	Document Title	TidGen® Reliability Model	Document Number	RE-TD20-10818
			Award Number	
			Project	TidGen®

Revision History

Rev. Num.	EC Num.	Description	Prep.	Date	Chck.	Date	Appr.	Date
01	NA	Initial draft	ACK	3/24/20				
02	NA	Input from JM, RT and MB	ACK	4/7/20				
A	NA	Initial release	ACK	4/14/20	MB	4/21/20	JM	4/21/20

CONTENTS

1. ABBREVIATIONS AND DEFINITIONS

CERL	Composite Engineering Research Lab
CFRP	Carbon Fiber Reinforced Polymer
DNV	Det Norsk Veritas
DOE	Department of Energy
FEA	Finite Element Analysis
FLS	Fatigue Limit State
MHK	Marine Hydrokinetic
MSU	Montana State University
RF	Reduction Factor
S-N	Stress (S) versus Number of Cycles to Failure (N)
SOPO	Statement of Project Objectives

2. REFERENCES

[1] Statement of Project Objectives (SOPO), DE-EE0007820.000. This is the project award document generated by the DOE describing the project.

[2] RE-TD20-10713, Deliverable 8.1, Technical Report, Composites Structural Testing. This describes the testing that was conducted on composites to determine optimal composite configuration.

[3] INEEL/CON-04-02017 Preprint, Fatigue Damage Evaluation in CFRP Woven Fabric Composites through Dynamic Modulus Measurements.

[4] DNV-OS-C501, Composite Components, October 2010. This is an Offshore Standard from DNV dealing with composite materials and components for use in marine environments.

[5] DNVGL-ST-0376, Rotor Blades for Wind Turbines, December 2015

[6] S-N Curve Models for Composite Material Characterization: An Evaluative Review.

[7] D-TD20-10009, TidGen® 2.0 Turbine Design Loads. This describes the design loads, including 2D FEA analysis of the loads caused by flow induced rotation of the turbines.

[8] D-TD20-10145, Deliverable D2.2: Test Report on Characterization Program. This report describes the testing and results of composite testing, including fatigue testing, that MSU performed for ORPC.

[9] D-TD20-10144, TidGen® 2.0 Technical Report on Final BP1 Turbine Design. This includes 3D FEA analysis of the turbine loads.

[10] D-TD20-10154, TidGen® 2.0 Fatigue Cycle Counts 2018_04_08. This spreadsheet determines load cycles for the TidGen® turbine foils and estimates a preliminary fatigue life.

[11] Fatigue Summary1. This document combined the modeling equations from reference [10] and the S-N data from reference [8] in a summary.

3. PURPOSE

3.1. The purpose of this document is to satisfy the requirements for deliverables D8.2 and D8.3 under the following project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

4. INTRODUCTION

4.1. Reference [1] describes task 8 as follows:

> **Task 8: Composites Accelerated Life and Structural Testing**
>
> **Summary**: Accelerated life testing will provide data for investigation of failure mechanisms and development of cumulative damage life models. Larger coupons and joint sections will be fabricated to verify structural properties and submitted to accelerated life tests to replicate critical failure mechanisms identified in Budget Period 1. These tests will inform turbine production process control requirements through periodic inspections of test specimens. (Objective 2)
>
> **Milestone M8.1 (1Q20):** Reliability models based on accelerated life test corroborate achievement of project LCOE target.
>
> **Major Deliverable(s):**
> - **D8.1:** Technical report, summary of structural testing results
> - **D8.2:** Test report with updated reliability models (Milestone M8.1)
> - **D8.3:** Technical report on Accelerated Life Testing and Reliability Models

4.2. Deliverable D8.1, (reference [2]) was completed and submitted to the DOE in January 2020. While the research covered the mechanical properties such as flexural strength, interlaminar shear strength, and ultimate tensile strength, and the testing determined shear strength and shear modulus, it did not cover accelerated life testing or fatigue testing. Discussions with MSU and CERL indicated that there were neither time nor materials to complete such testing. ORPC determined therefore to combine deliverables D8.2 and D8.3 into one document that describes the methodology, testing, and analysis needed in order to determine a fatigue life of the composite components of the foils.

4.3. The process of performing a fatigue analysis is given in the different sub sections within section 5. That process is then applied to ORPC's TidGen® in section 6 where fatigue damage will be determined for 6 different representative samples.

5. FATIGUE LIFE DETERMINATION

5.1. Fatigue in composites is complicated, with many factors influencing fatigue life calculations. These can include – but are not limited to:

- Fiber type
- Fiber sizing
- Fiber layup type
- Fiber density
- Fiber/layup direction
- Matrix type (vinyl ester, epoxy resins e.g.)
- Fiber Volume Fraction (FVF)
- Processing
    - Cure temperature
    - Cure pressure
    - Infusion method

Determining the effects of all these variables in developing a fatigue model would be a very detailed and complicated effort. A more practical alternative is a macroscopic method that tests cycles to failure for a given load amplitude, and to use that data to develop a model that predicts fatigue life based on predicted loading and cycles.

