# DELIVERABLE D1.2:
# TECHNICAL REPORT ON BP1 FINAL TURBINE DESIGN

## ADVANCED TIDGEN® POWER SYSTEM
## US DEPARTMENT OF ENERGY AWARD: DE-EE0007820

**DOCUMENT NUMBER: D-TD20-10144**
**REVISION 0 – 04/13/2018**


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## 2. Purpose

To fulfill deliverable D1.2: *Technical report with final design, supporting CFD analysis, structural analysis, and development plan* of the Advanced TidGen Power System project.

## 3. Final Design Overview

Upon completion of budget period one for task 1 of the Advanced TidGen Power System project, a final turbine design was produced. A model of the final turbine design can be seen in Figure 1.

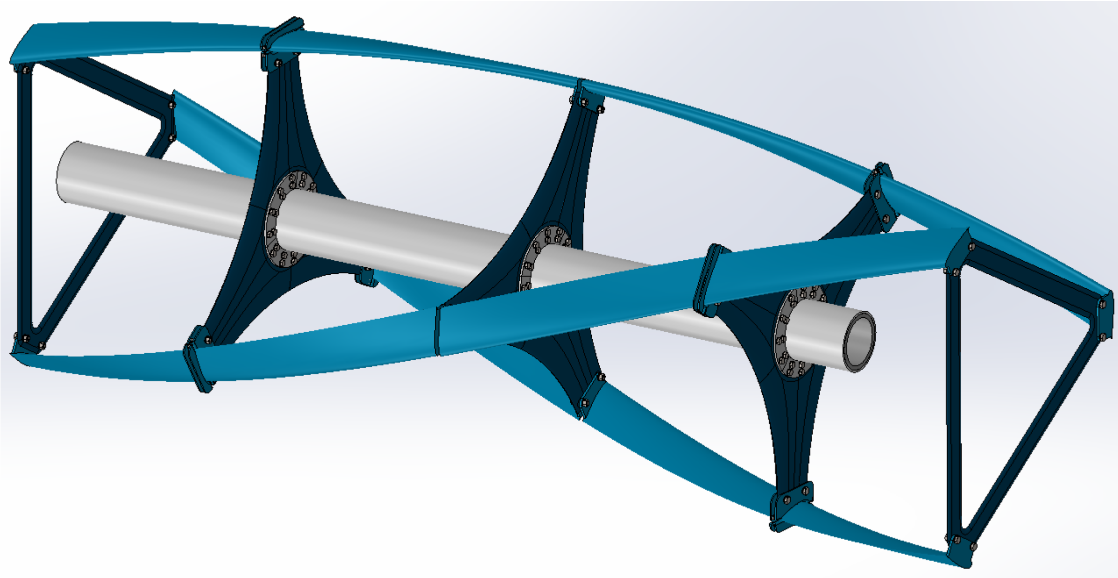
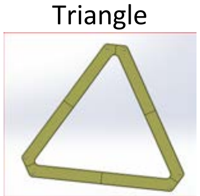
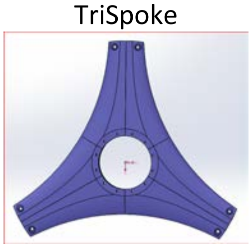


Figure 1: Advanced TidGen Final Turbine Design Model

A detailed description of each component on the turbine is outline in Figure 2. The item image, 1st and 2nd build quantity and a description of the component level design is outlined. The 1st build will consist of building one turbine for evaluation followed by a 2nd build of the remaining seven turbines.

| Item | Qty | Description |
|---|---|---|
| Triangle  | 1st Qty: 2<br>then<br>2nd Qty: 14 | Approx. weight 28.3 kg each<br>VectorPly, E-QX 6400 (approx. 1.67mm at 50% Volume Fraction(Vf) or equivalent, 12 layers in the main sides, overlap side strips and corner strips, butt layers as needed, having all continuous layers is not possible nor required.<br>6 Long side strips per side<br>6 Short side strips per side<br>6 Corner strips per corner |
| TriSpoke  | 1st Qty: 3<br>then<br>2nd Qty: 21 | Approx. weight 78.2 kg each<br>VectorPly E-QXM 6410 or equivalent (approx. 1.88mm @ 50% Vf). Overlap where possible, minimizes butted plys, do not stack butted plys without a continuous layer between. Taper as needed. No butted plys should be at the surface (overlaps are ok). |
| Saddle (Right h)  | 1st Qty: 6<br>then<br>2nd Qty: 18 | Approx. weight 1.7 kg each<br><br>Alternating layers of (0,90) and (+/-45), 18 oz/sqyd, e-glass (approx. 0.471mm at 50% Vf), 8 pairs of |

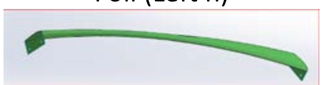
| | | |
|---|---|---|
| Saddle (Left h)<br> | 1st Qty: 0<br>then<br>2nd Qty: 24 | each, 16 layers total. VectorPly E-LT1800 and E-BX1700 or equivalent. Tooled inside and outside. |
| Foil (Right h)<br> | 1st Qty: 6<br>then<br>2nd Qty: 18 | Foam core: General Plastics FR7115 or equivalent.<br>Carbon fiber: Zoltek PX35 (0) Uni-Directional Fabric, UD600 or equivalent.<br>Glass fiber: Double bias (+/-45) 18 oz/sqyd, VectorPly E-BX1700 or equivalent.<br>Laminate:13 layers total, 5 glass, 8 carbon, ( (+/-45), 0, 0, (+/-45), 0, 0, (+/-45), 0, 0, (+/-45), 0, 0, (+/-45)). Surface veil may be required (TBD).<br>Flanges are a continuation of the upper and lower laminates, terminating 1 carbon from each pair at the foil end, and interleaving 4 layers of ELT-1800. Total flange thickness is 12mm. |
| Foil (Left h)<br> | 1st Qty: 0<br>then<br>2nd Qty: 24 | |

Figure 2: Turbine components overview with details on component level design details.

This CDR turbine design was produced with project contractor, Blusource Energy Inc., whom ORPC relied on for some design decisions. These decisions included making the foil half the length of the turbine and adding a flange to the ends of each foil section, so the foils could be bolted axially to the struts. The foil section center joint consists of a bolted saddle which clamps the foils to the struts. As seen in Figure 1 the turbine is connected to the shaft by means of a bolted flange that is welded to the shaft. Doubler plates are utilized for this joint.

## 4. Supporting CFD Analysis

During the design phase of the turbine development for Task 1 many 2D Computation Fluid Dynamic (CFD) analysis were carried out. Once the turbine was defined during the Critical Design Review (CDR) a final 2D CFD analysis including a buoyancy pod, a representative center nacelle and two counter rotating turbines was conducted. The velocity flow field can be seen interacting with the structure in Figure 2.

