Test Plan, Post Access Report

Investigation of Opportunities for Mass Reduction and Improved Integration of Wave Energy Converter Components

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EXECUTIVE SUMMARY

C·Power is developing the SeaRAY k20 Wave Energy Converter (WEC). This design is based on the SeaRAY k2, a patented three-body device utilizing a heave plate, dual Power Take Offs (PTOs), and single point mooring. The device is currently undergoing Pre-Installation and Test and Check Out. The 20 kW k20 is significantly larger than the 2 kW device upon which it is based but is still designed to be transportable in standard International Organization for Standardization (ISO) shipping containers or racks.

The heaviest single component of the k20 system is the central nacelle. Ocean conditions at deployment sites of commercial interest require a rugged, resilient structure. This has been achieved in the demonstration design with a reinforced steel structure. However, the mass of this structure challenges the limits of ISO container maximum weight.

To support continued development efforts of the k20, two design challenges were investigated in this study:

1. The definition of a certification path for a multifunctional structure that can serve as a shipping container for land transport, a barge to tow the WEC on station for deployment, and as the heave plate for the k20 after deployment. This design approach reduces the cost of deployment by allowing the use of smaller vessels, faster tow speeds, and fewer restrictions to weather suitable for safe marine operations. This concept also reduces costs by eliminating required shipping dunnage and potentially allowing for onshore connection of the heave plate to the WEC.
2. Improved design of the WEC center member, the nacelle, by investigating alternative materials and stiffening methods. The analysis resulting from this Request for Technical Support will inform the design of a lightweight, lower manufacturing and operating cost structure that increases energy conversion.

Two major conclusions can be drawn from the analysis study:

1. There is a clear path to developing a multifunctional heave plate/barge/shipping container. Engaging with the certification organizations early in the design process to establish unique requirements is beneficial.
2. Variations on many metallic and composite material systems can be employed to meet international standards for structural performance. In general, investing in proper design using composite material systems will lead to reduced weight, improved WEC performance, and reduced costs. Composites provide a very attractive alternative to metallic material systems for this application. Not only does a composite nacelle provide a cost reduction in up-front capital expenditures via reduced manufacturing costs, but there is also a reduction in operational costs that could be significant. Based on an examination at the limit of design life, the replacement of the device baseline nacelle due to corrosion is estimated to be $129,000 compared to refurbishment costs of $26,000 for a Fiber Reinforced Plastic (FRP) design. When the corrosion reduction is coupled with the estimated 25% capital cost reduction and the 107% increase in Power-to-Weight ratio, the composite material system becomes the clear choice. This is illustrated in Table 1 below.

Table 1 - CAPEX, OPEX, and Power-to-Weight Summary

Description	Units	Normal Steel	Extra High Strength Steel	Aluminum Alloy	Fiber Reinforced Composite
CAPEX					
Material Cost	$	6,893	$ 22,129	11,889	12,913
Fabrication Cost	$	96,107	$ 124,939	172,992	64,250
Total	$	103,000	$ 147,068	184,881	77,163
OPEX					
WEC Retrieval Cost / 2 year	$	25,000	25,000	25,000	25,000
RE Paint /2 year	$	1,000	1,000	1,000	1,000
Maximum Potential Loss due to Corrosion	$	103,000	147,068	184,881	-
Total	$	129,000	173,068	210,881	26,000
Power-to-Weight					
Hull Weight	kg	5,674	2,797	1,998	2,801
Power	kW	20.00	20.42	20.44	20.42
Power/Weight	kW/kg	0.0035	0.0073	0.0102	0.0073
Power/Weight Inc.	%	-	107	190	107

It is recommended to continue the design and development efforts of the SeaRAY k20 nacelle and other major WEC structural components with FRP material systems. Further analysis must be conducted to ensure compliance with all relevant load cases expected by the WEC, including the Fatigue Limit State. Analyses should be further supported by physical testing following the DNV-OS-C501 Offshore Standard, *COMPOSITE COMPONENTS*. The specification lays out a specific plan to ensure a robust design. Subsequentially, final updates to the Finite Element Model (FEM) properties and construction should be assessed. Per the DNV specification, the manufacturer making the test pieces should be the manufacturer of the component as consistency in the manufacturing process and workmanship are vital to the success of composite structures.

1 INTRODUCTION TO THE PROJECT

This project has demonstrated that marine energy device developers can successfully employ composite materials in WEC primary hull structure and major structural components. Thoughtful structural design utilizing composite materials can help device developers realize measurable performance improvements while reducing both upfront capital expenditures (CAPEX) and longer-term operational expenditures (OPEX).

Manufacturing and deployment costs will be reduced, and opportunities for deployment, by tolerating rougher sea conditions safely, will be enhanced by improvements to integration of structures and reduction of their mass.

Further, this study explored a potential certification path for a multifunctional WEC heave plate design. This component can and will be employed as a shipping platform for the WEC main body, as well as the transportation barge for towing into position, and finally as the device heave plate after deployment. The k20 heave plate will be designed to be conformant with ISO standards for shipping containers and Det Norske Veritas (DNV) standards for barge design. The certification path for this multi-use structure is described in this report.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

The roles and responsibilities for the applicant and network facility are defined below.

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

C·Power is US-based ocean energy and data company, started in 2005. C·Power has over a decade of experience in engineering, modeling, testing and conducting sea trials with 3rd party technical reviews by DNV for a broad WEC product range capable of meeting kW to MW scale power requirements. C·Power has provided Cardinal Engineering with a baseline system design using traditional normal strength steel (NS) as well as worst-case hydrodynamic load cases. C·Power also provided guidance to Cardinal Engineering regarding fabrication and operations of the WEC components to be analyzed and improved.

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

Cardinal Engineering has analyzed the baseline WEC nacelle design based on the provided loads and created alternative designs employing extra high strength steel (EHS), aluminum alloy (Al), and glass reinforced plastic (GRP). These designs have been evaluated in load cases provided by C·Power against the appropriate International Electrotechnical Commission (IEC) and DNV criteria.

Additionally, based on the desire to develop multi-functional components to drive down costs, Cardinal Engineering has developed a certification path for a hybrid heave plate, barge, and ISO shipping container that incorporates and is compliant with all relevant requirements.

3 Project Objectives

- The research project's overall objectives:
  - Establish a baseline understanding of both structural and hydrodynamic performance of these mass-reduction concepts and their suitability for inclusion in design improvements of C·Power SeaRAY WEC product line (500W to 20kW remote power and data). This research will facilitate CAPEX and OPEX reductions which reduce logistics constraints and further enhance commercial appeal.
  - Development of methods to conform a mobile/offshore floating structure to ISO shipping standards so it can easily be transported on a container vessel (boat or truck trailer).
- The important physical attributes that the project has investigated:
  - The heaviest single component of the system is the central nacelle. Ocean conditions at deployment sites of commercial interest require a rugged, resilient structure. This has been achieved in the demonstration design with a reinforced steel structure. However, the mass of this structure challenges the limits of ISO container maximum weight, as well as deployment site infrastructure. The analysis resulting from this Request for Technical Support (RFTS) has informed the design of a novel steel/GRP composite structure that reduces the mass by enabling reduced steel wall thicknesses and smaller steel stiffeners. This concept has the added benefit of insulating properties to enable optimization of internal battery performance in cold-climate sites.
  - Currently the system uses separate platforms for transport on land, deployment at sea, and operational stability. This study has successfully shown that they can be combined into one system with a clear path for certification to ISO, IEC, and DNV standards.
- The specific performance metrics that the project has targeted are:
  - A comparison of the power to weight ratio of the baseline and optimized configurations.
  - A comparison of the costs (CAPEX, OPEX) of the baseline and optimized configurations.

4 Test Facility, Equipment, Software, and Technical Expertise

Cardinal Engineering, a small business headquartered in Annapolis, Maryland, provides a broad range of engineering services in the marine industry to government and commercial clients. Cardinal Engineering has used its decades of structural engineering experience along with its expertise with SolidWorks CAD software, FEMAP Finite Element Analysis (FEA) pre and post processor, and NASTRAN FEA software to assess the multi-material structure. Cardinal Engineering is the incumbent design contractor for the k20 WEC, the project that identified the research needs for this request for support. Cardinal Engineering is also familiar with IEC specifications and DNV methodologies and calculations which are the governing specifications of the WEC.

5 Test or Analysis Article Description

C·Power is developing the SeaRAY k20. This design is based on the SeaRAY k2 WEC, which is currently undergoing Pre-Installation and Test and Check Out. The SeaRay k2 WEC is a patented three-body device utilizing a heave plate, dual PTOs, and single point mooring. The 20 kW k20 is significantly larger than the 2kW device upon which it is based but conforms to the requirement to be transportable in ISO shipping containers or racks.

Two challenges have been investigated:

1. The feasibility of reducing the mass of the WEC center nacelle by substituting a novel composite structure in place of the reinforced steel of the demonstration design. The heaviest single component of the k20 system is the central nacelle. Ocean conditions at deployment sites of commercial interest require a rugged, resilient structure. This has been achieved in the demonstration design with a reinforced steel structure. However, the mass of this structure challenges the limits of ISO container maximum weight. The analysis resulting from this RFTS will inform the design of a novel steel composite structure that reduces the mass by allowing reduced steel wall thicknesses and smaller steel stiffeners. The concept investigated will be a composite of steel, closed cell foam, and Fiber Reinforced Plastic (FRP). This concept has the added benefit of insulating properties to allow optimization of internal battery performance in cold-climate sites. This modeling project is intended to improve the understanding of structural properties and performance of reduced mass components.