5.2. Step 1: Generate Load Data

5.2.1. In order to determine the cyclic loading for testing material specimens, the loading of the components in actual or predicted use must be established. The loading might be random in nature, or more ordered in its nature. An analysis of the load data should be performed to determine what cyclic loads will have the greatest influence on the lifetime of the component. The maximum and minimum stresses and strains can be derived from that analysis and should be used as the maximum and minimum values for fatigue testing. The ratio of minimum stress / maximum stress in fatigue testing is known as the R-ratio.

5.3. Step 2: Generate S-N Diagrams

5.3.1. S-N diagrams have been used for many years and are very useful in analyzing fatigue in metals. Their use for composites has increased, and reference [4], DNV's standard to composite structures, describes their use in predicting cycles to failure for composites. As DNV is a major standards and classification organization for the marine industry, the procedures and methods described in reference [4] will be used as a basis for determining fatigue life in this report.

5.3.2. DNV Recommendations

5.3.2.1. Section 4 C 701 of reference [4] states, “The number of cycles N to failure under a cyclic stress is described by an S-N curve for a specified R-ratio.” Further details about generating an S-N curve are provided in section 4 C 700. When calculating R-ratios, the minimum stress is always the lowest value of stress, whether it is positive (tension) or negative (compression). For example, if the minimum stress is -10N and the maximum stress is 1N, R=-10N/1N or -10. Testing specimens of the composite components at the appropriate R-ratio will provide the most accurate data for generating the S-N curve. An graphic from reference [4] better illustrates this and is shown in Figure 1.

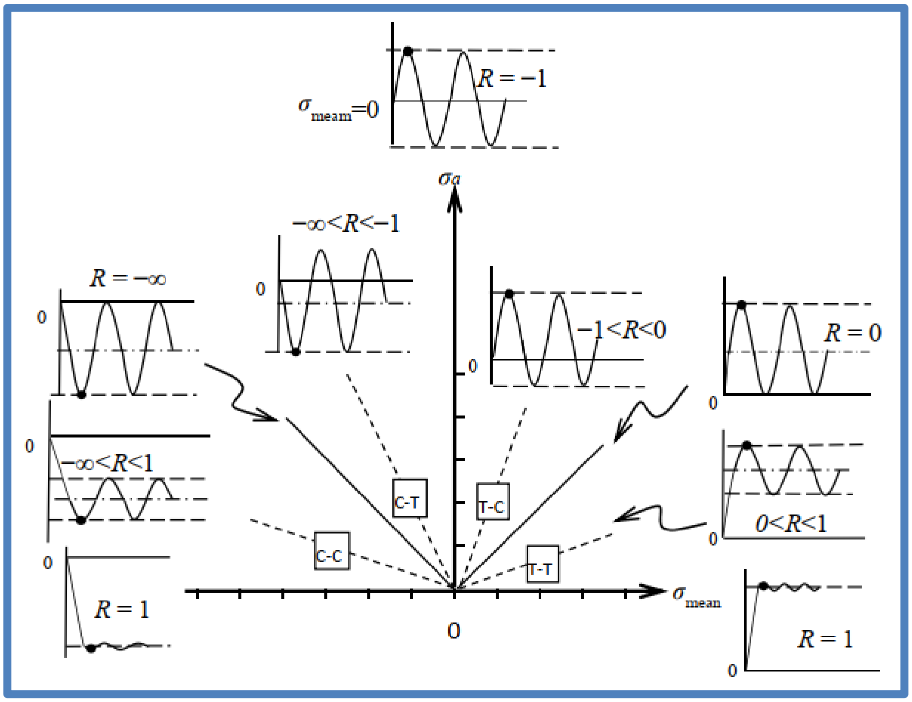

FIGURE 1: STRESS RATIO RANGES ON A σ_a - σ_{mean} DIAGRAM FOR THE LOADING TYPES: T-T, T-C, C-T, AND C-C.

5.3.2.2. In addition, a determination shall be made of the number of cycles at different strains that the component will experience over its intended lifetime. This will be used to establish accumulated damage during operation of the component.

5.3.3. S-N Testing

5.3.3.1. DNV (reference [4]) section C 708 recommends that S-N curves should be preferably obtained from the actual R-ratios for the application. Section C 707 states that the fatigue curves shall be obtained from load-controlled testing unless it is clear that the component is exposed only to deformation-controlled fatigue. Test coupons should be made out of the same material as the component whose fatigue properties are being investigated. A sufficient number of coupons shall be made so that the tests shown in Table 1 can be performed. The greater number of coupons (sample size) tested, the greater will be the reliability of the results.

5.3.3.2. Per reference [5], a reduction factor (RF) needs to be applied to the stresses or strains depending on the following partial reductions:

Base factor
Criticality of failure mode
Irreversible long-term degradation
Temperature effects
Manufacturing effects
Accuracy of analysis methods
Accuracy of load assumptions

This stresses or strains are divided by the reduction factor in determining the S-N curves.