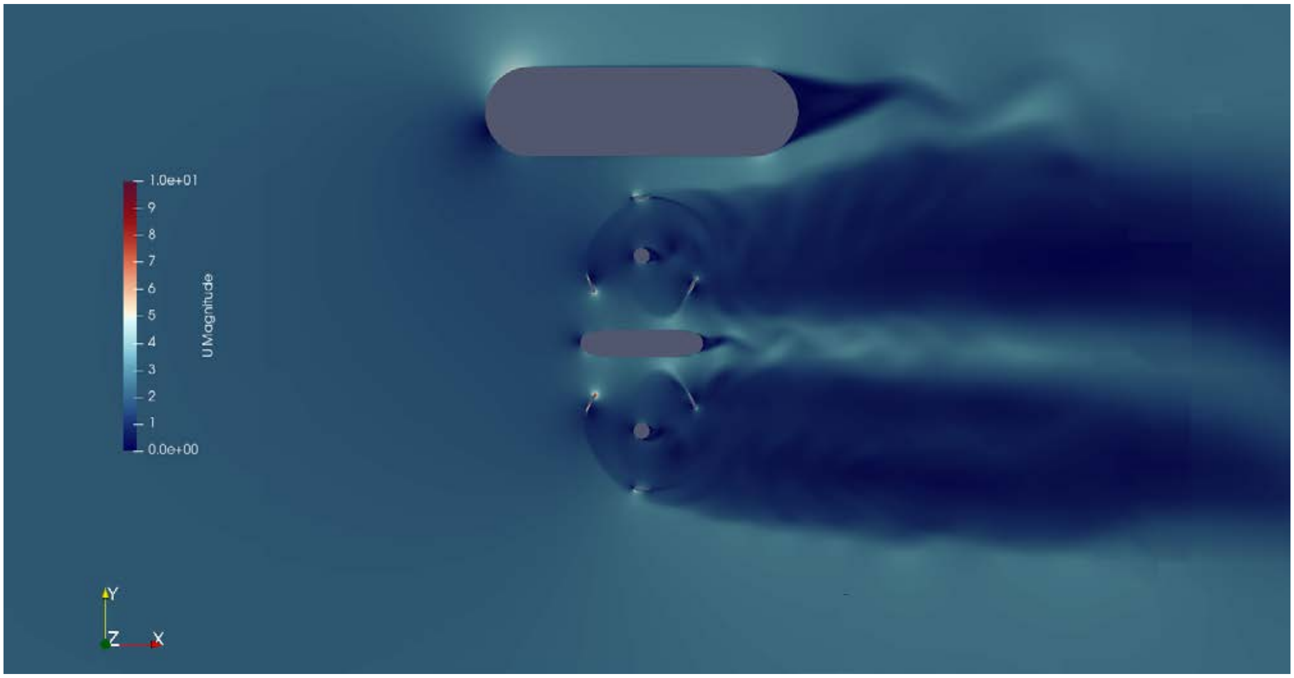


Figure 3: CDR Turbine Design CFD

The Coefficient of Performance (Cp) vs. Tip Speed Ratio (TSR) curves for the raw 2D data from this CFD analysis is represented graphically in Figure 3. It is interesting to note that the upper and lower rotor have different curves, the lower being a slightly better performer. This is due to the buoyancy pod interfering with the flow field near the upper rotor.

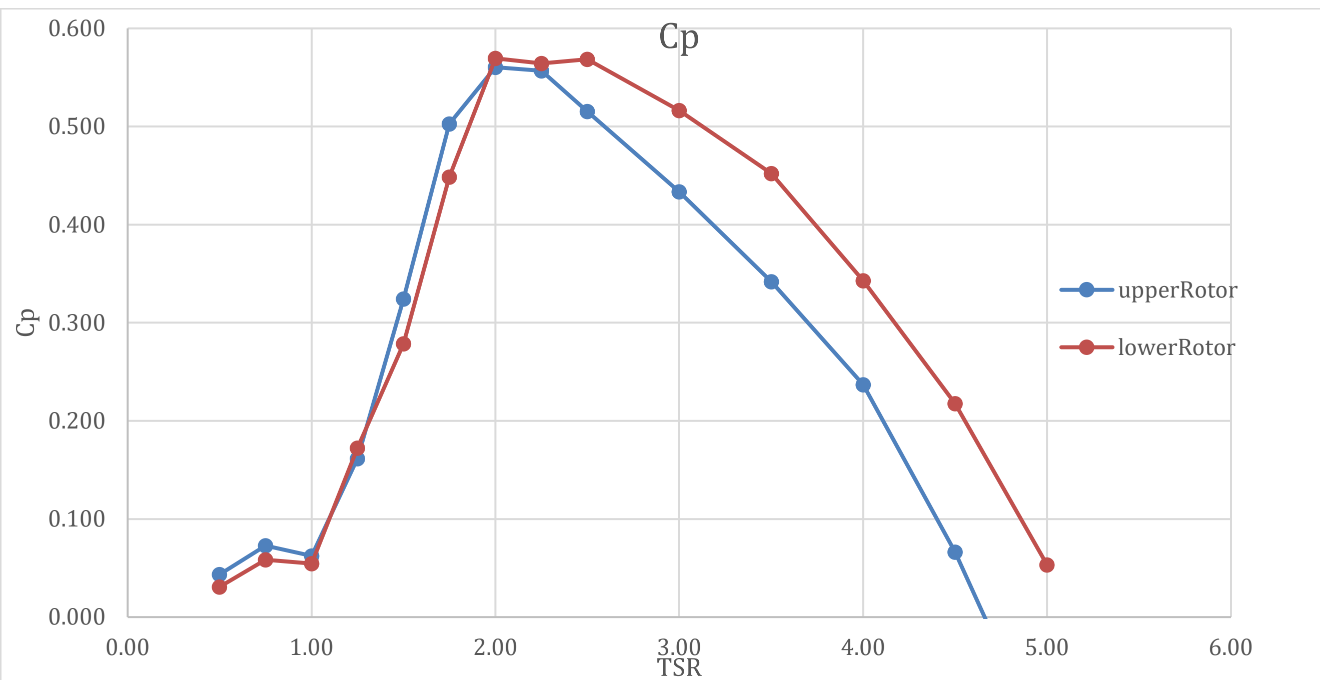


Figure 4: Cp - TSR curve for the raw 2D CFD analysis

ORPC have developed a post processing tool (LExCoSS) to convert 2D CFD into quasi 3D data by extrapolating the 2D loads along the span and helical twist. This process has proven valuable as full 3D CFD analysis is computationally intensive, costly and time consuming. The LExCoSS Cp – TSR curve for the dual rotor case can be seen in Figure 4.

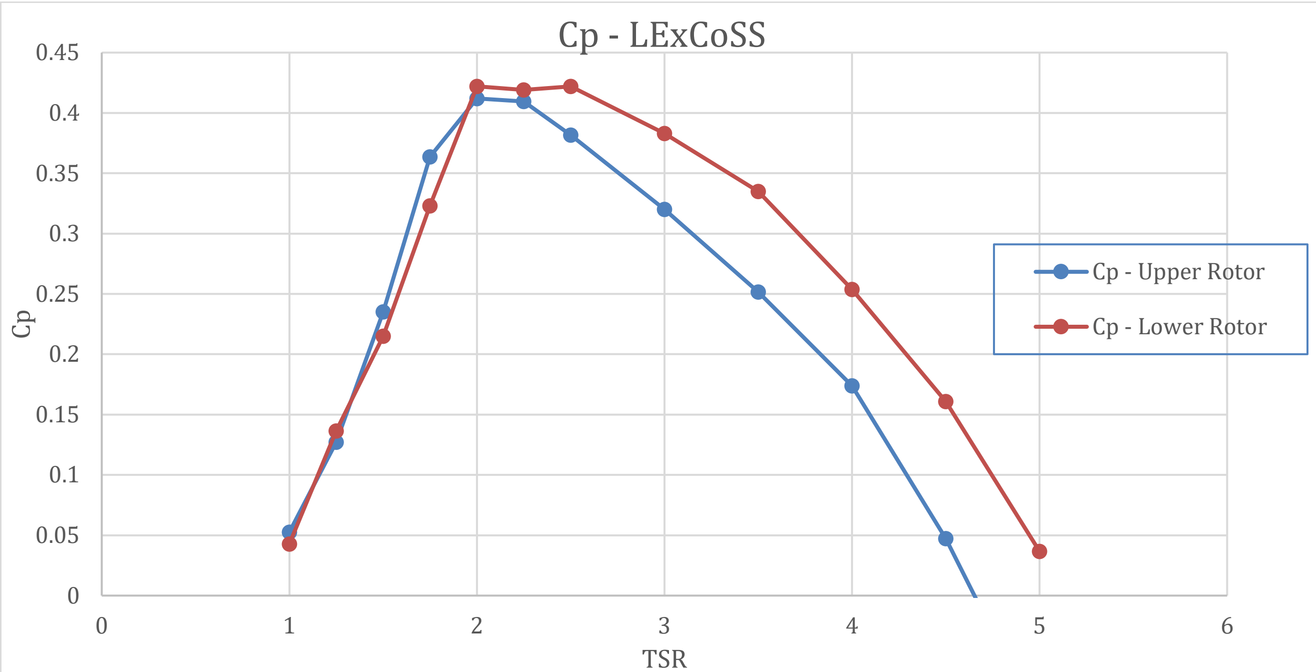



Figure 5: LExCoSS Cp - TSR curve for upper rotor

To conclude, from the raw 2D data the max Cp was 57% which is a high estimate because no loses are accounted for. After the 2D data is post processed with LExCoSS the max Cp drops to an average of 42% which is a reasonable estimate of the final turbine performance and is further verified when compared to the estimate outlined in D1.1 Preliminary turbine hydrodynamic design, D-TID2-1004.