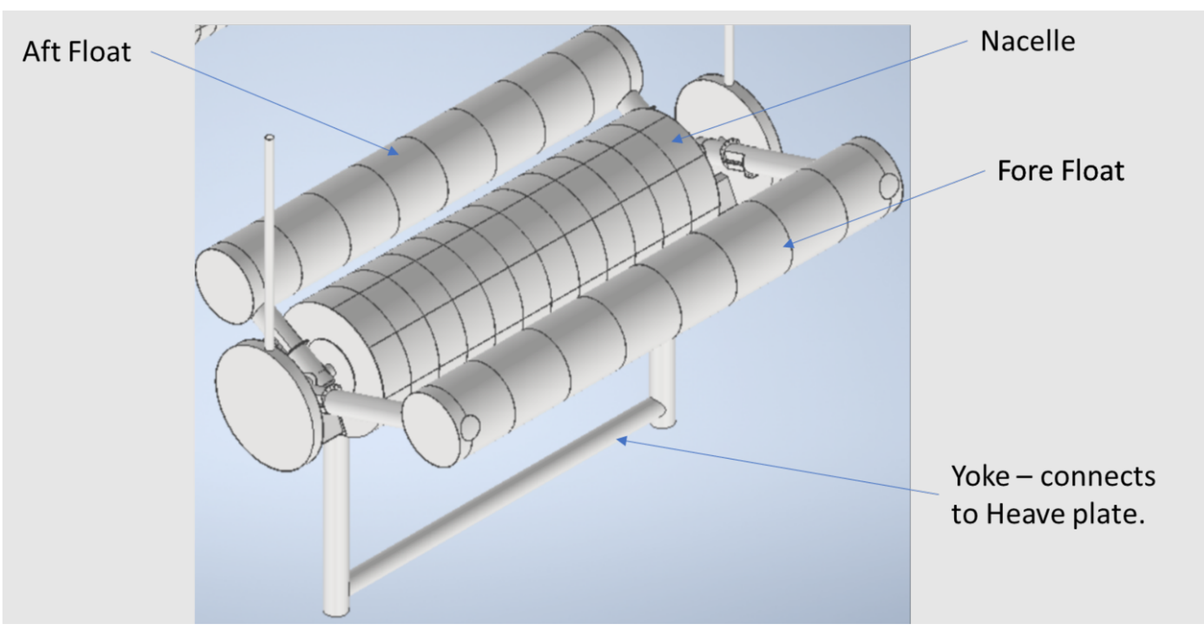

Figure 1- C·Power WEC Basic Configuration.

2. The development of methods and requirements for a certification path for a multi-functional mobile offshore floating structure, that can easily be transported on a container vessel (boat or truck trailer), which complies with IEC, DNV, and ISO specifications.

6 Work Plan

Cardinal Engineering has conducted a study with two goals under this agreement; (1) develop methods/requirements to conform a mobile/offshore floating structure to ISO shipping standards so it can easily be transported on a container vessel (boat or truck trailer), and (2) optimize the WEC nacelle for weight savings using alternate material and stiffening combinations.

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

This section is not applicable to numerical modeling tasking.

6.2 Numerical Model Description

The general system certification desired by C·Power is DNV. For this effort Cardinal Engineering will focus on Sections 4-9 of the DNV design flowchart in Figure 2. To further their ability to certify to DNV, Cardinal Engineering will use DNV-OS-C501 (*COMPOSITE COMPONENTS*) as the guiding method for design and analysis. It will be further supported with *Marine Composites* by Eric Green Associates, which is based on the US Navy's DDS 9110-9 (derived from MIL-HDBK-17) to describe unstiffened and stiffened single-skin panels and sandwich panels. These references provide closed form solutions and methods for a global look at the structure.

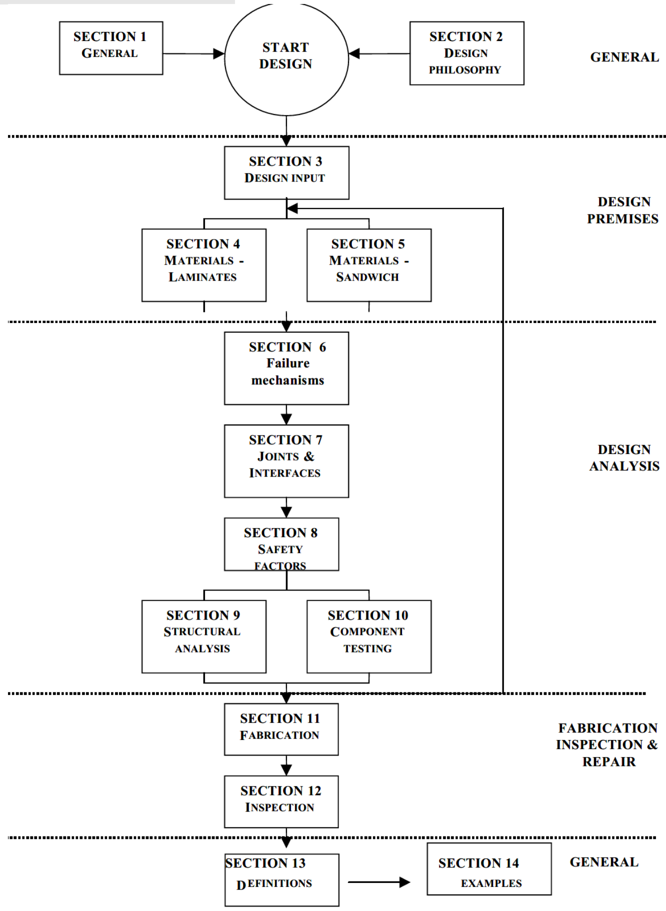

Figure 2- DNV Composite Design Flow Chart.

To optimize the structure, NASTRAN FEA software is used to create a detailed shell model of the nacelle, with massless beam model representations of the fore and aft floats and mass elements at the CG locations tied to the representative beams. This global model with detailed local features is a widely used technique to keep the highest element count in the areas of focus while getting the proper loading from all the other members. The shell model is meshed primarily with quadrilateral elements maintaining a low aspect ratio at joints and intersections. Additional mesh quality limits are placed on warping and interior angle between nodal locations to ensure mesh convergence and limit numerical errors. Mass elements are used to represent electronics/hardware and modeled at the center of gravity of each unit. The mass elements are attached to the nacelle with rigid links tied to beam elements to represent mounting bolts at the proper locations.

C·Power provided loading for three loading values: Ultimate Limit State (Extreme value with return period of 100 years) and Sustained or Service limit Case (average value over a long period that causes long-term degradation of material properties). The loads are developed with AQWA, a rigid body hydrodynamic simulation that C·Power has extensive experience with, and the methodology has been correlated to test data and shown to capture the body movements and accelerations. The hydrodynamic loads are applied to the mass elements with counteracting inertial loads and inertial relief applied to the system.

Fidelity of the models was verified by comparing global deflections, resultant boundary constraint forces, and eliminating any local stress gradients and discontinuities with mesh refinement. C·Power used DNV standards to design the initial unit, with applicable Safety Factors used during the assessment. The loads and materials are not directly debited, but the stress limits are (scaled stress limits: total 1.38 (20% on loads × 15% on material)).

The DNV standards are the basis for the material strength analysis, which is augmented by classic laminate theory as defined in MIL-HDBK-17F Vol 3 to develop material properties that do not exist in the standard. *Marine Composites* by Eric Green Associates uses the Navy's DDS 9110-9, which is derived from MIL-HDBK-17, to enhance the assessment of unstiffened and stiffened panels, single-skin panels, and stiffened sandwich Panels. The aim of the classic laminate theory analysis method is to distill the physical characteristics of the laminate to a standard method of describing the stiffness of a panel – i.e., an idealized 2D element. From there the laminate physical properties and stresses can be calculated. Furthermore, composite element formulations included in the finite element analysis allow individual layers to be defined in order to build the laminate.

Classical laminate theory, the same theory that is used to distribute the loads and moments into each ply for the ply-by-ply stress analysis approach, assumes that the strain in the laminate maintains a smooth, linear distribution. There is a necessity for the laminate to operate as a coherent cross-section when reacting to load. A step change in strain at a point across the thickness implies an inter-laminar failure.

Analysis of composite laminate sandwich structures must consider different failure modes compared to solid laminates. The tension strength of a sandwich laminate is the total strength of the structural facing plies, the inclusion of a sandwich core affects the out-of-plane bending and buckling strength. The in-plane compression and shear strength of the sandwich laminate are less than those for an equivalent solid laminate (taking the facing plies alone and laminating them together) because of additional failure modes that the inclusion of more material introduces such as those shown in the Figure 3.

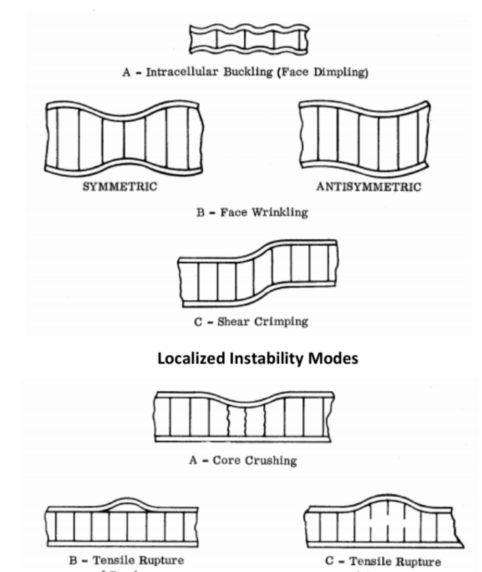

Figure 3- Sandwich laminate failure modes.

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There are two different approaches to fiber laminate stress analysis. One considers each ply within the laminate and develops a failure index (common methods are Tsai-Wu or Hill) for each ply within the laminate; this is the so-called lamina stress approach. With this approach, the failure of a single ply causes a sudden internal load redistribution that makes the laminate fail. This is a stress-based approach where the load applied to a particular laminate must be distributed onto each ply across the laminate thickness taking the direction of load in relation to the ply orientations into account. This produces a plot of stresses on each ply through the thickness. A margin of safety can then be generated for each ply using the full Tsai-Wu failure criteria.

The second analysis approach is the so-called laminate strain approach. In this method, the peak laminate strain is determined by analysis and compared with a strain allowable for a specific laminate configuration determined by test. Testing has not yet been conducted for this specific application and failure strain was not available for all materials, so the lamina stress approach was used. The specific methodology used to implement this approach is detailed in Section 7.1.2.2 of this report.

To fully investigate the compressive behavior of the fiber reinforced composites, buckling calculations using both hand and FEA were completed using calculations from DNV, MIL-HDBK-17, and FEA linear buckling. Initially ultimate stress levels were used for computational purposes. Initial safety factors of 4.0 on compressive failures and 2.0 on shear failures are general practices applied when developing scantlings for composite materials. These were refined during the task to align with the specifications.

The development of methods/requirements to conform a mobile/offshore floating structure to ISO shipping standards so it can easily be transported on a container vessel (boat or truck trailer) was accomplished by researching American Society of Mechanical Engineers (ASME), American Bureau of Shipping (ABS), DNV, IEC, and ISO specifications and pulling the appropriate requirements and sections out to compile a certification path.

6.3 Test and Analysis Matrix and Schedule

An analysis matrix identifying all simulations that will be performed and a corresponding schedule is presented in Table 2 and Figure 4.