TABLE 1: TESTING FOR FATIGUE ANALYSIS

Test	Description	Recorded Data	Derived Data
• Static tensile	• Tensile testing	• Load • Displacement	• Stress • Strain • Elastic Modulus
• Cycle	• Cycles to failure for specified R-ratio • Load controlled • Various max/min loads at constant R	• Load • Displacement • Cycles to failure	• Stress • Strain • Equations for cycles to failure versus strain

5.4. Step 3: Determine the number of cycles the component will see at each strain level throughout its lifetime.

5.4.1. This data can be determined through actual field data or from analysis

5.5. Step 4: Use S-N data to determine damage at each load amplitude.

5.5.1. The strain at each load amplitude needs to be determined through analysis. Once that is determined then for each strain level, a number of cycles to failure can be determined from the S-N curves.

5.6. Step 5: Sum up the damage

5.6.1. Equation 1, Miner's rule, allows one to sum up the damage at each strain level and obtain a total damage value, D. When D = 1, failure occurs.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \qquad \text{(Eq. 1)}$$

where:

D = total damage.
k = the number of different amplitude cycles the part will see in its lifetime.
n = number of cycles of a given amplitude that the part is subjected to in its lifetime.
N = total number of cycles of a given amplitude that a part can survive. This is determined from testing.

6. APPLICATION TO ORPC'S TIDGEN®

6.1. Step 1: Generate Load Data

Models of the TidGen® turbine loads have been generated and are described in references [7] and [9]. There are several different loads on the turbine, but the loads with the greatest effect on turbine lifetime are the cyclic hydrodynamic loads that occur with each revolution of the turbine. These loads can be resolved into radial loads, which act in the direction of the foil struts either towards or away from the axis of rotation, and tangential loads which act along the chord of the foil. Reference [7] calculated the radial and tangential loads along the span of the turbine foils and graphs of the results are shown in Figure 2, Figure 3, and Figure 4. The x-axes' units are meters (m) from the center of the foil, and the y-axes' units are newtons. These loads are calculated in the Fatigue Limit State (FLS) which is the load state to be considered for fatigue analysis. Each graph is for a particular foil at a specified rotational position (Ø = 100°, 220° and 340°). The radial forces are negative for compressive and positive for tensile. The tangential forces are negative in the direction of the trailing edge, and positive in the direction of the leading edge. The range of the radial and tangential forces are shown in Table 2. In addition, the R-ratio is calculated for both radial and tangential forces.

