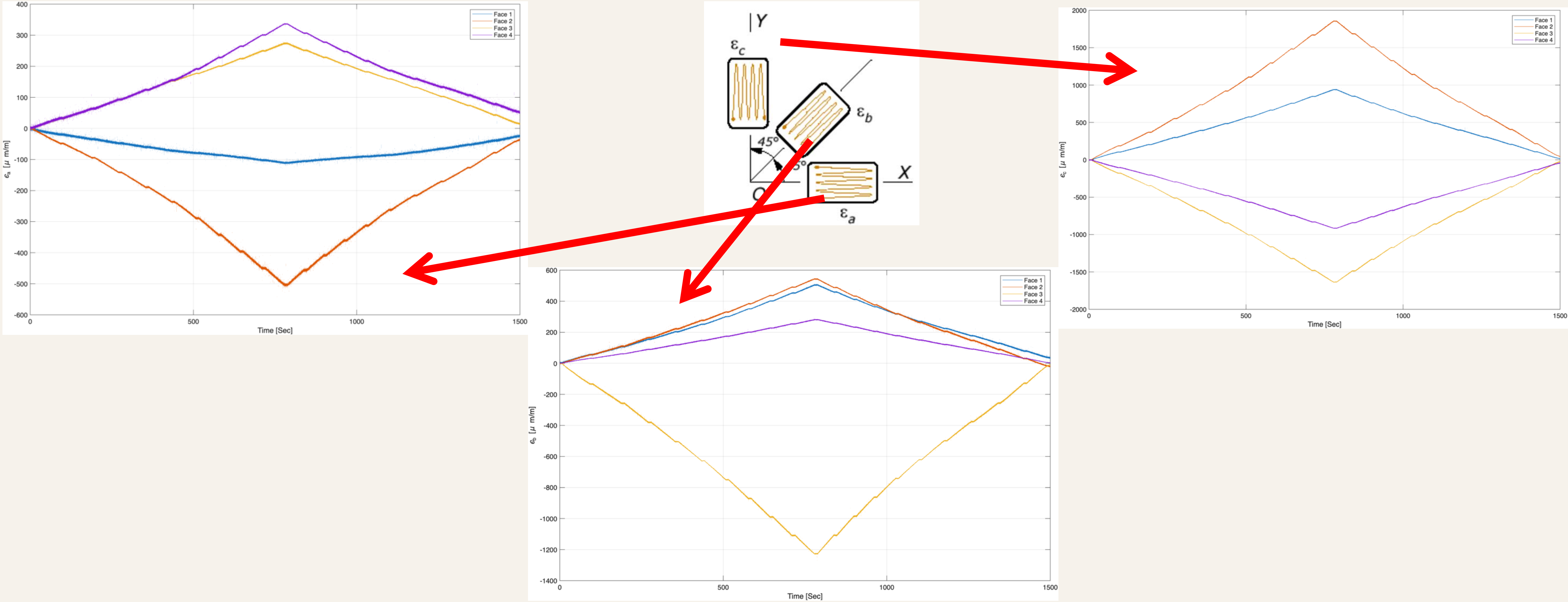
$$\epsilon_{axialEdgeEq} = (\epsilon_{axial1} - \epsilon_{axial2}) * \sin(\theta) + (\epsilon_{axial3} - \epsilon_{axial4}) * \cos(\theta)$$



Equations are only valid for ***square*** roots.