Table 2 - Analysis matrix.

Task	Description
Task 1: Nacelle Optimization	Investigate alternative materials to reduce nacelle mass
Simulation 1	Baseline – all DNV NS steel construction (yield = 34ksi)
Simulation 2	All EHS steel construction (yield = 80ksi)
Simulation 3	All Aluminum construction
Simulation 4	Fiberglass, Kevlar, metal and closed cell foam core.
CAD Work	Model/Drawings to aid in cost assessment
Cost Comparison	Engage industry for Build ROM's
Task 2: Multi-Function Heave Plate/Container Certification Methodology	Develop methods/requirements to conform a mobile/offshore floating structure to ISO shipping standards so it can easily be transported on a container vessel (boat or truck trailer).

Task 3: Reporting	Per Section 7

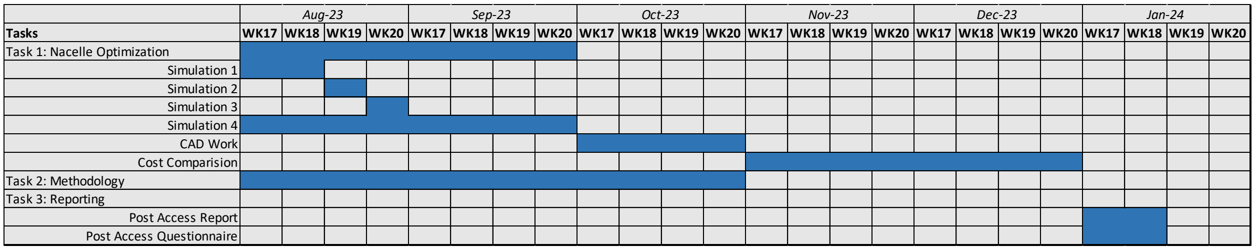


Figure 4- Tasking Schedule.

6.4 Safety

This is a numerical simulation; no safety procedures and protocols are needed.

6.5 Contingency Plans

No project contingency plans are anticipated currently.

6.6 Data Management, Processing, and Analysis

6.6.1 Data Management

Data provided is all CAD and FEA models with results in their native formats (SolidWorks, FEMAP, and NASTRAN).

Task 1: Nacelle Optimization	Description
Simulation 1	FEMAP and NASTRAN
Simulation 2	FEMAP and NASTRAN
Simulation 3	FEMAP and NASTRAN
Simulation 4	FEMAP and NASTRAN
CAD Work	SolidWorks, PDF, DXF
Cost Comparison	MS Word
Task 2: Methodology	MS Word
Task 3: Reporting	MS Word

6.6.2 Data Processing

This is a numerical simulation and data is processed with FEMAP and provided in graphical format.

6.6.3 Data Analysis

Standards and guidance used for the analysis are based on DNV with modifications to meet Cardinal Engineering quality standards of analysis modeling and reporting developed over decades working in the Naval and commercial marine industry. Specifically, DNV-OS-C501 (*COMPOSITE COMPONENTS*) serves as the guiding method for design and analysis. It is further supported with *Marine Composites* by Eric Green Associates uses the Navy's DDS 9110-9 which is derived from MIL-HDBK-17. MIL-HDBK-17 and material data sheets are used to establish material properties.

7 Project Outcomes

7.1 Results

The task consisted of two main parts. First, a certification path consisting of methods/requirements to conform a mobile/offshore floating structure to ISO shipping standards so it can easily be transported on a container vessel (boat or truck trailer) was produced. Second, a lightweight nacelle was developed and the cost and performance benefits were shown.

7.1.1 Multi-functional Component Certification Path

The first task was to provide a path to certify a single multi-functional heave plate/barge/shipping container that may be designed to transport the C·Power SeaRAY WEC in compliance with various aspects of applicable ISO, DNV, and IEC specifications. Currently, the WEC uses separate platforms for transport on land, transport at sea, and operational stability. The goal of this study is to research the feasibility of combining these platforms into one system, by showing how a design can be compliant with all relevant ISO, DNV, and IEC standards. When on land functioning as a shipping bed, the system will be governed by applicable ISO standards. While underway at sea functioning as a barge, the system will be governed by appropriate DNV standards for vessels. When the WEC is operating and the system functions as a heave plate, the system will be governed by applicable IEC (or alternatively, DNV) standards. Seeing as the same system will be used for all three (3) functions, it must meet all applicable standards for certification.

A thorough review of industrial and maritime standards has been completed and portions of the standards, specifications, and requirements that apply to the certification of a mobile offshore floating structure, which is intended to serve as a hybrid heave plate/barge/shipping bed, are described below. The general certification process necessary for all three (3) functions of the system is outlined in Figure 5 and key elements of applicable certification/classification standards are emphasized through a checklist (included as the Appendix) that may be used to ensure that certification/classification proposals for a candidate designs include all aspects required for the approval of the requests. This document only serves to present the requirements and methods for certifying (and not designing) a mobile offshore floating semi-submersible structure capable of being transported as a container on land and as a barge at sea. . While alternative certification paths may exist, the process outlined below has been identified as a conservative and efficient approach to ensure that all requirements are effectively met.

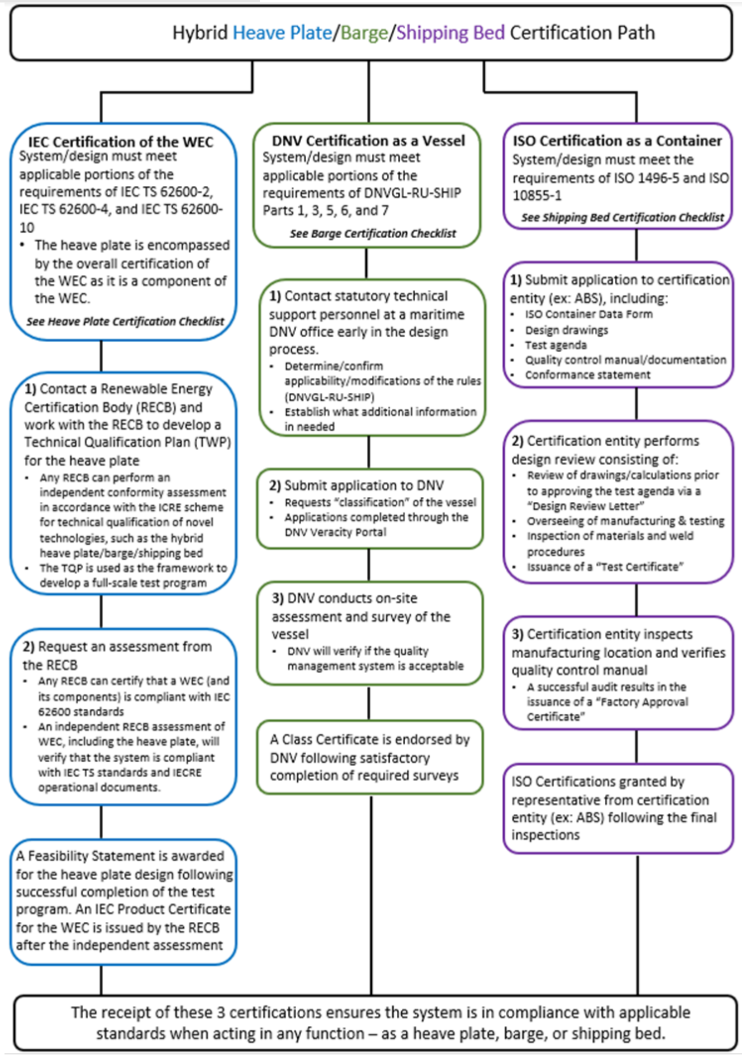


Figure 5 - Summary of Certification Path for a Mobile Offshore Floating Semi-Submersible Structure capable of being transported at sea and on land.

The design requirements for the WEC transportation system, which directly relate to the certification/classification requirements emphasized in this document, are encompassed by DNVGL-RU-SHIP Part 3 – Hull (for its function as a vessel/barge) and IEC TS 62600-2 or DNV-OS-312 (for its function as a heave plate). Additionally, any design of a hybrid heave plate/barge/shipping bed for the WEC system must, at a minimum, comply with the applicable portions of the specifications that are listed in the Appendix 11 "Design Parameters & Certification Requirements – Checklist" section to be certified by the necessary certification entities. The fabricated system must be subject to testing and inspection a designated facility. The results of testing must satisfy the requirements listed below in the Section 6 of ISO 1496-5, Section 7 of ISO 10855-1, and DNVGL-RU-SHIP Part 7 Chapter 1 portions of the checklist. Furthermore, the system must be surveyed at the builder's premises, as described in the DNVGL-RU-SHIP Part 7 Chapter 1 portion of the checklist. The survey, required by DNV in some capacity for all vessels, may consist of a combination of visual inspection, review of records, witnessing of manufacturers' tests and measurements, and additional non-destructive and functional testing. The process of formally certifying the system to all certification standards, ISO, DNV, and IEC, is described in detail below. It is important to note that the certification/classification requirements outlined throughout this document pertain only to the hybrid heave plate/barge/shipping bed system alone, and that the entirety of the SeaRAY Wave Energy Converter will have to be certified separately in accordance with IEC TS 62600-2 or DNV-OSS-312.

7.1.1.1 Certification Path Detail

To be operated as a shipping bed, the system must receive ISO certification as a container. A submission must be made to a specific organization capable of granting ISO certification. The American Bureau of Shipping (ABS) is considered the predominate certification entity because it is the most reputable organization that has been designated as an authorized entity to ensure compliance by the United States Coast Guard. The ISO certification process is the same if an alternative organization, also designated as an authorized certification entity, is selected to perform the certification.

The submittal must include an ABS Application Form, an ISO Container Data Form, all design drawings, a test agenda, and quality control documentation. The submittal must also state that the container will be built in conformance with ISO rules, manufactured with an acceptable quality control program, tested in accordance with prescribed procedures, and available for inspection always during manufacture and testing.

The quality control manual to be submitted must include a description of the design/manufacturing organization, material identification procedures, and workmanship/fabrication practices. Essential design parameters are highlighted in the Section 4 of ISO 1496-1, Section 5 of ISO 1496-1, and Section 5 of ISO 10855-1 portions of the checklist.