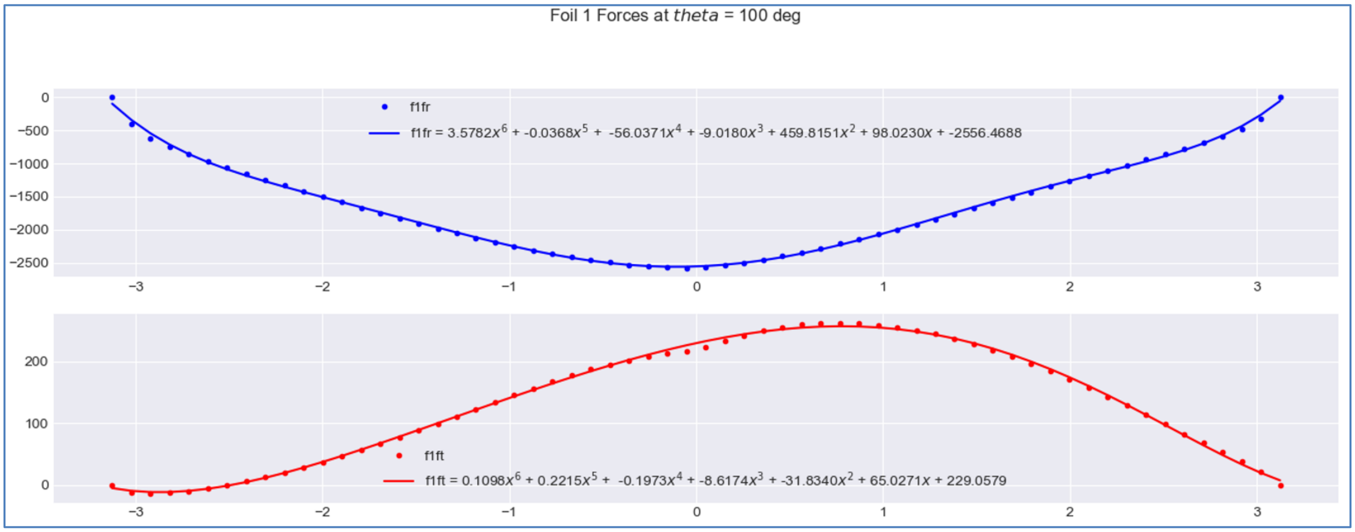

FIGURE 2, RADIAL LOADS (TOP) AND TANGENTIAL LOADS (BOTTOM) FOR FOIL 1 AT 100 DEGREES OF ROTATION

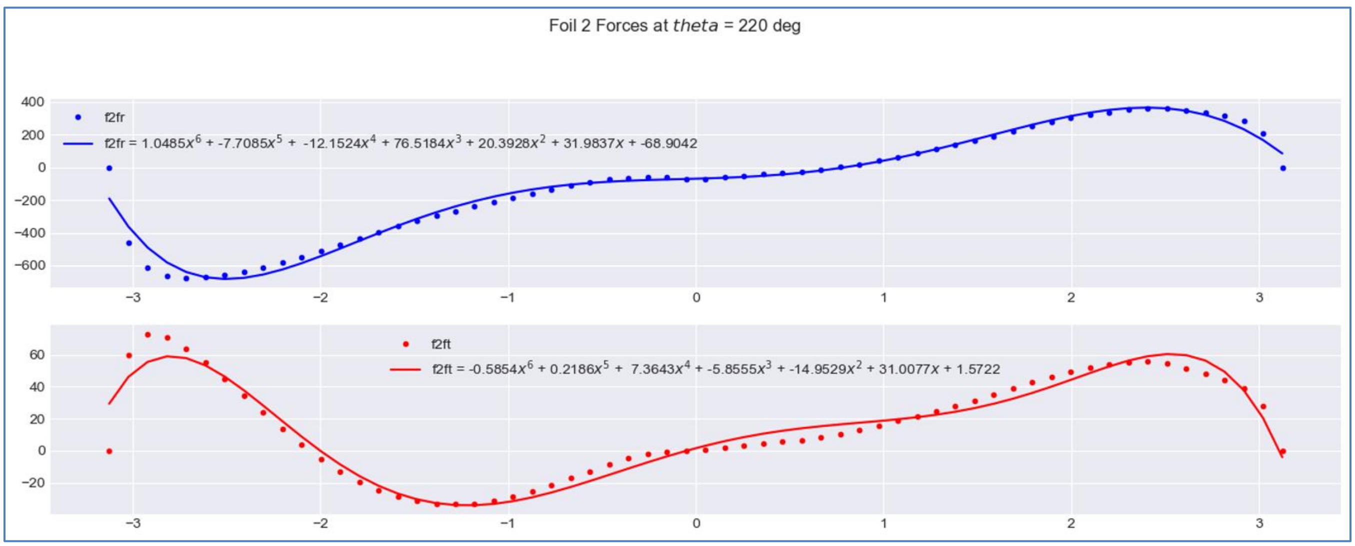

FIGURE 3, RADIAL LOADS (TOP) AND TANGENTIAL LOADS (BOTTOM) FOR FOIL 2 AT 220 DEGREES OF ROTATION

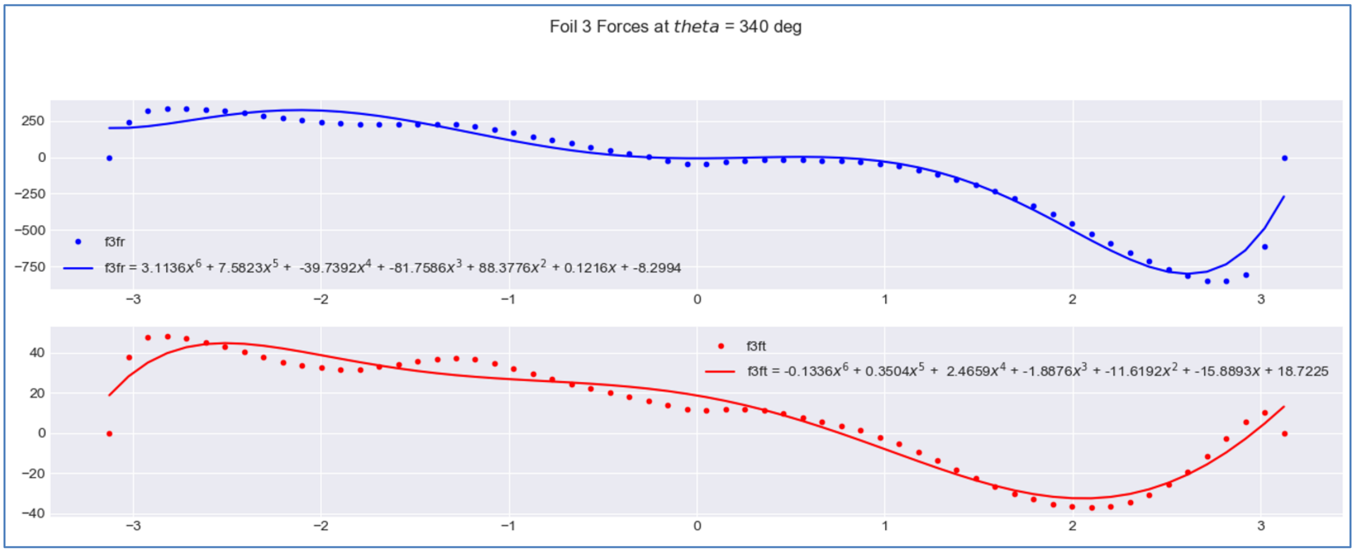

FIGURE 4, RADIAL LOADS (TOP) AND TANGENTIAL LOADS (BOTTOM) FOR FOIL 3 AT 340 DEGREES OF ROTATION

TABLE 2, RANGE OF RADIAL AND TANGENTIAL FORCES

Force Range (maximums)	Positive	Negative	R-ratio
F (radial)	+380 N	-2550 N	-6.7
F (tangential)	+256 N	-32 N	0.125

6.2. Step 2: Generate S-N Diagrams

6.2.1. Reference [9] characterized a proposed laminate construction of 16 layers of carbon and glass fibers. FEA was performed to determine the stresses and strains on foils made of this laminate subject to operation in the field. It calculated the maximum strain on the foils to be .00258. It then performed another calculation of maximum strain on a foil of 13 layers of carbon and glass and determined the max strain to be .00314. This 13-layer material was deemed to be suitable for the foil construction, and thus the .00314 max strain is the value of maximum strain to be used in the damage calculations. The scope of that investigation did not include fatigue testing, however, and in order to perform a fatigue analysis, test specimens and coupons should be fabricated out of that proposed material. Coupons should be conditioned by long-term saturation in seawater and the testing should be performed at different min/max stresses with R = -6.7 per Table 2 since the radial stress is higher magnitude than the tangential stress.

6.2.2. Examination of Table 2 shows that the radial forces are an order of magnitude greater than the tangential forces, and so fatigue testing should be done with radial forces considered. DNV (reference [4]) states that if a structure is exposed to both tensile and compressive fatigue, data for at least R=-1 shall be available. Testing should be performed at that ratio with tensile and compressive loads at equal magnitudes. In addition, DNV says that S-N curves should preferably be obtained for R-ratios relevant to the application, so testing should also be performed at R=-6.7 which would give a more complete data set.

6.2.3. For demonstrative purposes, other fatigue data will be used. Reference [8] is a report of testing of 6 different composites that MSU performed for ORPC. S-N curves were generated in that report, and the data was used to generate graphs of maximum strain on the x-axis and cycles to failure on the y-axis. In addition, a “reference” material from MSU (labeled MSU1) was also used, although not shown in all results. These are shown in reference [11]. Trendlines and their equations were generated in Excel. A graph of all 6 samples plus the reference material and their trendlines is shown in Figure 5. CE1-L through CE5-L are carbon and glass fiber laminates while CE6-L is an all glass laminate. This graph allows one to calculate cycles to failure for any strain.