B3R3 5.27 kN flapwise

Results



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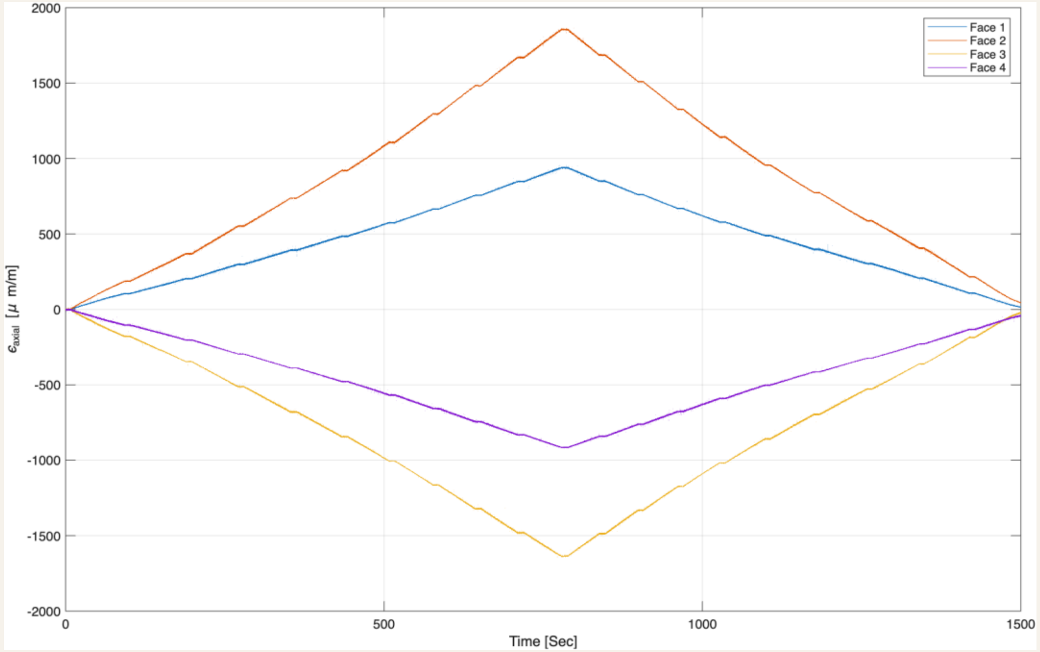
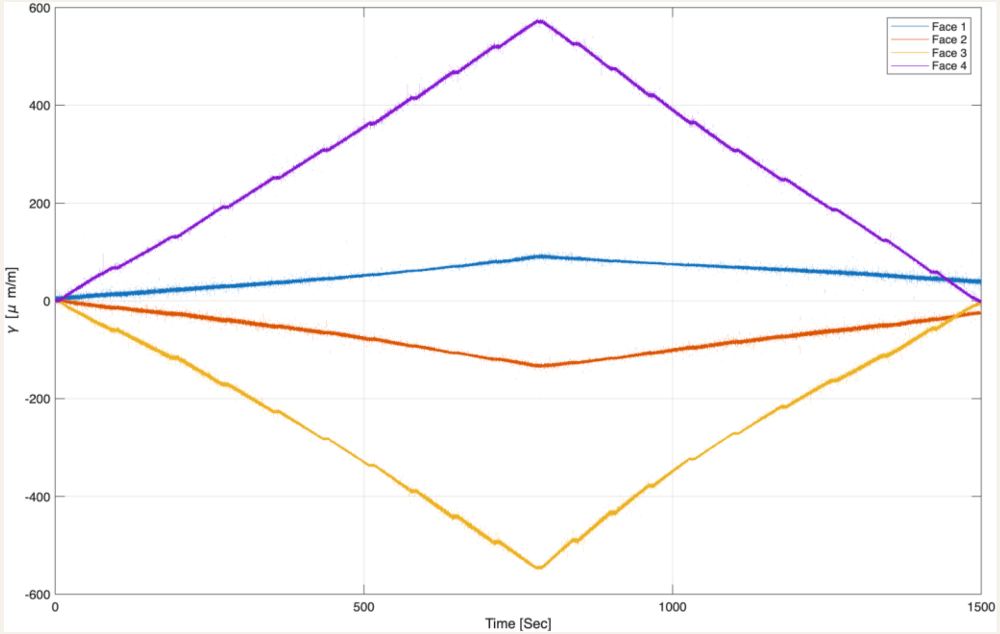
Results