ABS submissions may be initiated online:

https://ww2.eagle.org/en/Products-and-Services/vendor-certification/container-certification.html

An engineering team from ABS (or an alternative authorized organization capable of granting ISO certification) will perform a design review of drawings and calculations. If successful, the design review will result in a "Design Review Letter". A Design Review Letter approves the proposed test agenda. After receiving approval, the container must be manufactured under the surveillance of an inspector from ABS (or an alternative authorized organization capable of granting ISO certification). Upon manufacturing completion, a Container Statement of Fact is issued to travel with the container to the designated testing facility. At the testing facility, a representative from ABS will oversee prototype testing at a designated facility and inspect materials and welding procedures used during construction of the prototype (as described in Section 8 of ISO 10855-1 portion of the checklist).

The results of testing must satisfy the requirements listed below in the Section 6 of ISO 1496-5, Section 7 of ISO 1496-5, and Section 7 of ISO 10855-1 portions of the checklist. Upon successful prototype testing results, an ABS Prototype Test Certificate with a completed test report will be provided and provides permission to manufacture.

Prior to manufacturing, an ABS inspector, or representative from an alternative organization capable of granting ISO certification, will inspect the manufacturing location. The inspector will need the quality manual and it will be reviewed prior to and then verified during the inspection. A successful audit/inspection of (each of) the manufacturing locations results in an ABS Factory Approval Certificate.

An ABS inspector will grant certification for a container following a successful final inspection concluding that the container meets applicable ISO standards. The container must be marked appropriately as emphasized in the Section 9/10 of ISO 10855-1 portion of the checklist.

To be operated as a barge, the system must receive DNV vessel classification to certify that the system is compliant with conventional requirements. For novel designs, such as the hybrid heave plate/barge/shipping bed, DNV must be contacted at an early stage in the design process to determine the applicability of their rules (design, survey, and test requirements) and establish what additional information will be required for the submission. This initial stage will require C·Power to initiate contact with statutory technical support personnel at a maritime DNV office and be prepared to submit a white paper to DNV which includes preliminary design and operation concepts. Contact information for the eight (8) maritime DNV offices in the United States can be found at:

https://www.dnv.com/maritime/contact/index.html#USA-USSEA-details

Once the applicability of the rules and appropriate classifications for the hybrid heave plate/barge/shipping bed are agreed upon, the vessel may be manufactured. It should be noted that the internal quality management system is developed to track the requirements of the classification standards that must be met.

A formal request for a classification of a new vessel needs to be submitted through the DNV Veracity Portal. If additional contact information for requests for a classification of a new vessel is necessary, such information can be found at: https://www.dnv.com/services/ship-classification-newbuilding-1625.

Based on the review of the documentation, the hybrid heave plate/barge/shipping bed is expected to have to meet the requirements for both a barge and a semi-submersible heavy transport vessel (without propulsion), as described in the *DNVGL-RU-SHIP Part 1 Chapter 2* portion of the checklist, where the information required for the submission must demonstrate that the structural safety of the design is equivalent or superior to the safety requirements listed in DNV specifications. To ensure the system meets all applicable classification requirements, review of the *Barge Certification: Det Norske Veritas DNV* checklist and confirmation that the system meets all requirements listed in this checklist are required. If adjustments are needed working with DNV will allow for certain modifications to the requirements as they can determine the “equivalence with the rules” in Step 2.a.

After the design and manufacturing of the vessel, DNV will conduct an on-site assessment to survey the vessel, as described in the *DNVGL-RU-SHIP Part 7, Chapter 1, Section 1* portion of the checklist, and will verify the quality management system meets their standards after a classification application has been accepted. With successful completion of the inspection, a Class certificate endorsed upon satisfactory completion of annual and intermediate Surveys will be granted by DNV. The Class certificate needs to renew every 5 years through a renewal Survey.

To be operated as a heave plate, the hybrid heave plate/barge/shipping bed system must meet requirements associated with IEC (or alternatively, DNV) certification of WECs. The SeaRAY WEC itself will need to be certified separately from its means of transportation (the barge/shipping bed functions of the system). The system, in its function as a heave plate, will be encompassed (in that it is a sub-system of the WEC) by the certification of the entirety of the WEC. This document does not review the aggregate of all certification requirements for WECs as the mobile offshore floating semi-submersible structure is just a portion of the WEC. The entirety of such requirements considers all entities of the WEC (including energy conversion units, PTOs, and other sub-systems), which are not applicable to the scope of this investigation. This document emphasizes portions of WEC certification requirements that relate to heave plates and mooring systems as applicable to the hybrid heave plate/barge/shipping bed system.

For WEC certification to IEC standards, the system will have to be assessed by a renewable energy certification body (RECB) that meets the requirements of ISO/IEC 17065 accreditation which the IEC Conformity Assessment Board has approved. The International Electrotechnical Commission Renewable Energy (IECRE) is the IEC system for certification to standards relating to equipment for use in renewable energy applications. An RECB can perform an end-to-end independent conformity assessment consisting of all activities within the IECRE scheme for technical qualification of novel technologies and WECs seeking certification of compliance with IEC 62600 technical specifications.

The operator may work with an RECB to develop a Technical Qualification Plan for the hybrid heave plate/barge/shipping bed system, as described in the *IEC TS 62600-4* portion of the checklist. Then the RECB will independently assess the system for conformity and issue a certificate after verifying that the technology is in accordance with applicable standards and published IEC/IECRE operational documents. For this certification, the hybrid heave plate/barge/shipping bed is expected to have to meet the requirements for technical qualification as a sub-system of the WEC, and requirements associated with WEC mooring systems, as described in the *IEC TS 62600-2*, *IEC TS 62600-4*, and *IEC TS 62600-10* portions of the checklist.

The operator may develop a full-scale test program founded on the certified Technical Qualification Plan, which will form the basis for an award of a Feasibility Statement. Following successful assessment of the program by an RECB, a Feasibility Statement will be awarded by IEC through the RECB to validate Technology Qualification. A product certificate will then be issued by an RECB as confirmation that the WEC equipment is compliance with all applicable requirements.

Alternatively, if WEC Certification by DNV-OS-312 is to be pursued, the heave plate must be registered as a product through the DNV Veracity Portal. To accomplish this, the hybrid heave plate/barge/shipping bed is expected to have to meet the requirements for a mooring apparatus, as described in the *DNV-OS-312* portion of the checklist. A letter of approval or design verification report will be issued by DNV when compliance with the requirements for the design has been confirmed.

7.1.2 Alternative Material Nacelle Design

The nacelle weight optimization explored four materials, normal strength steel (NS), a high strength steel (EHS), aluminum alloy (Al-5059), and a sandwich composite structure of foam core and FRP skins. The overall nacelle is 21 ft long and has a 7 ft diameter, as depicted in Figure 12.

To investigate the use of alternative materials in the nacelle design, the main body of the k20 WEC, both closed form solutions and FEA were employed. The analysis methodology is based on the DNVGL-OS-C501 (Composite Components) for composite structures and DNVGL-OS-C101 (Structural Design of Offshore Steel Structures, General LRFD Method) for metallic structures. Both systems are based on the limit state design methodology where the material limits are debited by factors to account for material/manufacturing and load uncertainties. This is consistent with Section 5.10 of IEC 62600-2. IEC 62600-2 also notes that special care should be taken when specification surfing or combining sources. This can lead to using mixed factors and designs that are not sound. For these reasons, DNV was used as it is a Load and Resistance Factor Design (LFRD) methodology, has detailed methodologies that cover the entire design process, and provides a consistency between factors and evaluation methods.

7.1.2.1 Loads Development

From the specifications the loadings used to assess the nacelle are permanent loads (mass of structure, mass of permanent ballast or equipment, internal or external pressure), and environmental loads (the worst-case wind, wave, and current loads that the structure may experience during its design life). Loads were provided by C·Power and derived from AQWA simulations. AQWA, a rigid body hydrodynamic simulation that C·Power has extensive experience with, and the methodology of using AQWA to develop loadings has been correlated to test data and shown to capture the body movements and accelerations.

C·Power performed extensive hydrodynamic modeling for site conditions. The environment used to assess the WEC was derived from PacWave South test site (PWS) with a design requirement of survival through extreme sea conditions (50-year with sea states from two directions and several wave amplitude, period, and random phase variations). Resource data was gathered from “Characterization of U.S. Wave Energy Converter Test Sites: A Catalogue of Met-Ocean Data, 2nd Edition” by Sandia National Laboratories. The WEC’s performance with full PTO and power electronics system was numerically modeled using ANSYS AQWA.

The AQWA data was processed using a filter to isolate the worst-case load cases that are defined as having the peak component accelerations or loads in the time histories. The filtered load case time histories were then applied to a simplified structural beam finite element model, which provides forces and bending moments over the time history. The beam model results were then further filtered to provide the time points of worst-case values of stresses and bending moments. The identified time points and their associated forces and moments could then be used in more complex structural models to optimize the design of the structure. The structure was then iteratively modified and rerun through the FEM software. This process is shown in Figure 6 and discussed in greater detail below.

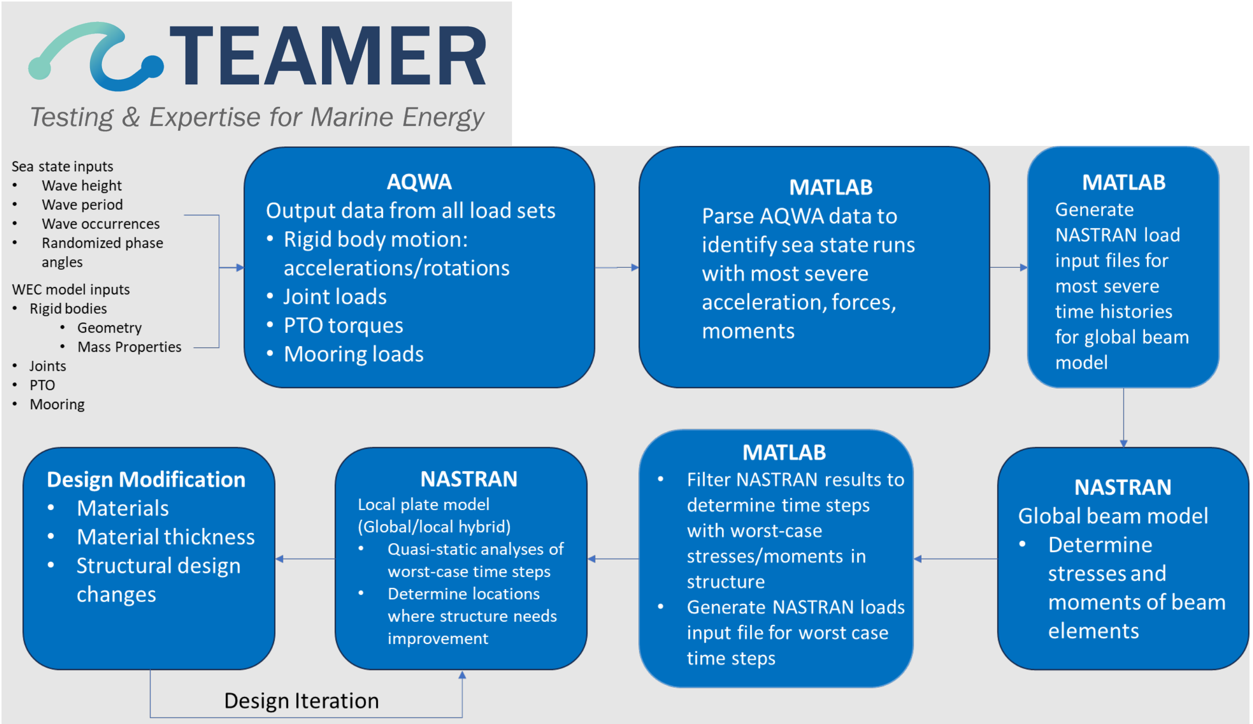


Figure 6 - Overall process of developing loads for WEC design optimization.