## 5. Structural Analysis

For the structural analysis Blusource Energy Inc. received a design package from ORPC including the following:

- Turbine model with rough dimensions
- A document (D-TD20-10023) providing the design loads for the operating condition and the fatigue limit state.

### Geometry

The geometry developed with the aid of Blusource is as follows:

- Source: D-TD20-10023 R00 - Turbine Design Cases, TidGen 2.0.xlsx
- SolidWorks model developed reference: Turbine assembly 3 for FEA.SLDASM
- 6.25m overall turbine foil length, outer flange to outer flange.
- 120 degree twist
- Thickness of center support at foil connection = 25mm
- Thickness of center support at shaft connection = 50mm
- ½ Foil length (6.25-0.025)/2 = 3.1125m
- Strut spacing: one at center, two offset Center to Center is 1.700m (flange to flange, rotation = 32°)
- Foil bolts 25mm diameter, on 1.000m radius, 0.200m apart about centerline

## Loads

- Source: D-TD20-10023 R00 - Turbine Design Cases, TidGen 2.0.xlsx
- Baseline load case is assumed unless noted otherwise. Normal and tangential loads on all foils, at 3.5 m/s and TSR 3.0, without factors.
- Maximum foil axial load is taken as 10% of the maximum single foil normal load of 150,000N, yielding 15,000N, applied as a line load on the foil leading edge.
- This information was presented in an Excel document with the pressure loads calculated over the foil chord along the foil length as seen in Figure 6.

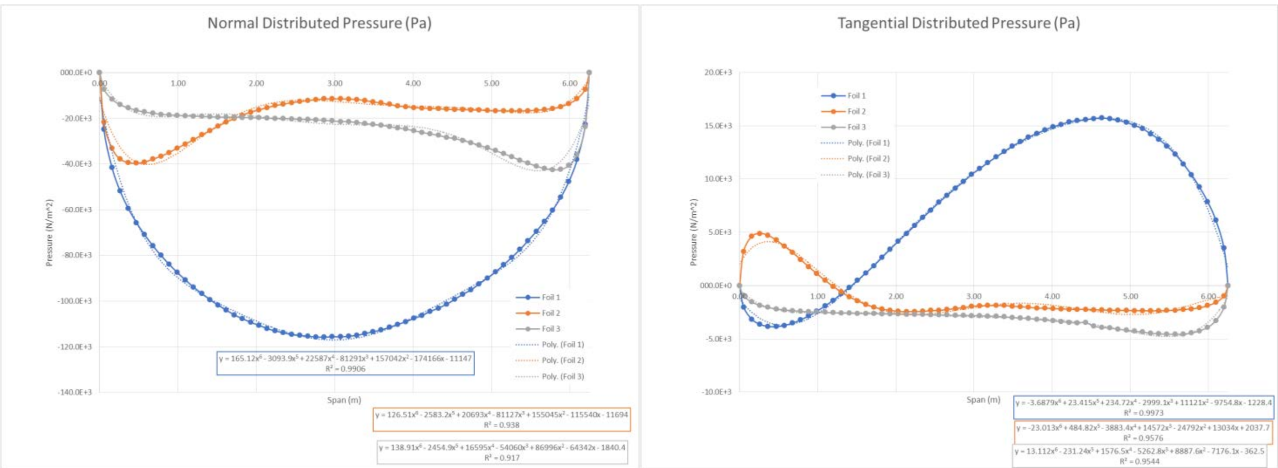



Figure 6: Turbine Pressure loads on all three foils. One line representing the pressure loads on a single foil. Blue line is Foil 1 perpendicular to the flow, grey and orange lines are foil 2 and 3 each offset by 120 and 240 degrees respectively. Left chart show Normal loads, right chart shows Tangential loads.

## Using pressure loads

The tangential pressure was applied as a line load applied to the leading edge of each foil respectively as seen in Figure 7.

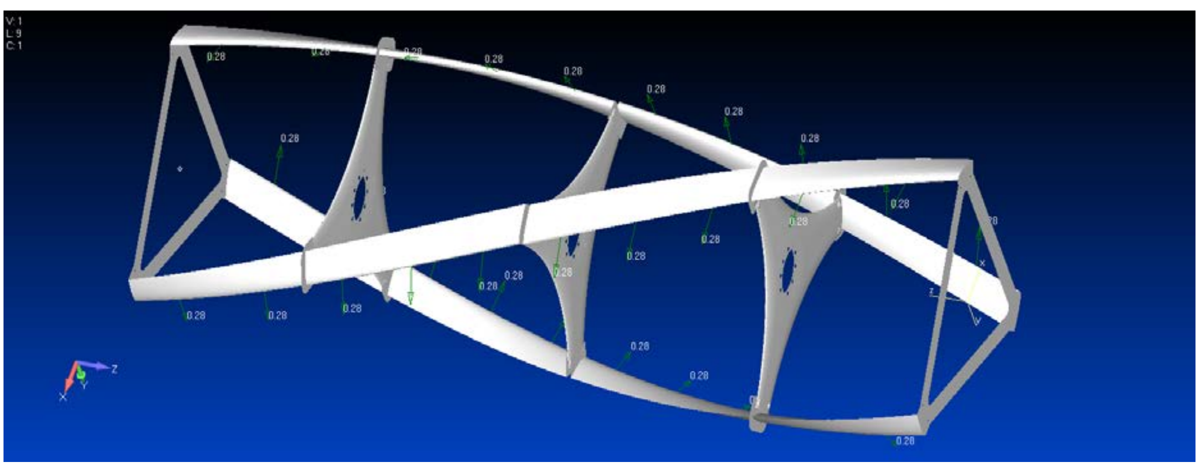


Figure 7: Tangential loads applied to the leading edge of each foil

The radial pressure load was applied over three chordwise elements on the surface, approximately at the 1/4 chord. This can be seen graphically in Figure 8.

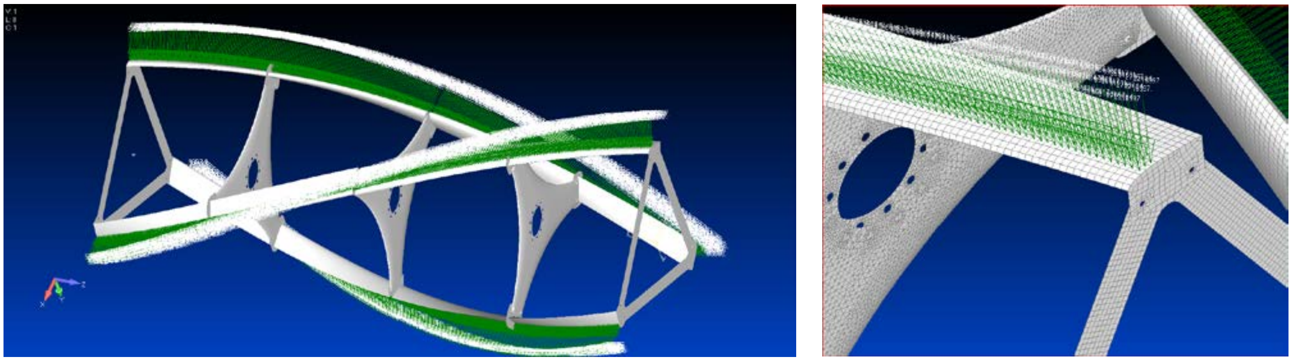


Figure 8: Radial (normal) pressure load applied to three chordwise elements along the foil span.