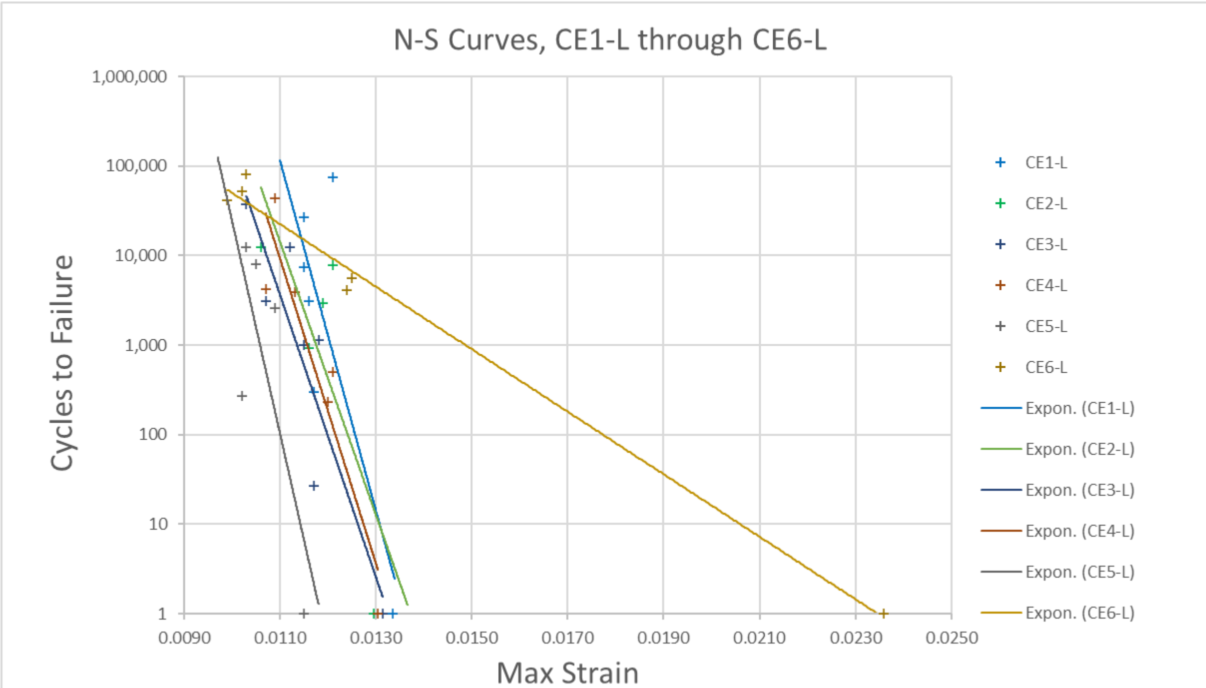

FIGURE 5: CYCLES TO FAILURE VS. STRAIN

6.2.4. Reduction Factors

6.2.4.1. Using reference [5], Table 3 was generated showing a range of partial reduction factors. The reduction factor is computed by multiplying all the partial reduction factors together. A complete understanding of the partial reduction factor types is unknown and so a determination of a precise overall reduction factor is difficult. Complete damage calculations were run with reduction factors of 1.00 and the maximum of 3.94. The total damage amounts are shown in Table 4. Inspection of Table 4 shows that the total damage over the range of RF values changes from 3 to 20 orders of magnitude. Closer examination of the RF types resulted in changing the partial RF for long-term degradation from 1.20 to 1.10 due to the use of epoxy resin rather than vinyl ester resin. This brought the maximum RF down to 3.60. To better understand the effects of RF values on total damage S-N curves were generated for reduction factors ranging from the minimum to the maximum, with equally spaced increments, in addition to a reduction factor = 1. S – N (and N – S) curves were therefore determined for values of reduction factor of 1.000, 1.430, 1.973, 2.515, 3.058, 3.600 and 3.940.

TABLE 3: PARTIAL REDUCTION FACTORS

Partial Reduction Factor Type	Partial Reduction Factor Value
Base Factor	1.20
Criticality of failure mode	1.08
Irreversible long-term degradation	1.10 – 1.20
Temperature effects	1.00
Manufacturing effects	1.00 – 1.30
Accuracy of analysis methods	1.00 – 1.25
Accuracy of load assumptions	1.00 – 1.56
Total:	**1.43 – 3.94**

TABLE 4: TOTAL DAMAGE FOR RF = 1.000 AND 3.940

Total Damage		
	Red. Factor	
Sample	1.000	3.940
MSU1	7.82E-14	5.88E+03
CE1-L	4.34E-15	4.87E+02
CE2-L	1.70E-10	1.24E+03
CE3-L	2.52E-10	5.83E+03
CE4-L	8.12E-12	3.16E+03
CE5-L	2.19E-15	2.94E+06
CE6-L	3.77E+00	3.42E+02

6.3. Step 3: Determine the number of cycles the component will see at each strain level throughout its lifetime.

6.3.1. Reference [10] models the rotation of the turbine due to current speed. It calculates the number of rotations over a 20-year lifetime at current speeds from 0 m/s up to 3.5 m/s at increments of 0.125 m/s. The data was generated by UTide, a tidal harmonic analysis program, for a representative location near False Pass, Alaska. A graph of these results is shown in Figure 6. For the purposes of this fatigue analysis the blue curve (# of Cycles at Peak Power) and its data were used.