A segment of the data showing the maximum or minimum values highlighted in green for all time histories for each part and load case is given in Figure 7. The next step was to consider the rest of the loads and identify loads on the nacelle that are near the peak, highlighted in yellow in Figure 7, for the time histories for load case ID# N7294cs15.

	N7294cs12	N7294cs13	N7294cs14	N7294cs15	N7294cs16	N7294cs17	N7294cs18	N7294cs19	N7294cs20
Nacelle Max Heave Acceleration (m/s^2)	8.4673	8.1455	8.4878	9.0764	7.7198	6.6706	7.7248	7.7817	7.5451
Nacelle Min Heave Acceleration (m/s^2)	-16.907	-12.737	-9.9886	-18.225	-11.672	-14.333	-10.125	-14.4	-17.085
Nacelle Max Radial Acceleration (m/s^2)	19.077	13.786	10.479	19.16	12.476	15.31	10.179	14.623	17.287
Nacelle Max Pitch Acceleration (rad/s^2)	9.2751	6.8435	5.8094	7.5774	9.7509	6.4287	6.2944	11.178	8.2624
Nacelle Min Pitch Acceleration (rad/s^2)	-11.255	-9.9747	-9.1529	-10.75	-9.5249	-8.7653	-6.0395	-8.5336	-11.952
Fore Float Max Heave Acceleration (m/s^2)	11.72	10.808	10.779	11.193	13.001	10.556	9.5443	11.767	9.6477
Fore Float Min Heave Acceleration (m/s^2)	-11.803	-11.329	-11.594	-13.244	-13.6	-10.286	-9.8883	-9.5587	-9.1584
Aft Float Max Heave Acceleration (m/s^2)	17.133	13.667	14.13	16.021	16.388	14.301	15.391	20.411	13.889
Aft Float Min Heave Acceleration (m/s^2)	-11.318	-7.8866	-13.415	-9.1753	-11	-11.102	-14.988	-10.11	-7.4381
Fore Float Max Pitch Acceleration (rad/s^2)	8.5115	6.6475	6.0086	6.9935	7.9223	6.6732	5.4055	6.0845	10.475
Fore Float Min Pitch Acceleration (rad/s^2)	-4.1174	-5.1237	-5.4962	-5.4964	-5.4119	-4.9729	-5.9653	-6.4768	-4.4046
Aft Float Max Pitch Acceleration (rad/s^2)	5.24E+00	5.36E+00	4.40E+00	4.77E+00	5.63E+00	4.2516	4.38E+00	6.26E+00	7.49E+00
Aft Float Min Pitch Acceleration (rad/s^2)	-3.12E+00	-3.04E+00	-4.30E+00	-3.47E+00	-3.32E+00	-3.2786	-4.68E+00	-3.42E+00	-2.78E+00
Nacelle to Yoke Max Bending (Nm)	1.32E+05	1.84E+05	2.00E+05	1.88E+05	1.81E+05	1.34E+05	1.60E+05	2.04E+05	1.29E+05
Nacelle to Yoke Min Bending (Nm)	-1.10E+05	-5.87E+05	-2.91E+05	-1.64E+05	-3.58E+05	-1.66E+05	-5.26E+05	-1.26E+05	-1.96E+05
Nacelle to Yoke Max Tension(Fz) (N)	-9.47E+05	-6.82E+05	-6.16E+05	-1.01E+06	-7.02E+05	-7.90E+05	-5.33E+05	-7.27E+05	-7.42E+05
Nacelle to Yoke Min Tension(Fz) (N)	-9.47E+05	-6.82E+05	-6.16E+05	-1.01E+06	-7.02E+05	-7.90E+05	-5.33E+05	-7.27E+05	-7.42E+05
Nacelle to Fore Float Arm Max Radial Load (N)	2.62E+05	1.75E+05	1.29E+05	2.42E+05	1.77E+05	1.86E+05	1.39E+05	1.68E+05	1.82E+05
Nacelle to Fore Float Arm Min Radial Load (N)	2.02E+02	1.73E+02	4.40E+02	6.65E+02	2.18E+02	150.78	1.21E+02	5.39E+02	1.70E+02
Nacelle to Aft Float Arm Max Radial Load (N)	1.49E+05	1.35E+05	1.43E+05	1.27E+05	1.15E+05	1.40E+05	1.29E+05	1.28E+05	1.23E+05
Nacelle to Aft Float Arm Min Radial Load (N)	178.3	100.53	486.61	164.59	185.01	83.88	76.605	140.63	121.53

Figure 7 – Spreadsheet (partial) of peak component accelerations or load values from AQWA time histories

An additional load case assessed was the maximum external pressure on the nacelle. The maximum pressure of 14psi simulates hydrostatic loading due to extreme submersion. A nonlinear collapse analysis was performed using a pressure value of 28psi, which is two times greater (for conservatism) than the maximum pressure of 14psi due to extreme submersion. A Progressive Ply Failure Analysis (PPFA) was also performed using the conservative pressure value of 28psi. Pressure loading due to extreme submersion was the only load considered for both the nonlinear collapse analysis and PPFA; no operational loads were included in these analyses. The nonlinear collapse analysis and PPFA were run to twice using a maximum pressure value of 28psi to ensure the nacelle could carry load without any issue past the maximum expected pressure.

7.1.2.1.1 Global Beam Model

To identify the load cases of interest, a global beam FEM was built to incorporate the proper stiffness and accurately find the points of interest. The peak load cases were applied to the FEM, which consists of beam and mass/inertia elements. Counteracting inertial loads and inertial relief are also applied to the system. The beam FEM is illustrated in Figure 8 showing the base construction, loading locations, and boundary conditions. Hydrodynamic loads were applied at the center of gravity (CG) for each body of the WEC which was modeled. The hydrodynamics loads were then spread to the elements making up each body using rigid elements to spread the load across the body. Mooring loads were applied at the location where the mooring lines would be attached to the bodies. Joint loads and torques (e.g., between the power take off (PTO) shaft and the float arms) were applied to the respective joints. Additional torques such as calculated generator torque and friction were also applied at the appropriate locations. The deflected shape of the beam model is illustrated in Figure 9.

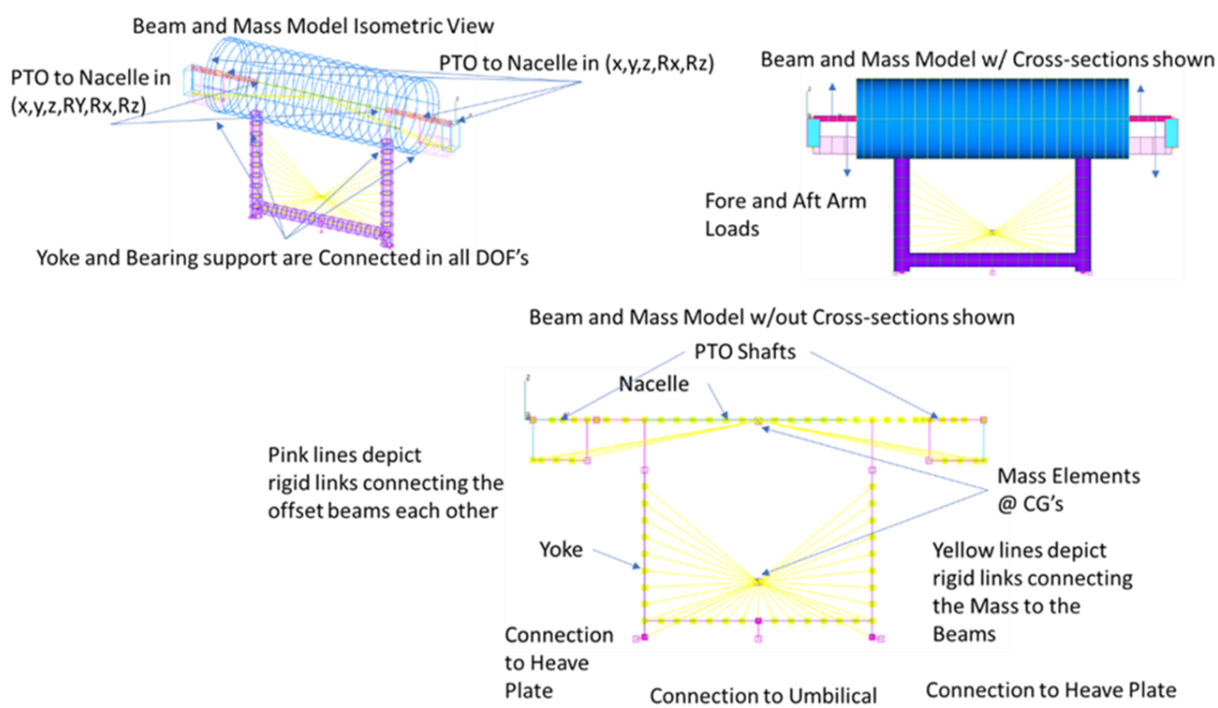


Figure 8- Beam Model

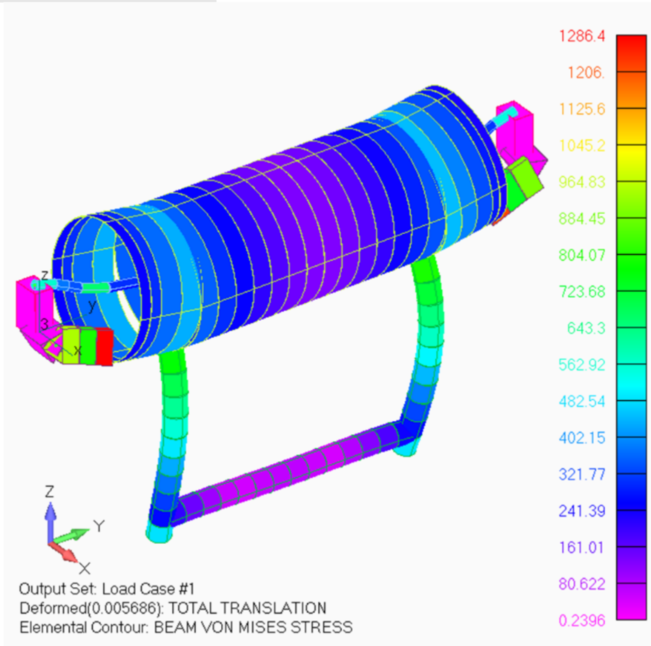


Figure 9 – Example Beam Model Deflected Shape.