A simplified method to estmate the maximum foil axial load is to take 10% of the maximum single foil normal load of 150,000N, yielding 15,000N, and is applied as a line load on the foil leading edge as seen in Figure 9.

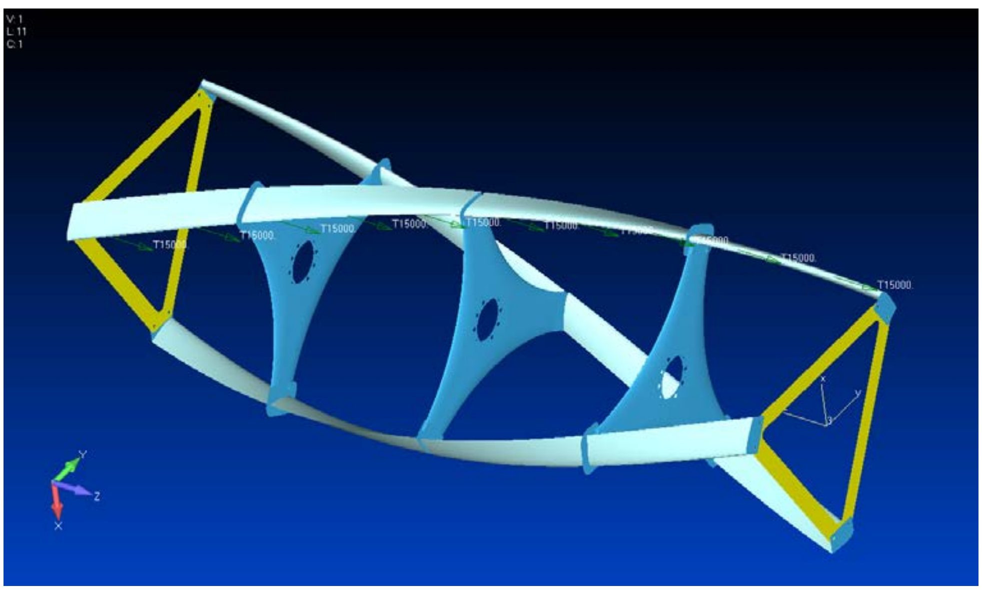



Figure 9: Axial load applied as a line load to the leading edge of each foil

To verify the loads were applied to the FEA model correctly a reaction load check was performed. Load balance check outputs from FEA can be seen in Table 1 and Table 2.

Table 1: Load Balance Check, FEA MODEL (Foil normal loads + tangential loads) ALL FOILS together.

```
Summation of Forces, Moments, Pressures and Body Loads for Set 10 (CSys 0)
  Nodal Force               FX =     11125.65  FY =    -14940.68  FZ =           0.
  Nodal Moment              MX =           0.  MY =           0.  MZ =           0.
  Pressure Force            FX =      125491.  FY =    -2262.504  FZ =    -1067.296
  Body Translational Accel  FX =           0.  FY =           0.  FZ =           0.
  Body Varying Trans Accel  FX =           0.  FY =           0.  FZ =           0.
  Body Rotational Accel     FX =           0.  FY =           0.  FZ =           0.
  Body Rotational Velocity  FX =           0.  FY =           0.  FZ =           0.

Totals (CSys 0)
  About Location             X =           0.   Y =           0.   Z =           0.
  Forces                    FX =     136616.6  FY =    -17203.18  FZ =    -1067.296
  Moments                   MX =     100790.1  MY =     422148.6  MZ =     3630.157
```

Table 2: Load Balance Check (Tangent foil loads only)

```
Summation of Forces, Moments, Pressures and Body Loads for Set 9 (CSys 0)
  Nodal Force               FX =     11125.65  FY =    -14940.68  FZ =           0.
  Nodal Moment              MX =           0.  MY =           0.  MZ =           0.
  Pressure Force            FX =           0.  FY =           0.  FZ =           0.
  Body Translational Accel  FX =           0.  FY =           0.  FZ =           0.
  Body Varying Trans Accel  FX =           0.  FY =           0.  FZ =           0.
  Body Rotational Accel     FX =           0.  FY =           0.  FZ =           0.
  Body Rotational Velocity  FX =           0.  FY =           0.  FZ =           0.

Totals (CSys 0)
  About Location             X =           0.   Y =           0.   Z =           0.
  Forces                    FX =     11125.65  FY =    -14940.68  FZ =           0.
  Moments                   MX =     36492.83  MY =     23302.65  MZ =     6815.228
```

## Materials

The foils are made from a composite with Fiberglass and Carbon fiber. The material properties for both materials used in the FEA analysis are provided in Figure 10.

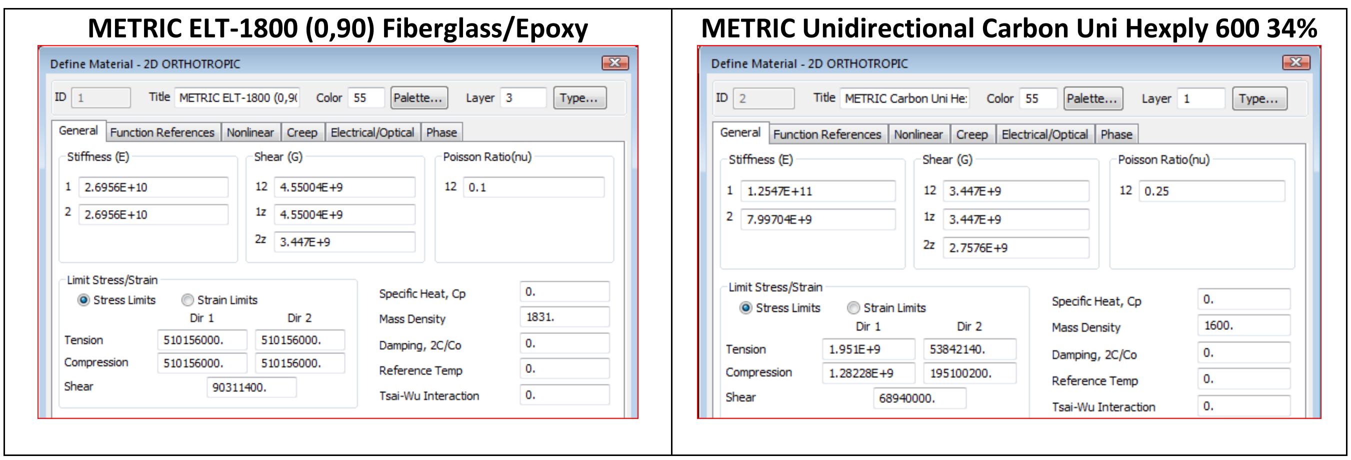



Figure 10: Material properties for Fiberglass (left) and Carbon Fiber (right)

## Layups

The layup schedule for the initial FEA analysis (baseline) is detailed in Figure 11. Note that the end triangle support laminate schedule has the same properties as the strut but is 19mm thick.

### Foil Layup @ 8.89mm

Layup Editor

ID 2 Title METRIC Foil Laminate

Global Ply ID (optional) AutoCreate Material

0..None

--- Top of Layup --- Total Thickness = 0.008892

| Ply ID | G... | Material | Thickness | Angle |
|---|---|---|---|---|
| 16 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |
| 15 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 14 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 13 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |
| 12 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 11 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 10 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |
| 9 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 8 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 7 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |
| 6 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 5 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 4 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |
| 3 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 2 | | 6..METRIC Carbon Uni He... | 0.000615 | 0. |
| 1 | | 5..METRIC ELT-1800 (0,9... | 0.000457 | 45. |

--- Bottom of Layup ---

**Laminate Equivalent Properties**

16 Plies - Total Thickness = 0.008892

In-Plane Properties
Ex = 9.1317E+10 Ey = 1.1347E+10 Gxy = 6.1624E+9
NUxy = 0.39771 NUyx = 0.0494182
Alphax = -1.3474E-7 Alphay = 7.25038E-6 Alphaxy = 0.
Bending/Flexural Properties
Exb = 8.23E+10 Eyb = 1.2174E+10 Gxyb = 6.87501E+9
NUxyb = 0.4226 NUyxb = 0.0625132
Alphaxb = -1.5425E-7 Alphayb = 5.94709E-6 Alphaxyb = 0.