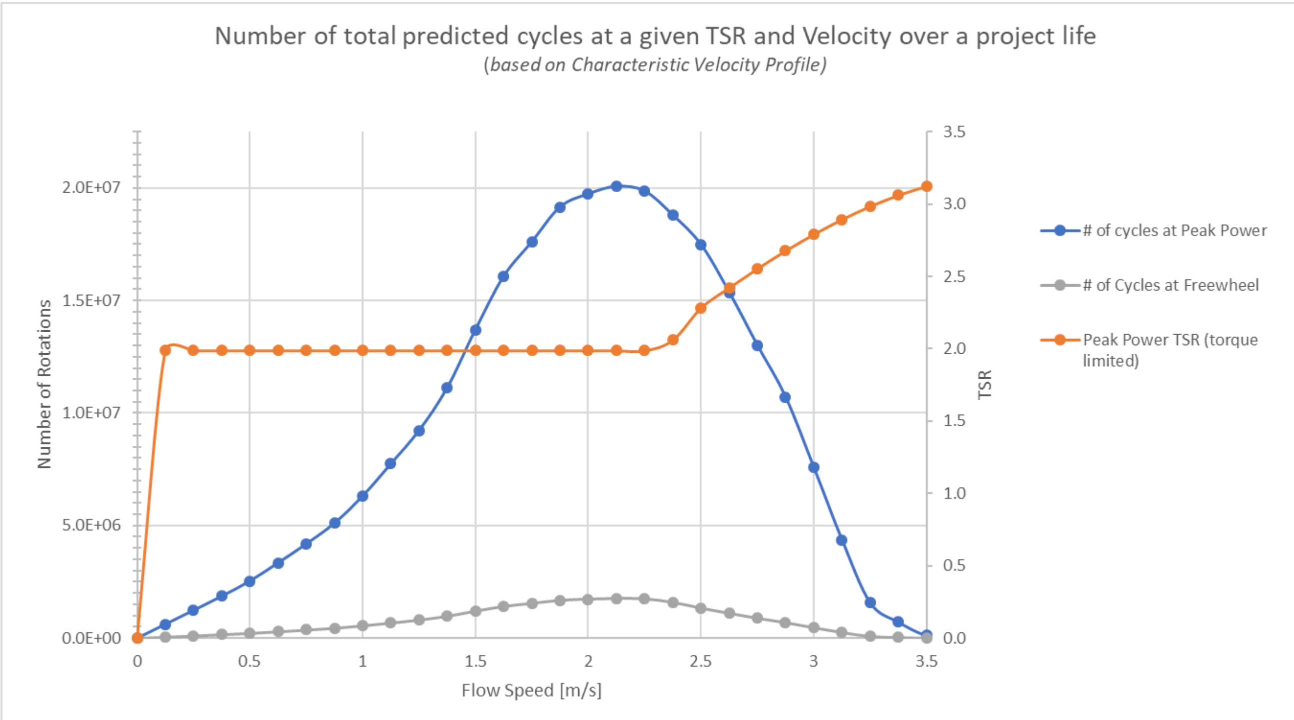

FIGURE 6, NUMBER OF TURBINE ROTATIONS VERSUS FLOW SPEED

6.3.2. For each flow speed, it then calculates according to equation 2 the nominal strain at each increment based on the maximum strain of 0.00314 that was calculated in reference [9].

$$\varepsilon_v = \varepsilon_{max} \left(\frac{v}{v_{max}} \right)^2 \qquad \text{(Eq. 2)}$$

where: ε_v = strain at speed
ε_{max} = .00314 (ref. sec. 6.2.1)
v = speed (m/s)

$$v_{max} = 3.5m/s$$

This equation is based on the fact that hydrodynamic force (and therefore stress and strain) is proportional to the square of the fluid speed.

6.4. Step 4: Use S-N data to determine damage at each load amplitude.

6.4.1. Using the 7 S-N curves and equations for MSU1 and CE1-L through CE6-L, reference [10] then calculated the number of cycles to failure at each current speed. This data was used in the Fatigue Summary1 (reference [11]). These calculations were repeated for all the RF values described in section 6.2.4.1. Note that reference [11] is essentially a damage calculation for RF = 1.000.

6.5. Step 5: Sum up the damage

6.5.1. For each current speed, reference [11] calculated the damage (n_i/N_i) at that current speed from equation 1 and RF = 1.000, and finally summed them all up to give a total damage. The same calculation performed for all the other RF values including RF = 1.00 are given in Table 5. Recall that when the damage = 1, the part will fail.

TABLE 5: TOTAL DAMAGE

Total Damage by Sample and Reduction Factor							
	Material Factor						
Sample	1.000	1.430	1.973	2.515	3.058	3.600	3.940
MSU1	7.82E-14	1.31E-11	1.36E-08	1.86E-05	3.03E-02	5.28E+01	5.88E+03
CE1-L	4.34E-15	1.54E-12	8.62E-10	1.27E-06	2.23E-03	4.18E+00	4.87E+02
CE2-L	1.70E-10	7.41E-09	1.36E-06	3.32E-04	9.81E-02	3.18E+01	1.24E+03
CE3-L	2.52E-10	1.30E-08	2.96E-06	8.98E-04	3.28E-01	1.31E+02	5.83E+03
CE4-L	8.12E-12	6.29E-10	2.43E-07	1.25E-04	7.69E-02	5.16E+01	3.16E+03
CE5-L	2.19E-15	1.58E-12	1.04E-08	8.77E-05	8.55E-01	8.77E+03	2.94E+06
CE6-L	3.77E+00	6.39E+00	1.34E+01	3.01E+01	7.26E+01	1.85E+02	3.42E+02