The analysis results were then filtered to find the worst-case instances of time identified as having peak bending, shear, axial load, or torque on the nacelle. Peak load values are shown in Table 3 with their corresponding load case. Peak load cases are highlighted in green in Table 3. Note load cases 509, 1358, and 4055 produce the worst-case loading.

Table 3 - Maximum Values for Bending Moment, Shear Force, Axial Force and Torques

	Value	Element	Load Case
Nacelle Max Bending A	4.2518E+06	18	1358
Nacelle Max Bending B	4.5404E+06	17	1358
Nacelle Max Shear A	7.5784E+04	18	1358
Nacelle Max Shear B	7.5784E+04	18	1358
Nacelle Max Axial A	8.0476E+03	22	1358
Nacelle Max Axial B	8.0476E+03	22	1358
Nacelle Min Axial A	-2.4857E+03	22	4055
Nacelle Min Axial B	-2.4857E+03	22	4055
Nacelle Max Torque A	4.8412E+05	22	1358
Nacelle Max Torque B	4.8412E+05	22	1358
Yoke Max Bending A	6.6263E+05	1	4055
Yoke Max Bending B	7.1151E+05	34	1358
Yoke Max Shear A	1.7501E+04	34	1358
Yoke Max Shear B	1.7501E+04	34	1358
Yoke Max Axial A	1.2092E+05	34	1358
Yoke Max Axial B	1.2092E+05	34	1358
Yoke Min Axial A	-4.6321E+03	10	4055
Yoke Min Axial B	-4.6321E+03	10	4055
Yoke Max Torque A	1.2904E+05	1	2588
Yoke Max Torque B	1.2904E+05	1	2588
NES Max Bending A	5.8862E+04	2	1088
NES Max Bending B	2.5880E+05	2	1358
NES Max Shear A	8.7107E+03	1	1358
NES Max Shear B	8.7107E+03	1	1358
NES Max Axial A	1.7444E+04	2	1358
NES Max Axial B	1.7444E+04	2	1358
NES Min Axial A	-4.6331E+03	1	4055
NES Min Axial B	-4.6331E+03	1	4055
NES Max Torque A	2.5767E+04	2	1358
NES Max Torque B	2.5767E+04	2	1358
PTO Max Bending A	3.2305E+05	5	1358
PTO Max Bending B	3.2970E+05	4	1358
PTO Max Shear A	2.5515E+04	5	1358
PTO Max Shear B	2.5515E+04	5	1358
PTO Max Axial A	5.7002E+03	9	4055
PTO Max Axial B	5.7002E+03	9	4055
PTO Min Axial A	-9.3079E+03	10	1358
PTO Min Axial B	-9.3079E+03	10	1358
PTO Max Torque A	2.8492E+04	5	509
PTO Max Torque B	2.8492E+04	5	509
NBSS Max Bending A	8.1214E+05	5	1358
NBSS Max Bending B	4.3255E+05	5	1358
NBSS Max Shear A	3.3209E+04	5	1358
NBSS Max Shear B	3.3209E+04	5	1358
NBSS Max Axial A	8.3361E+03	1	1358
NBSS Max Axial B	8.3361E+03	1	1358
NBSS Min Axial A	-2.3158E+03	5	4055
NBSS Min Axial B	-2.3158E+03	5	4055
NBSS Max Torque A	8.2367E+04	5	2589
NBSS Max Torque B	8.2367E+04	5	2589

With the time steps of interest identified, the NASTRAN load files were written out to be used with more detailed plate based FEM. A detailed FEM, Figure 13 further described in Section 7.2.1.4 of the report, was then developed, and incorporates the pressure and the loading from the worst-case timepoints to identify areas of concern that were updated until the material limits were satisfied.

7.1.2.2 Material Properties and Limits

Metallic properties were adopted from DNVGL-RU-NAVAL Pt3Ch1, E-Glass properties were adopted from stitch-bonded unidirectional (UD) plies in DNVGL-OS-C501 Appendix F, and the rest of the material properties were adopted form manufacture data sheets. Additional modifications of the elastic properties were done for the E-glass. It was desired to use a higher E-glass Fiber Volume Fraction (FVF) of 60%, the use of an epoxy resin (EPOM 826), and a 10% water emersion debit. These properties are for a single layer and are combined in layers to create a laminate. The material properties are tabulated in Table 4 and Table 5 for isotropic and orthotropic materials respectively where the elastic properties are the characteristic value (mean). The strength properties given are the minimum defined and are further reduced to account for load and material uncertainties.

Table 4- ISOTROPIC MATERIAL PROPERTIES

MATERIAL	Strength LEVEL	Yield Strength	Stress Limit	Young's modulus	Poisson's ratio	Shear modulus	Mass Density	Tensile Strength	Comp. Strength	Shear Strength
		psi	psi	psi		psi	lb/in³	psi	psi	psi
VL-A 36	NS	51,488	37,311	30,457,980	0.3	11,714,608	0.2836			
VL-M550	EHS	79,771	57,805	30,457,980	0.30	11,714,608	0.2836			
AL-5059	H116	37,565	27,221	10,152,660	0.33	11,501,513	0.0979			
AL-5059 welded	H116	22,481	16,291	10,152,660	0.33	11,501,513	0.0979			
NB21-16-5-3 (Stainless)	HS	62,366	45,193	28,282,410	0.27	11,134,807	0.2836			
Loctite EA 9628				345,000	0.35	132,692	0.0400	7,500	11,500	4,000
Epom 826 (EPOXY RESIN)				400,000	0.35	148,148	0.0419	12,900	18,800	9,400
DIVINYCELL HCP CORE*				56,560	1.079	13,600	0.0110	1,450	1,015	600
G10 SHEET				3,000,000	0.106	362,000	0.0650	38,100	25,100	11,600
*NOTE: SET POISSON'S RATIO TO .45 TO KEEP FEA REALISTIC **Note: Shear limit at 80C										

Table 5 - ORTHOTROPIC MATERIAL PROPERTIES AND LIMITS

Description	Material Properties									Material Limits						
	Fiber Volume (FV)	Void Vol (VV)	E1	E2	G12	nu12	nu23	nu31	p	UTS11	UTS22	UCS11	UCS22	USS12	USS23	USS31
			psi	psi	psi	-	-	-	lb/in³	psi	psi	psi	psi	psi	psi	psi
Appendix F Stitch-bonded UD Plies E Glass Polyester	0.35	0.02	3,872,500	1,218,300	507,632	0.29	0.29	0.29		89,053	5,221	61,931	7,977	3,336	2,031	2,031
UD E-glass ply Estimate ratioed per sect 4 F700 in DNV. based on increased FV and EPOM 826 Resin. Limits ratioed by fiber volume in ply dominated, micro mechanics for matrix dominated	0.60	0.02	6,224,819	1,979,738	824,902	0.26	0.29	0.29	0.0725	152,663	16,181	106,168	13,675	5,637	5,703	7,797
Estimate with 10% water immersion debit on Fiber dominant props.	0.60	0.02	5,602,337	1,979,738	824,902	0.26	0.29	0.29	0.0725	137,396	16,181	95,551	16,181	5,637	5,703	7,797
Max Stress Limits with 1.68 factor										90,871	9,631	56,876	9,631	3,356	3,395	4,641
Tsai-Wu Limits w/ factor 1.93										71,190	2,963	49,508	2,963	2,921	2,955	4,040
Connel Tube (Reduced limits by 30% to account for 2 standard deviations & factor)			1,750,000	2,500,000	1,300,000	0.23	0.23	0.23	0.0670	5,917	5,917	9,479	9,479	2,232	2,232	2,232

The metallic strength properties were debited by a factor of 1.38 which is comprised of a 1.15 material partial factor and a 1.20 load partial factor as defined in DNV. The metallic hull analysis used linear material properties and linear analysis for all loads except the collapse loading. The nonlinear collapse analysis used elastic-perfectly plastic properties.

For the composite assessment, the simplified factors from the DNV specification were used as they are conservative, and a material supplier and manufacture are not yet chosen. To aid in the conservatism the Ultimate Limit State (ULS) values were used throughout instead of the lower reduction for environment and permanent loads. Based on the DNV specification, to obtain the stress limits the failure modes being assessed are identified in Table 6 long with the failure type and reliability levels in Table 7. The E-glass laminates were considered brittle, so matrix cracking is considered. This approach uses matrix crack initiation to provide a conservative assessment of leaking and delamination as it occurs prior to both failures. DNV further articulates a desire for the use of maximum strain as a failure criterion but allows for stress given that the analysis and materials are linear and Tsai-Wu failure criteria was used. Stress and

Tsai-Wu methods were utilized as failure criteria since a failure strain was not available for all materials. Both failure criteria were used since only using stress would not account for the interaction of the principal stresses, but the Tsai-Wu method does. Tsai-Wu criteria is similar to the Von Mises criteria used for isotropic materials. For the Tsai-Wu criteria, the failure limit perpendicular to the warp direction is adjusted by the ratio of E2/E1, .35, per the DNV specification, and has a higher resistance model factor of 1.15 with the use of -.5 for the Tsai-Wu interaction term. The use of the -.5 term is common in literature when testing data is not present. This also makes the Tsai-Wu criterion nearly equivalent to Hoffman criterion.