### TriSpoke (strut) Laminate @ 12 mm

Layup Editor

ID 1 Title METRIC ELT-1800 (0,90) glass

Global Ply ID (optional) AutoCreate Material

0..None

--- Top of Layup --- Total Thickness = 0.012704

| Ply ID | G | Material | Thickness | Angle |
|---|---|---|---|---|
| 16 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 15 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 14 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 13 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 12 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 11 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 10 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 9 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 8 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 7 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 6 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 5 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 4 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 3 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |
| 2 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 45. |
| 1 | | 4..METRIC ELT-1800 (0,90) glass | 0.000794 | 0. |

--- Bottom of Layup ---

**Laminate Equivalent Properties**

16 Plies - Total Thickness = 0.012704

In-Plane Properties
Ex = 2.1528E+10 Ey = 2.1528E+10 Gxy = 8.40138E+9
NUxy = 0.281225 NUyx = 0.281225
Alphax = 0. Alphay = 0. Alphaxy = 0.
Bending/Flexural Properties
Exb = 2.2678E+10 Eyb = 2.2678E+10 Gxyb = 7.67926E+9
NUxyb = 0.242833 NUyxb = 0.242833
Alphaxb = 0. Alphayb = 0. Alphaxyb = 0.

Figure 11: Laminate schedule and ply layup for the foils (left) and the strut (right)

## 6. Analysis Results

The 3D model was meshed by Blusource Energy Inc. to carry out an FEA analysis. The meshed model can be seen in Figure 12.

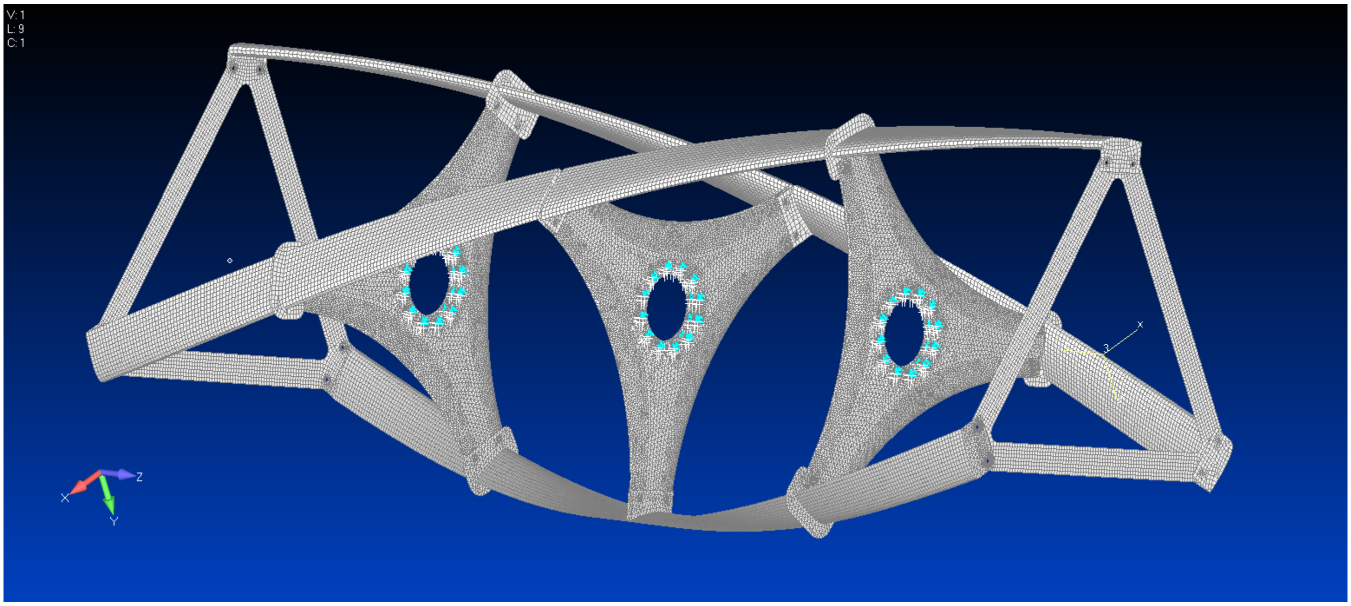


Figure 12: FEA Mesh with pinned bolt holes at the shaft flanges

### Axial Load

Figure 13 and Figure 14 show the FEA results from the axial load case.

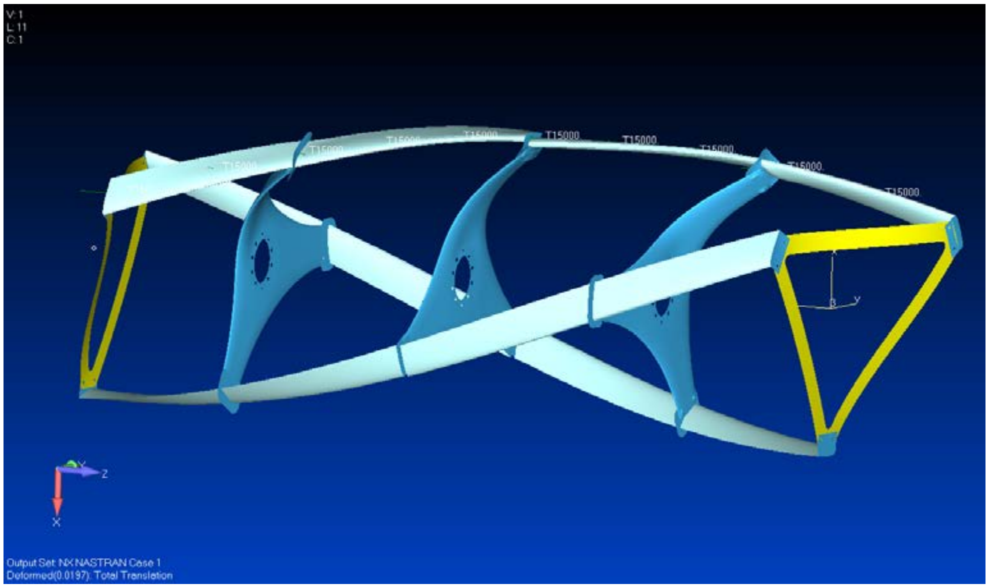



Figure 13: Deformed Shape (19mm displacement)

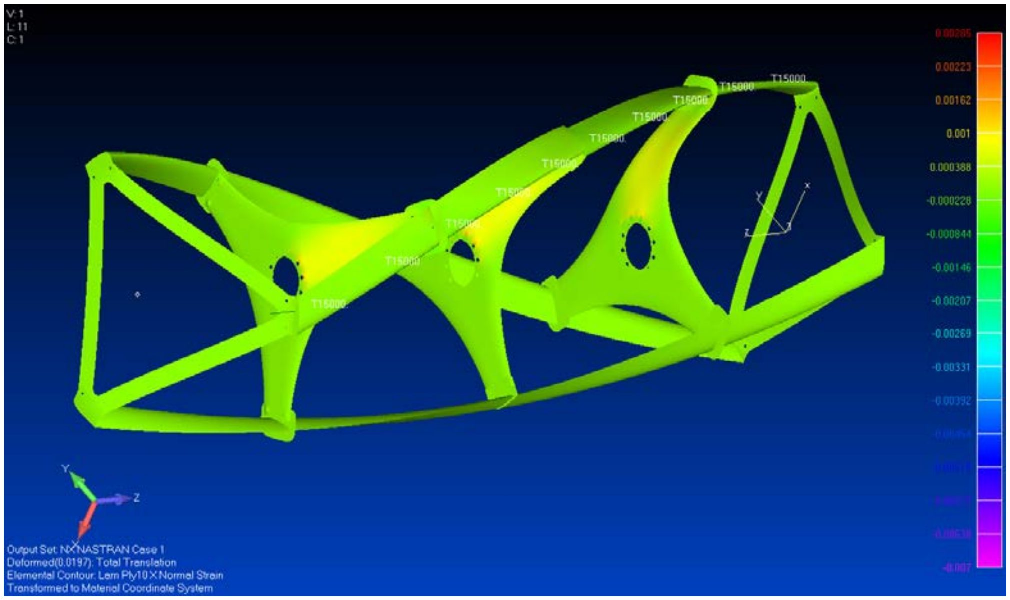



Figure 14: X-Direction Strain (Max 0.001 in TriSpoke laminates), very low strain in the foils.