B3R3 5.27 kN flapwise

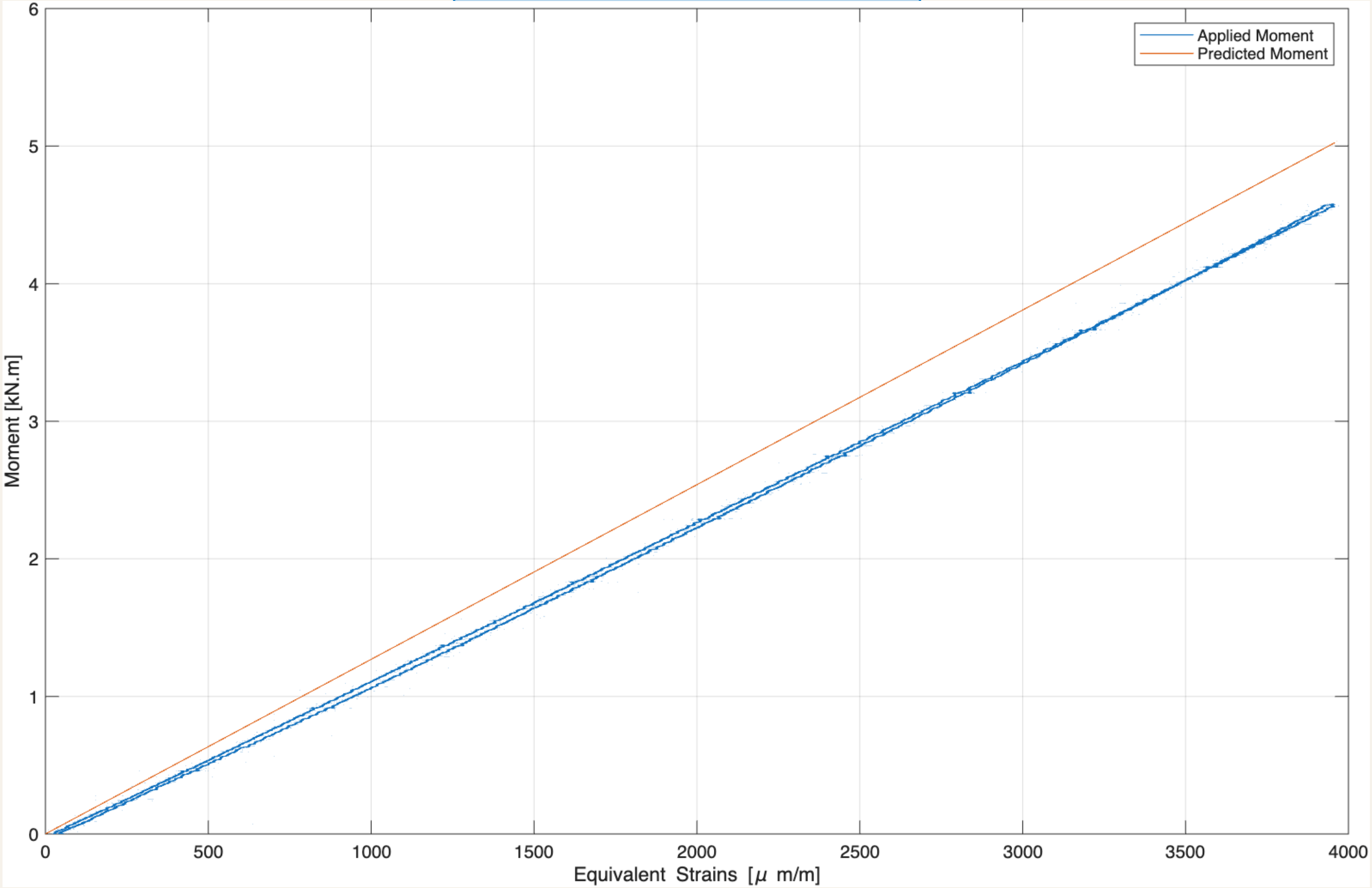


$$
\begin{cases}
\varepsilon_x = \varepsilon_a \\
\varepsilon_y = \varepsilon_c \\
\varepsilon_{xy} = \varepsilon_b - \dfrac{\varepsilon_a + \varepsilon_c}{2}
\end{cases}
$$