For the PPFA, DNV states the material properties go to zero or near zero when the ply reaches a failure limit for the rest of the analysis as it progresses through time.

Table 6 - Composite Failure Mechanisms

Failure Modes	**Failure Mechanism**	**Comments**
Fracture (Local/Global)	Fiber Failure	Assumed to cause fracture. Shall always be checked.
	Matrix Cracking	Causes leakage and conservatively used as fracture.
	Matrix Crack Growth	Not assessed as failure is assumed a crack inset
	Delamination	Critical due to compressive loading and thru thickness stresses.
	Yielding	Core Material and Metallic parts will be checked
	Buckling	Stiffened shells are predisposed to this with compressive loads and will be checked.
	Large Displacements	No large deflections of the bearing locations to reduce the impact to the shafting system
Leakage	Fiber Failure	Shall be checked.
	Matrix Cracking	Shall be checked.
	Matrix Crack Growth	Using first crack as conservative leak condition.
	Delamination	Since matrix cracking begins prior to delamination, we do not need to consider delamination.
	Yielding	Core Material and Metallic parts will be checked
	Buckling	Shall be checked.
	Large Displacements	Shall be checked.

Table 7 - Failure Type and Target Reliability levels

Failure Mechanism	Failure Type	Target reliability level for Operation Phase	Failure Assessment	Comment
Fiber Failure	Brittle	C – NORMAL SAFETY CLASS	# < 1.0	DNV suggest Tsai-Wu, but the interaction term is found experimentally and the suggestion in literature is -.5. This makes it equivalent to Hoffman criteria.
Matrix Cracking	Brittle	C – NORMAL SAFETY CLASS	$\sigma_{ij} < \sigma limit_{ij}$	
Delamination	Brittle	C – NORMAL SAFETY CLASS	$\sigma_{12} < \sigma limit_{12}$	
Yielding	Ductile	C – NORMAL SAFETY CLASS	$\sigma_{vonMises'} < \sigma_{yield}$	Foam Cores
Buckling	Brittle	C – NORMAL SAFETY CLASS	Linear Bifurcation buckling Then Nonlinear Collapse analysis	Initial assessment done with linear elastic properties. The Nonlinear Collapse will use degraded properties on plies that exceed their limits. Properties fall to 1% of their elastic value to maintain stability in the analysis. Assumption - the geometric imperfections are within 10%, therefore may be neglected per section 6 I408
Large Displacements	Ductile	C – NORMAL SAFETY CLASS		

The last step in obtaining the limit factors was to identify the coefficient of variance (CoV) of the strength (standard deviation/mean). Since a material supplier/manufacture has not yet been identified, an estimated value of 10% was used and will need to be revisited when suppliers are defined. Table 8 shows that the normal safety class is identified and provides a combined safety factor of γ_{fmrdsd} = 1.54 for all except the core with a γ_{fmrdsd} =1.60. Table 8 also shows the High safety class with a factor = 1.68 for the brittle modes. To increase the conservativeness, γ_{fmrdsd} = 1.68 was used for all failure modes. This represents the factors for these materials and considers all the failure modes as brittle and high safety class. For the Tsai-Wu calculations γ_{rd} = 1.15 which makes the γ_{fmrdsd} = 1.95.

Table 8 - Material Limit Modifying Factors from the Simplified Set.

Partial Factor	symbol	CoV 10%, High Safety Class		CoV 10%, Normal Safety Class	
		Brittle	Ductile	Brittle	Ductile
Combined load effect and resistance Factor	γ_{fm}	1.53	1.4	1.4	1.28
Resistance model factor	γ_{rd}	1	1	1	1
Load model factor	γ_{sd}	1.1	1.25	1.1	1.25
Combined factor	γ_{fmrdsd}	1.68	1.75	1.54	1.60

7.1.2.3 Baseline Geometry Development

To establish a baseline design and narrow the FEA runs, the DNV calculation for buckling cylinders (DNVGL-RP-C202 Buckling Strength of Shells) was used. The summary of the results is in Table 9 along with a cost comparison of each material and geometry combination relative to a baseline A36 steel version. Classic laminate theory was used estimate the quasi-isotropic properties of the different laminates. Note this calculation is not specific to composites so a higher factor of 2.1 was used when assessing the composite or sandwich materials.

The A36 steel version is considered the baseline for the assessment, which is summarized in Figure 10. Based on this initial comparison, the choice was made to use an E-Glass and Foam sandwich structure with stiffeners to get 60% of the maximum performance gain at 40% of the cost of the maximum performance. Additional rational to support our design choice is that stiffeners will most likely be needed when assessing slamming and wave slap loads. Both of those loads cause localized bending that could make the core thickness unrealistic. Actual manufacturing costs were not available at this point so material costs were considered. The cost difference between e-glass and carbon fiber builds will be even greater as working with carbon fiber is generally more costly to process.

Table 9- Summary of Comparable Geometry and relative costs.

DNV-RP-C202 (Buckling Strength of Shells)									
	A36 w/ hoop Stiffeners	D500 w/ hoop Stiffeners	5059 w/ hoop Stiffeners (t<=.75")	Carbon cloth, Epoxy	Eglass cloth, Carbon cloth,Foam Core, Epoxy	Kevlar cloth, Carbon cloth,Foam Core, Epoxy	Eglass cloth, Carbon cloth,Foam Core, Epoxy	Eglass cloth, Carbon cloth,Foam Core, Epoxy	Eglass cloth w/ foam hoop stiffeners
E1 (psi) NOT DEBITED FOR COMPOSITES	29,877,766	29,877,766	10,152,639	117,157,973	42,896,733	65,544,439	82,103,688	82,103,688	2,839,775
E2 (psi)	29,877,766	29,877,766	10,152,639	117,157,973	42,896,733	65,544,439	82,103,688	82,103,688	2,839,775
G12 (psi)	11,762,900	11,762,900	3,816,782	8,219,932	3,728,004	5,943,211	7,128,170	7,128,170	1,186,813
NU12	0.27	0.27	0.33	0.182	0.074	0.119	0.119	0.182	0.353
NU23	0.27	0.27	0.33	0.182	0.074	0.119	0.119	0.182	0.353
Density (lb/in^3)	0.289	0.289	0.000	0.079	0.072	0.036	0.029	0.027	0.092

Shell Length (in)	252	252	252	252	252	252	252	252	252
Shell Diameter (in)	84	84	84	84	84	84	84	84	84
Shell Thickness (in)	0.375	0.250	0.375	0.170	2.080	1.080	0.710	0.650	0.125
# Stiffeners	11	11	11	0	0	0	0	0	5hoop 1 long
Stiffener thickness (in)	0.250	0.250	0.368						6.000
Stiffener Height (in)	3.000	3.000	4.000						4.000
I about NA (in^4)	1.17E+07	5.53E+06	1.44E+07	1.48E+06	2.21E+08	7.82E+07	3.50E+07	2.93E+07	1.49E+08
Weight Change	0%	-32%	-64%	-90%	-24%	-63%	-82%	-89%	-50%
Material Cost Change (%)	0%	69%	42%	79%	84%	79%	78%	76%	47%
Fabrication Cost Change (%)	0%	30%	70%						
Life cycle Cost Change (%)	0%	Lower: lighter = lower transportation costs. Lighter = more efficient (how can we quantify this)	Lower due to lower corrosion issues and lower handling/shipping costs, Lighter = more efficient (how can we quantify this)	Lower: No corrosion issues. Potentially leave it in place and scrub off bio growth. lower handling/shipping costs, Lighter = more efficient (how can we quantify this)					

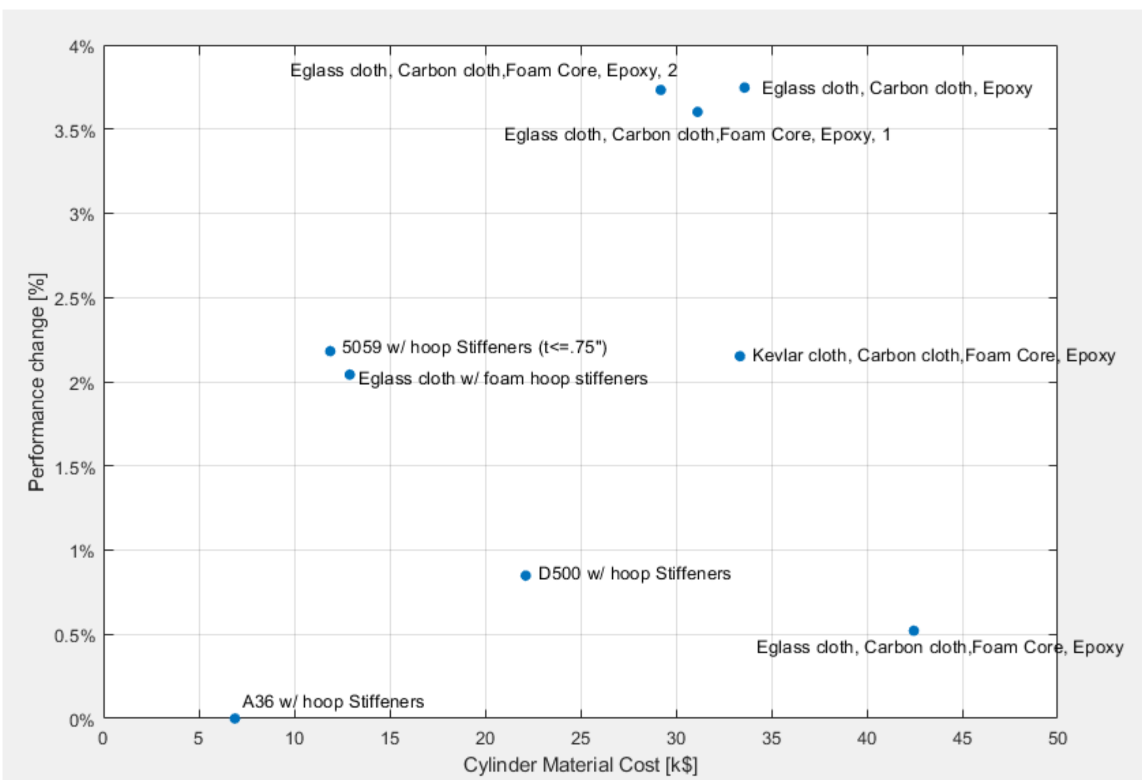


Figure 10- Material Cost to Performance Change

With the buckling calculation based on metallic structures, additional checks were run. Closed form calculations for cored composite panels from NASA CR-1457, 1969 (Manual for Structural Stability Analysis of Sandwich Panels) were used. Using the initial quasi-isotropic layup $(0,45,-45,90)_2$ for the face sheets, a total thickness of 0.11, and a 0.5 core, the ABD Matrix can be calculated. Equivalent sandwich properties are shown in Table 10.