## Combined load all foils

All loads were applied to the turbine and the results can be see graphically in Figure 15, 16 and 17 and tabulated in Table 3. Note that the max strain of 0.0026 is found in the foil laminate (corresponding to a stress of 236MPa using the strain and the foil laminate equivalent modulus). The max strain in the TriSpoke strut is less than 0.001.

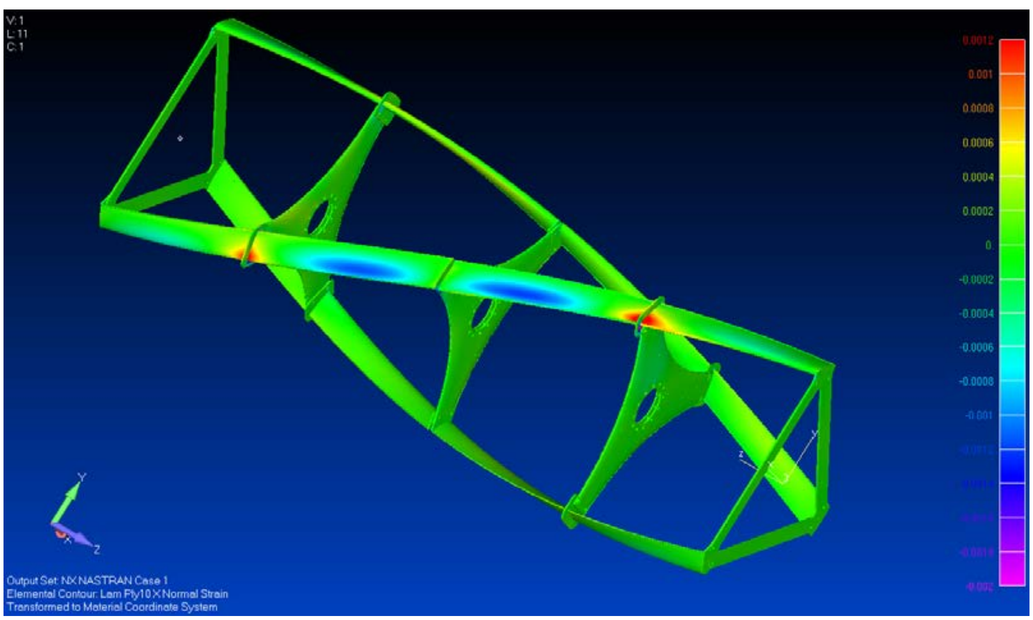



Figure 15: X Normal strain

Table 3: FEA analysis - tabulated results

| Foil Laminate | Thickness (mm) | Max Strain "X" | Deflection (mm) |
|---|---|---|---|
| Baseline 16 Layers | 8.89 | 0.00258 | 18.2 |

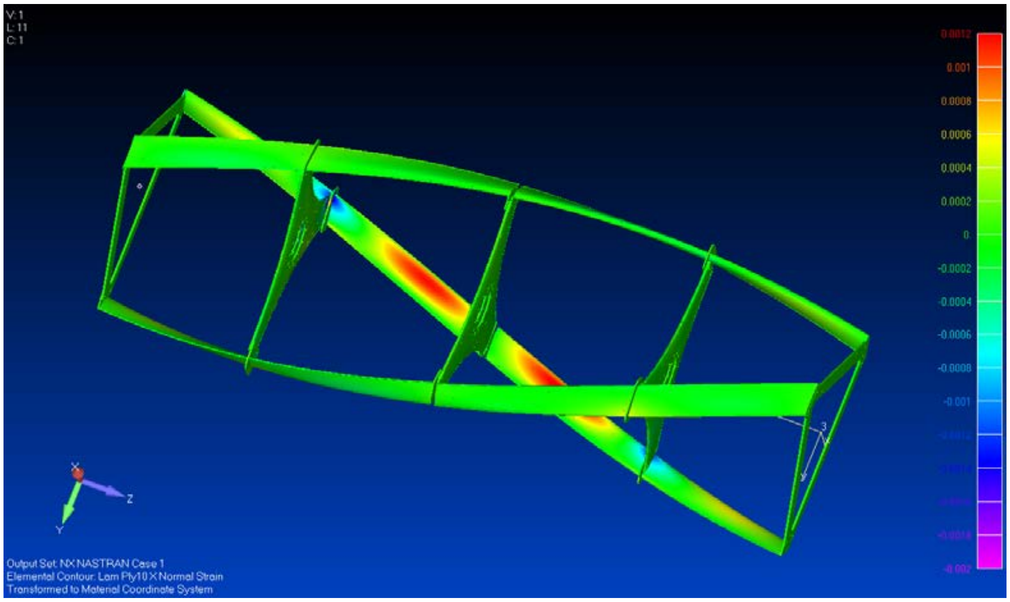



Figure 16: Bottom view of normal strain in the 'X' direction.

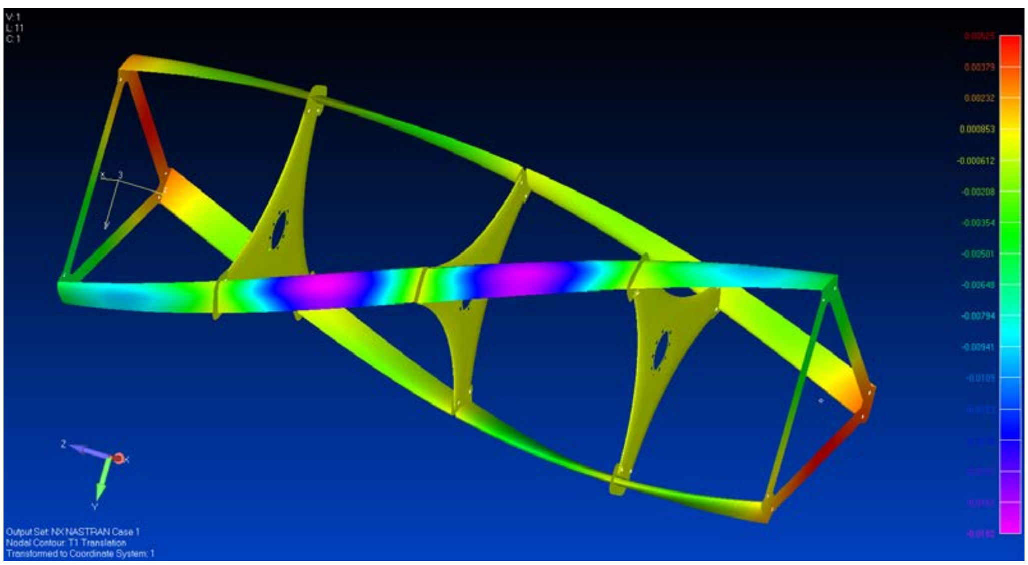



Figure 17: Radial deflection contour of the most highly loaded foil.

The maximum foil displacement is 17.8mm while the maximum total displacement is 18.2mm, indicating the majority of the displacement is from foil bending and radial displacement. Note the uniform color plots across the foil at any particular axial location, showing similar radial displacement at the leading and trailing edge, indicating a low amount of twist.

To gain further understanding into the foil behavior under load a twist calculation was carried out (Figure 18). The outcome of this simple analysis was that the foil angular deflection would not affect the turbine performance in a significant way.

Taking a chordwise section across the most highly loaded foil, in a region of maximum deflection, figure at right, the difference in leading and trailing edge displacement is used to estimate twist. The leading-edge displacement is -0.0177mm, while the trailing edge is -0.0161, indicating a twist, over the 0.3m cord, of -0.304 degrees. Leading edge radially inward, positive twist about "Z" axis.