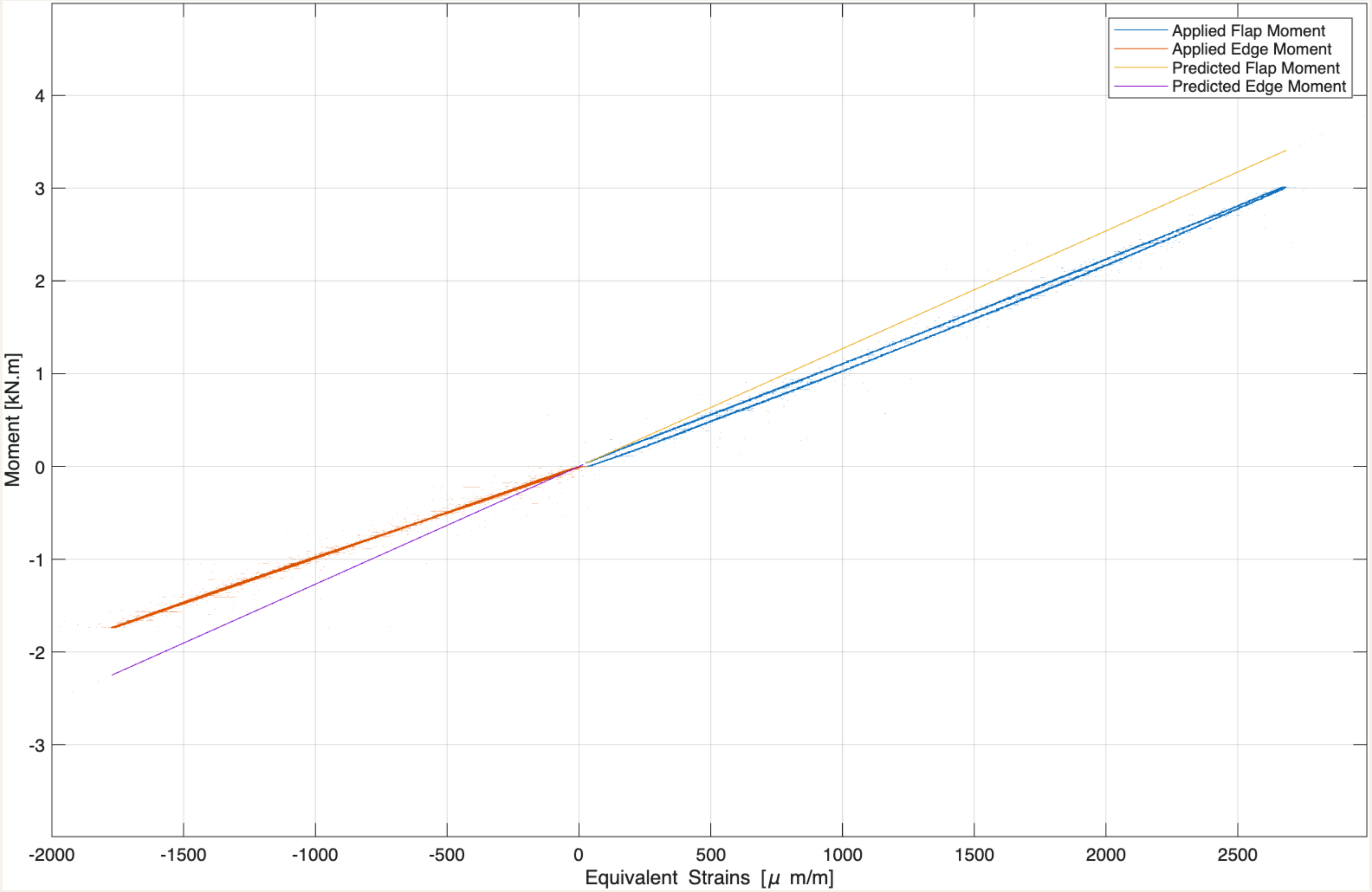
Results

B3R3 5.27 kN flapwise



Results

B3R3 4 kN (-30º Pitch)



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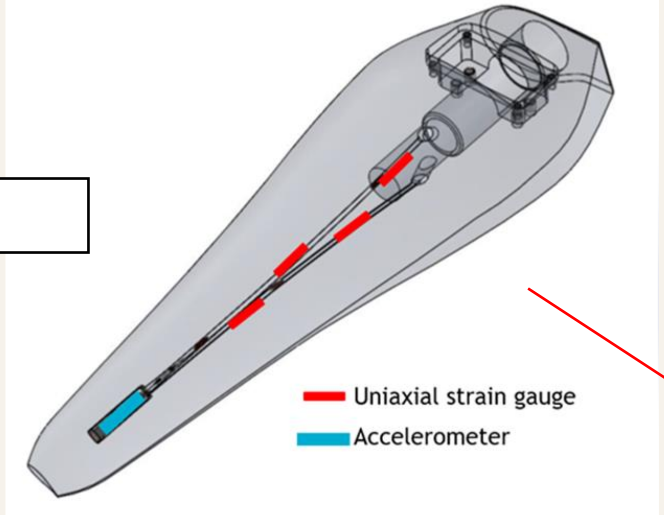
Conclusions