6.5.2. A graphical summary of Table 5 is shown in Figure 7.

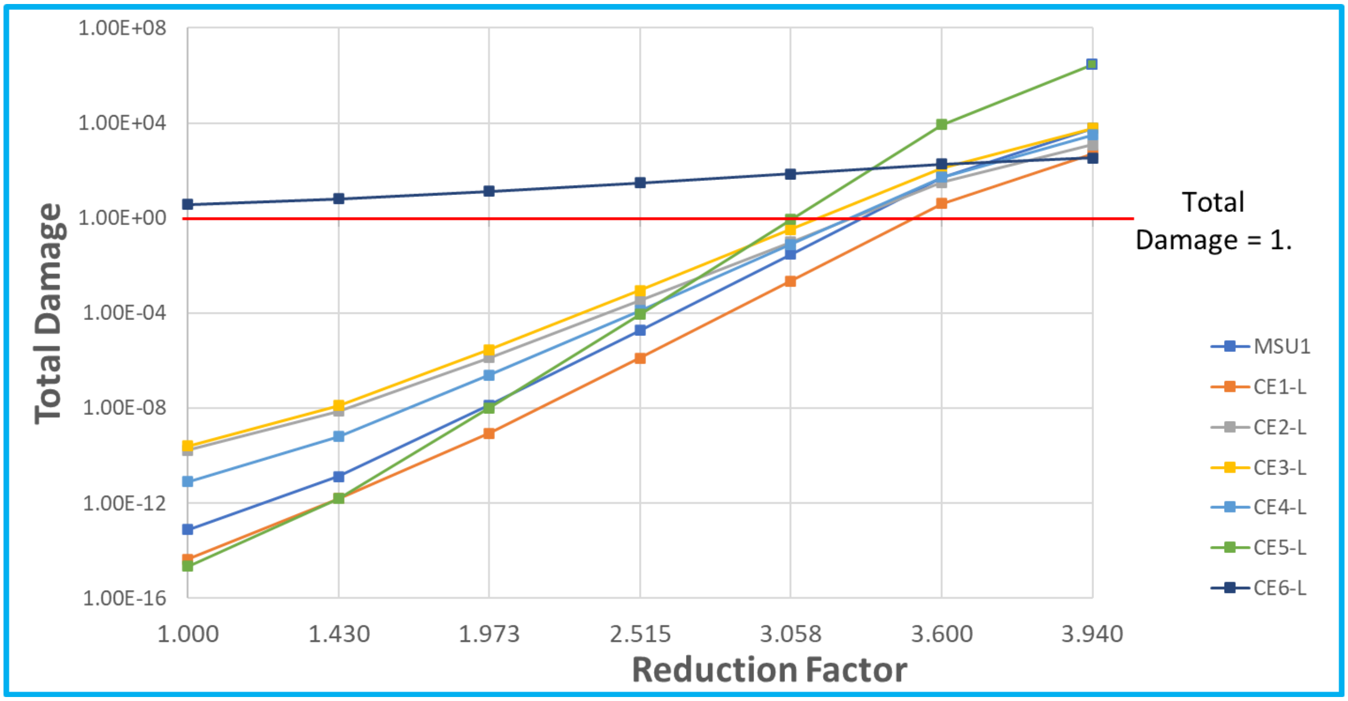

FIGURE 7: TOTAL DAMAGE SUMMARY GRAPH

7. DISCUSSION

7.1. The process outlined in this report follows as closely as possible the fatigue analysis process outlined in DNV-OS-C501, Composite Components (reference [4]). It is a robust and straightforward process that is suitable for a deterministic lifetime prediction. However, it relies on accurate data, specifically S-N data from large sample sizes, and loading. For MHK systems in tidal environments, it also requires accurate current speed predictions. While these data require much effort to gather and derive, they will be helpful in maximizing the determination of damage.

7.2. It should be clearly noted that the materials used for the damage calculations are NOT the material used in the FEA analysis in reference [9]. While the results show that failure will occur with RF values above 3.058, that says nothing about the 13-layer material used for the TidGen®.

7.3. The results show a strong influence of reduction factor in total damage. Obviously, accurate determination of the correct partial reduction factors to use will produce the most accurate results. Given the variability inherent in the partial reduction factors, and the multiplicative effect of combining them all, an accurate determination may be problematic. Future design efforts will have to consider this and use best engineering practices, as well as system history and experience in determining the best partial reduction factors.

7.4. The actual results show a significant difference in damage between the carbon/glass laminates and just glass laminates. Details of the specific laminates can be found in reference [8], but that report did not control for aspects of the laminate construction such as matrix type, fiber type and processing parameters such as cure time/temp. Thus, statistically significant differences cannot be quantified.

8. APPENDIX A: REFERENCE [1]

Attachment 3 -
Statement of Project (

9. APPENDIX B: REFERENCE [2]

RE-TD20-10713, Rev A.pdf

10. APPENDIX C: REFERENCE [3]

2761769.pdf

11. APPENDIX D: REFERENCE [4]

OS-C501_2010-10.pdf

12. APPENDIX E: REFERENCE [5]

DNVGL-ST-0376,
Rotor Blades for Wiin

13. APPENDIX F: REFERENCE [6]

jcs-02-00038.pdf

14. APPENDIX F: REFERENCE [7]

D-TD20-10009 R01 -
TidGen 2.0 Turbine De

15. APPENDIX G: REFERENCE [8]

D2.2_D-TD20-10145
R00 - TidGen 2.0 Deli

16. APPENDIX H: REFERENCE [9]

D1.2_DE-EE0007820_
D-TD20-10144 - TidG

17. APPENDIX I: REFERENCE [10]

D-TD20-10154
TidGen 2.0 Fatigue Cy

18. APPENDIX J: REFERENCE [11]

Fatigue
Summary1.xlsx