Figure 18: Twist calculation

A free body diagram was created for the bolt holes of the turbine joint to determine adequate bolt sizes can be seen in graphically in Figure 19 and listed in Table 4.

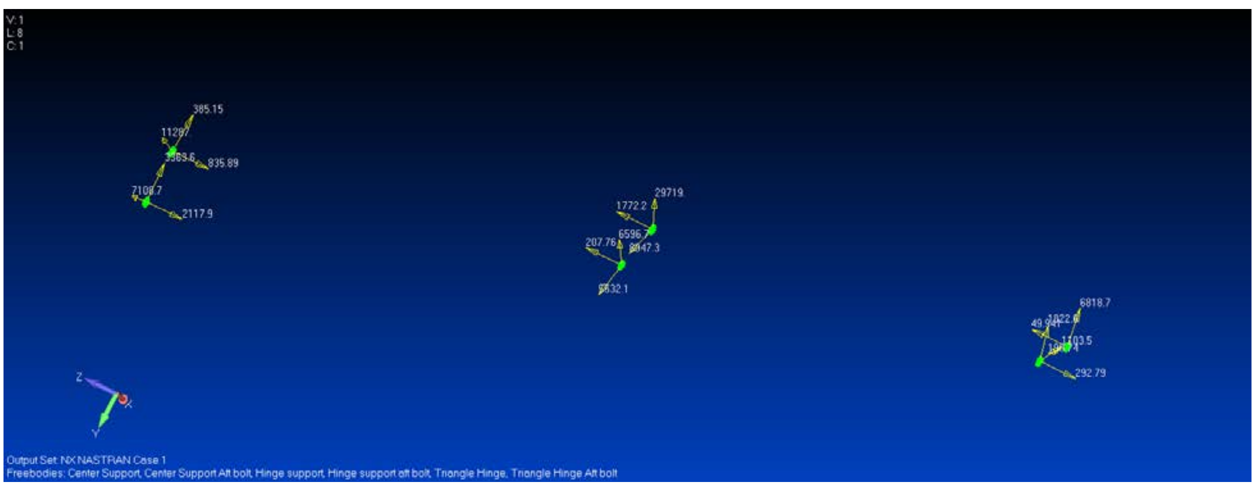



Figure 19: Foil connections freebody (Connection Loads)

Table 4: Bolt load summary for free body (all loads)

| | Radial Load (N) | | Tangent (N) | | Axial (N) | |
|---|---|---|---|---|---|---|
| | Forward | Aft | Forward | Aft | Forward | Aft |
| Hinge | -11287 | 7108 | 385 | 3363 | -835 | -2117 |
| Center | -29719 | 6596 | -8047 | -5532 | 1772 | 207 |
| Triangle | -6818 | 1822 | -198 | 1103 | 49 | -292 |

The maximum bolt load is 30789N (6911 lbs.), at 25mm bolt diameter in double lap lap shear (using the saddle), the shear stress is 31.4MPa (4484 psi). Grade 2 tensile strength is 60ksi, estimating the shear strength at ½ of this value gives 30ksi; with a safety factor of 6.7.

The same calculations were carried out for the connection between the strut and the shaft as follows.

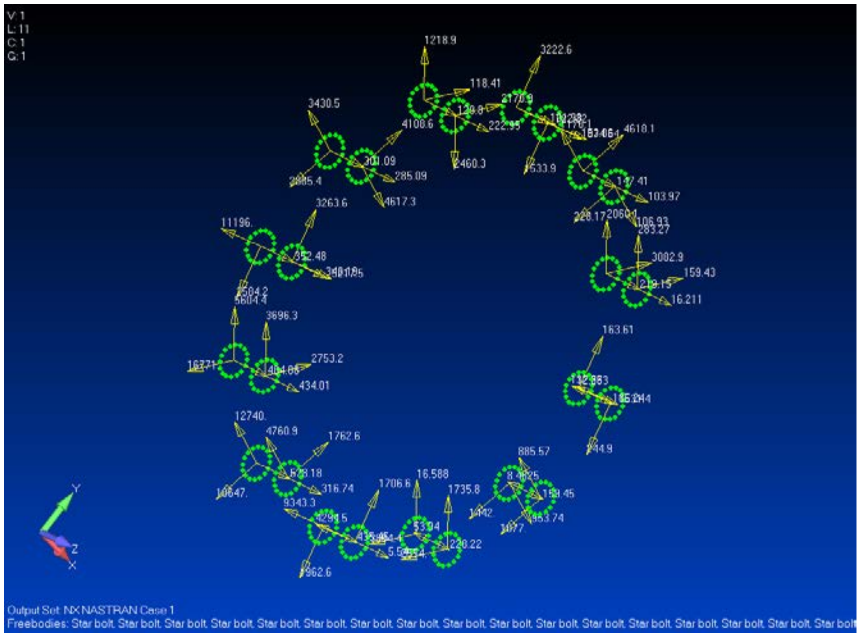


Figure 20: Free body diagram of Tristar strut to shaft bolted connections

Max bolt load is 17681N, at 25mm bolt diameter in single lap shear, the shear stress is 36.0MPa (5208 psi). Grade 2 tensile strength is 60ksi, estimating the shear strength at ½ of this value gives 30ksi; with a safety factor 5.8.

## Thinner Laminates

Thinner foil laminates are considered to lower cost, simplify the manufacturing, and improve quality. The laminate set properties and FEA results can be seen in Table 5 and 6.

Table 5: Summary of thinner laminates mechanical properties.

| Foil Laminate 13 Layers | Foil Laminate 10 Layers |
| --- | --- |
| **Laminate Equivalent Properties**<br><br>13 Plies - Total Thickness = 0.007205<br><br>In-Plane Properties<br>Ex = 9.034E+10  Ey = 1.1438E+10  Gxy = 6.23966E+9<br>NUxy = 0.4006  NUyx = 0.0507197<br>Alphax = -1.371E-7  Alphay = 7.09903E-6  Alphaxy = 0.<br><br>Bending/Flexural Properties<br>Exb = 7.9036E+10  Eyb = 1.2465E+10  Gxyb = 7.13267E+9<br>NUxyb = 0.430712  NUyxb = 0.0679301<br>Alphaxb = -1.6011E-7  Alphayb = 5.52234E-6  Alphaxyb = 0. | **Laminate Equivalent Properties**<br><br>10 Plies - Total Thickness = 0.005518<br><br>In-Plane Properties<br>Ex = 8.8765E+10  Ey = 1.1584E+10  Gxy = 6.36416E+9<br>NUxy = 0.405154  NUyx = 0.0528733<br>Alphax = -1.4077E-7  Alphay = 6.86057E-6  Alphaxy = 0.<br><br>Bending/Flexural Properties<br>Exb = 7.3659E+10  Eyb = 1.2933E+10  Gxyb = 7.55696E+9<br>NUxyb = 0.443181  NUyxb = 0.0778137<br>Alphaxb = -1.6844E-7  Alphayb = 4.86929E-6  Alphaxyb = 0. |

Table 6: FEA results with thinner foil laminates.

| Foil Laminate | Thickness (mm) | Max Strain "X" | Stress (MPa) | Deflection (mm) |
|---|---|---|---|---|
| Baseline 16 Layers | 8.89 | 0.00258 | 236 | 18.2 |
| 13 layers | 7.21 | 0.00314 | 287 | 21.5 |
| 10 Layers | 5.52 | 0.00396 | 361 | 27.3 |

## Fatigue Data

During the design phase of task 1, in absence of material set data ORPC used a generic data set from a carbon fiber and e-glass coupon test found on the MHK database hosted by Sandia National Labs and Montana State University (MSU). The scatter plot and trend line seen in Figure 21 shows the S-N curve for the generic material set. On this graph is also three lines showing the stress level of the various foil laminate thicknesses.