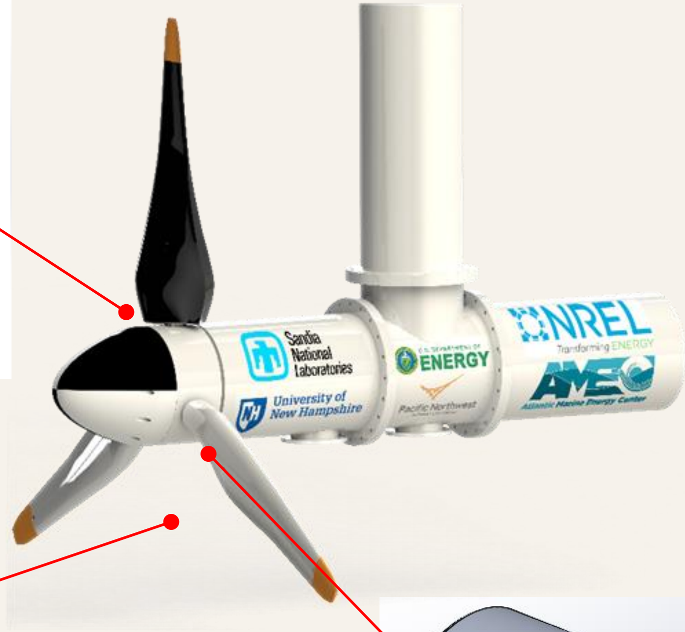
- ***Quasi-static*** blade performed at Sandia National Laboratories
- ***Calibrate*** and ***validate*** FOS measurements for ***open-water*** deployment on the rotor assembly of the open-source tidal energy converter (***OSTEC***).
- The applied flapwise, edgewise, and pitch moments estimated via ***OpenFAST*** simulations for the ***OSTEC*** turbine rotor under different design load cases and turbulent inflow conditions specified in the ***IEC 62600-2***.
- The blade was ***extensively*** instrumented, including ***four strain rosettes*** on ***each face*** of the blade's ***cubical roots***.
- Blade represented as a ***cantilever beam***, the ***strain rosette measurements*** were used to ***predict*** and ***compare*** with the ***applied loads***.
- This ***simplified structural model*** predicts applied loads with reasonable accuracy, within about ***10%*** of the testing measurements.

Future Work

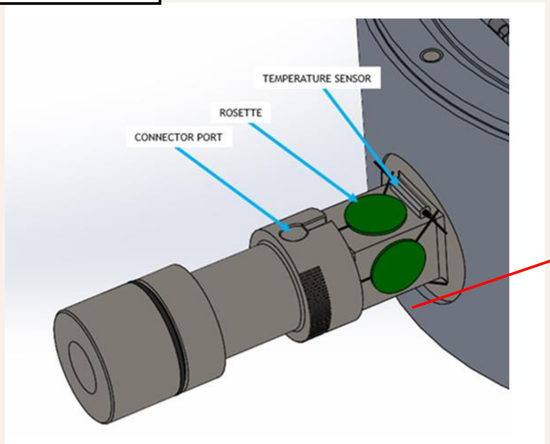
SNL smart FOS-sensor blade



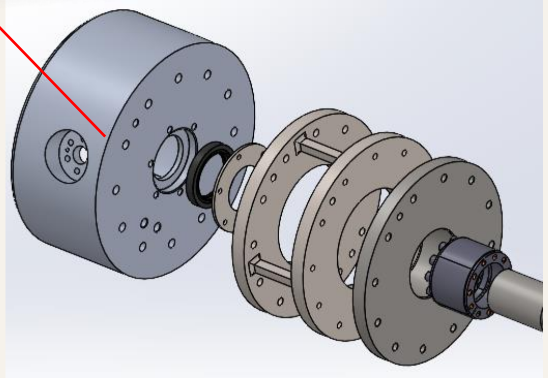
OSTEC testbed



SNL precision
FOS blade root sensor



4 DOF rotor load cell



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  Brek J. Meuris
  Martin C. Jang

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THANK YOU!

QUESTIONS