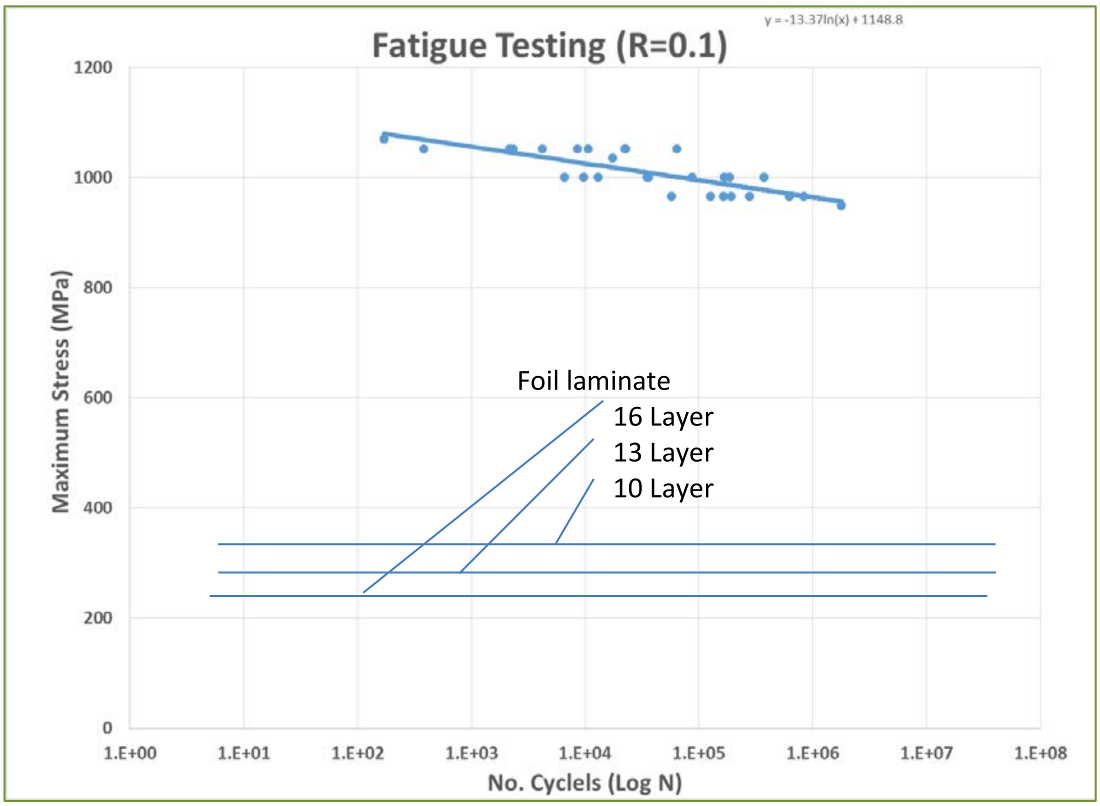



Figure 21: Generic fatigue data from the MHK database showing the current stress levels of various laminate thicknesses.

## 7. Development Plan

ORPC have engaged manufacturers to quote the turbine build aspect of this project and have received feedback on the manufacturability of the CDR turbine design. Two key areas are targeted for design refinement based on manufacturers input. Firstly, the Foil/Strut joint design.

The joint to connect the foil to the strut has been designed with a bolted saddle connection as seen in Figure 2. It is understood that this design is not hydrodynamically efficient and the manufacturers have suggested a fully adhesive joint that would result in a more reliable high-performance joint. This design can be seen in Figure 6.

Secondly, the cost of incorporating foil profile and chord span wise variation is less than previously anticipated so we can use this to increase the hydrodynamic performance of a turbine. At the tips of the foils the chord can be reduced without altering the structural performance, so it is proposed that the foils will taper to a smaller chord at the foil tips. It is also wise to make the foil profile thicker in the areas of highest strain at the center of the foils. This can be done by tapering the thickness of the foil from a NACA 1524 at the foil center to a NACA 1520 at the tips. This proposed foil modification promises to increase both the structural and hydrodynamic performance.

Along with turbine design refinement, ORPC also intends to perform barge testing of a single turbine for many reasons.

1) Hydrodynamic performance predictions.
   ORPC is aware that CFD analysis are not validated with performance measurements so it is important to characterize the turbine performance with a subsystem test of a single turbine. This testing will give a realistic Cp - TSR curve that can be used to accurately calculate Annual Energy Production (AEP) and Levelized Cost of Energy (LCOE).
2) Turbine Load Predictions.
   To-date all the loads applied to the turbines are calculated with 2D CFD and are anticipated to be conservative. For this reason, ORPC intend to measure the turbine loads and use that information to refine the affected components of the system, namely the mooring system. The Advanced TidGen Power System uses a buoyant tension mooring system with large gravity anchors which prove to be a challenging engineering problem. The updated turbine loads will allow ORPC to design an appropriately sized anchor and buoyancy pod reducing cost and deployment difficulty.
3) Turbine Durability.
   There are many novel design features on the Advanced TidGen® turbine so it is important to verify the structural performance and durability of the turbine before a full-scale deployment. The first turbine build can be used for this test.

## 8. Conclusion

At present ORPC have a turbine as defined during the CDR which after engaging manufactures many design refinements have been suggested which ORPC intend to implement. Figure 6 shows a model of a turbine with some of the proposed design changes. Also, from initial input from manufacturers, this turbine is expected to be cheaper than the CDR turbine design due to less manufactured parts and simplified design.

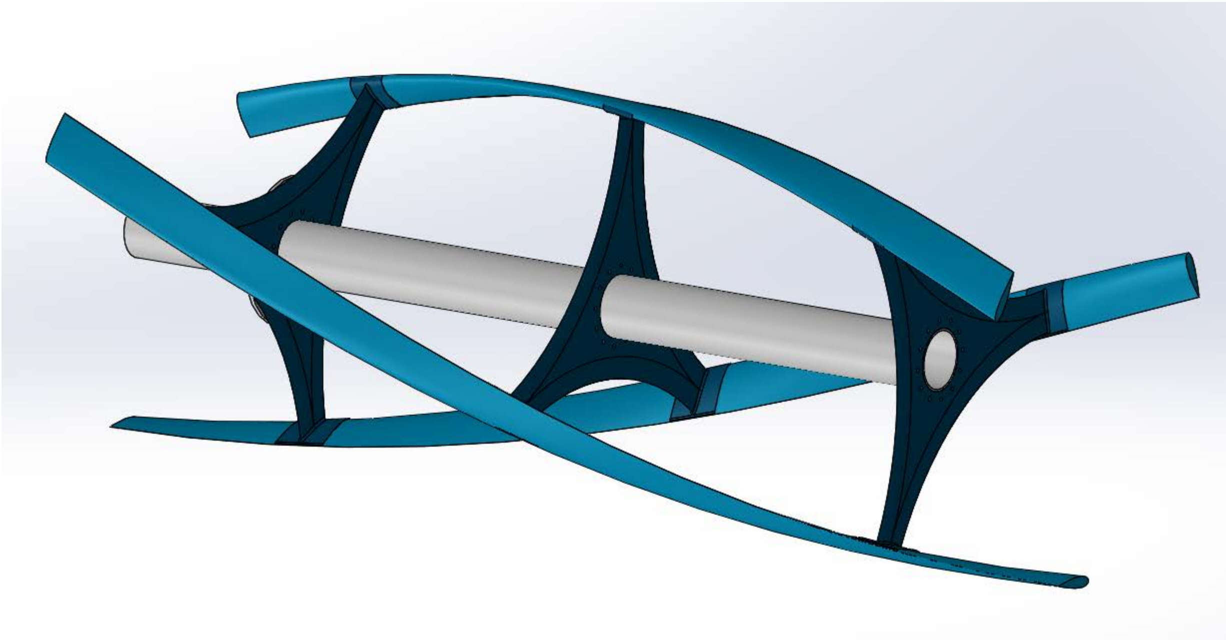


Figure 22: Advanced TidGen Turbine design improvements

# 9. REVISION HISTORY

| Revision | Date | Description | Author | Reviewer |
|---|---|---|---|---|
| R00 | 04/13/18 | Initial | MEB | C. Marnagh |
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