Table 10 - Equivalent Sandwich Properties.

Equivalent Properties		
Exx =	6.443e+005	psi
Eyy =	6.443e+005	psi
Gxy =	3.359e+005	psi
vxy =	0.284	
vyx =	0.254	

Using 14psi as an end load on the cylinder and external pressure, the stresses in the plies were calculated and are provided in Table 11. This calculation is for a flat panel; the dimensions are for the 45° shell arc that is unsupported in the initial design. Note that Hoffman and Tsai-Wu produce the same Margin of Safety since -0.5 was used for the Tsai-Wu interaction term. Figure 11 graphs the ply stresses and shows that the peak normal stress is 20ksi and shear stress is 2.3ksi.

Table 11 – Simplified Flat Panel Dimensions, Loads, and Ply Margin of Safety

Panel Dimensions					
X =	31.75	in			
Y =	75.39	in			
Loads					
$Load_{xx}$	77,584.8	lb	$Moment_{XX}$	0.0	inlb
$Load_{yy}$	0.0	lb	$Moment_{YY}$	2,896.6	inlb
$Load_{xy}$	0.0	lb	$Moment_{xy}$	0.0	inlb
Failure Margin of Safety (MS)					
Tsai-Wu Criteria	514%	Ply 18			
Hoffman Criteria	514%	Ply 18			

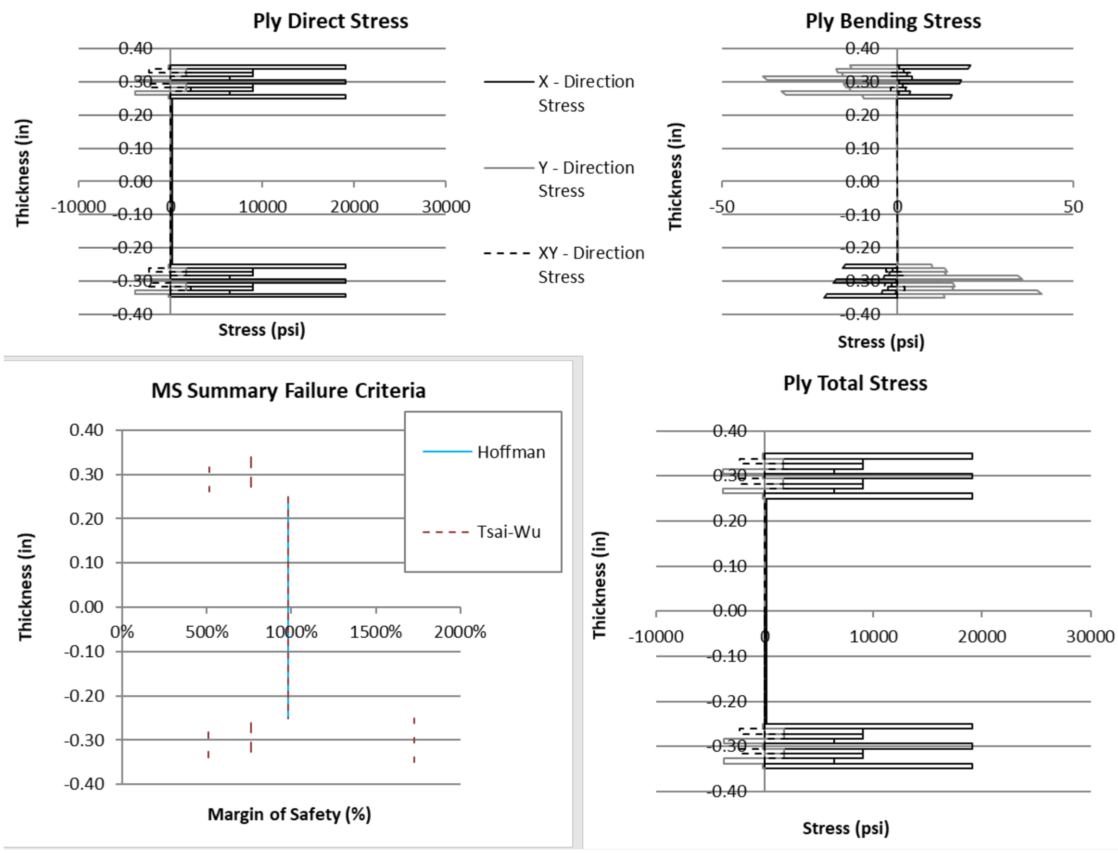
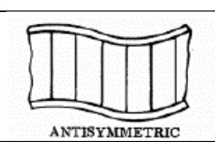


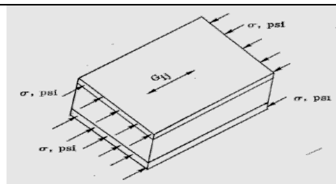
Figure 11 – Simplified Flat Panel Ply Stresses

With the shell stress known, the core failures (wrinkling, shear crimpling) can be assessed with the equations below. Wrinkling is assessed with Equation 1 as the limit, 36.3ksi. This provides a Margin of Safety (MS) of 2.16 to the 20ksi previously calculated. Cored panel shear crimping limit for axial loads can be calculated with Equation 2 resulting in 46ksi or a MS of 3.0. Shear crimping due to shear or torsion can be assessed with Equation 3 resulting in 11ksi or a MS of 2.7.

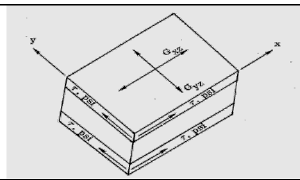
Equation 1 - Face Wrinkling

	$\sigma_{wr} = 0.5 \cdot \left[\frac{\eta \cdot E_f \cdot E_c \cdot G_c}{(1-\nu_e{}^2)}\right]^{\frac{1}{3}}$

Equation 2 - Shear Crimping due to Axial Loads

	$\sigma_{cr} = \frac{h^2}{(t_1 + t_2)t_c} G_{ij}$

Equation 3 - Shear Crimping due to Shear or Torsion

	$\tau_{cr} = \frac{h^2}{(t_1 + t_2)t_c} \sqrt{G_{xz} G_{yz}}$

7.1.2.4 Finite Element Model

The FEM geometry covered the full extent of the nacelle including the PTO shaft and external bearing supports as shown in Figure 12. The detailed FEM was defined with shell elements for the nacelle and beam elements for the bolts, yoke, and the PTO shaft. The mass elements were maintained from the beam FEM and tied to the shell elements with the same rigid element type as in the beam model. The weight is reduced by the amount of the individual modeled parts. The rigid link is a NASTRAN RBE3 element, which distributes the weight without adding stiffness to the structure. The rigid links used to tie the PTO to the bearing and bulkheads are a classic rigid link. The basic shell model detailed in Figure 13 through Figure 23 is the NS steel model and it is the basis of all the FEM's. The other models only vary in material properties, component thickness, and number of hoop stiffeners. Additional exceptions exist in the composite FEM where the external bulkhead is a hemispherical head, and the shell elements are layered shells with the ply orientation using the axis of cylinder as 0° and the hoop axis as 90°. All the skins' laminates are designed as quasi-isotropic following (0,45, -45,90) repeated schedule and each layer has its own thickness. With all the fiber layers being the same material, they all have a thickness of 0.011inches and the core thickness varies as needed. The composite FEM is detailed in Figure 16 through Figure 20. Table 12 provides the thickness of the various components, and the attached pdf of the composite design provides a detailed layout and ply schedules.

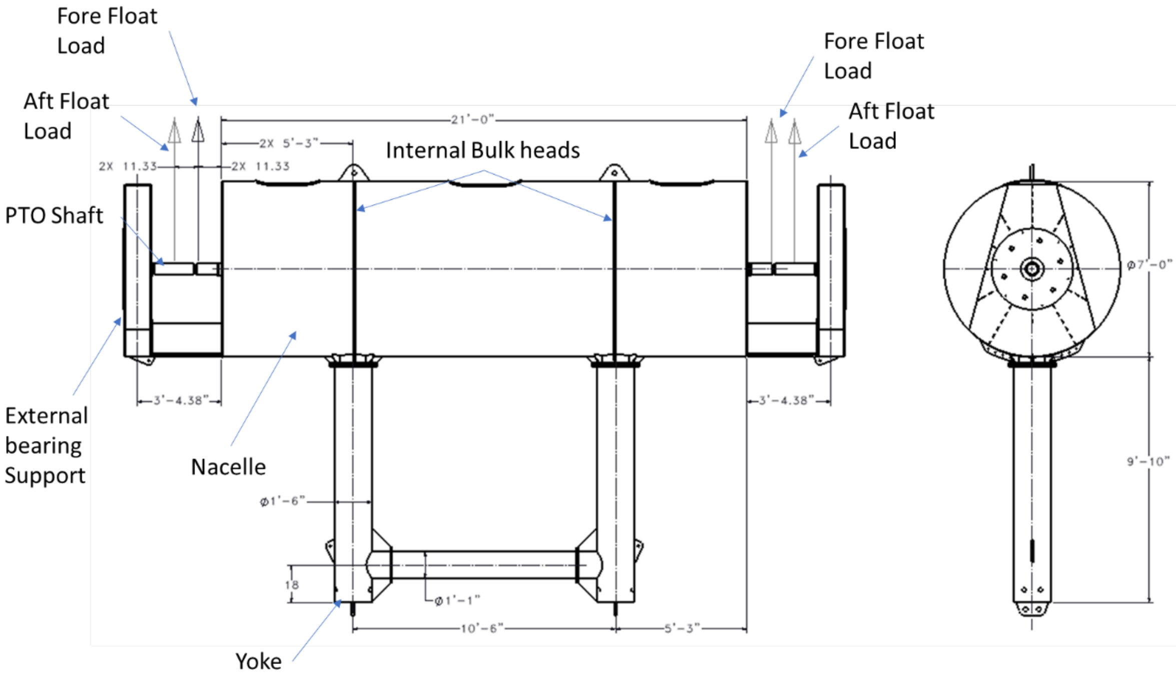


Figure 12 - overall dimensions of the nacelle to be assessed.

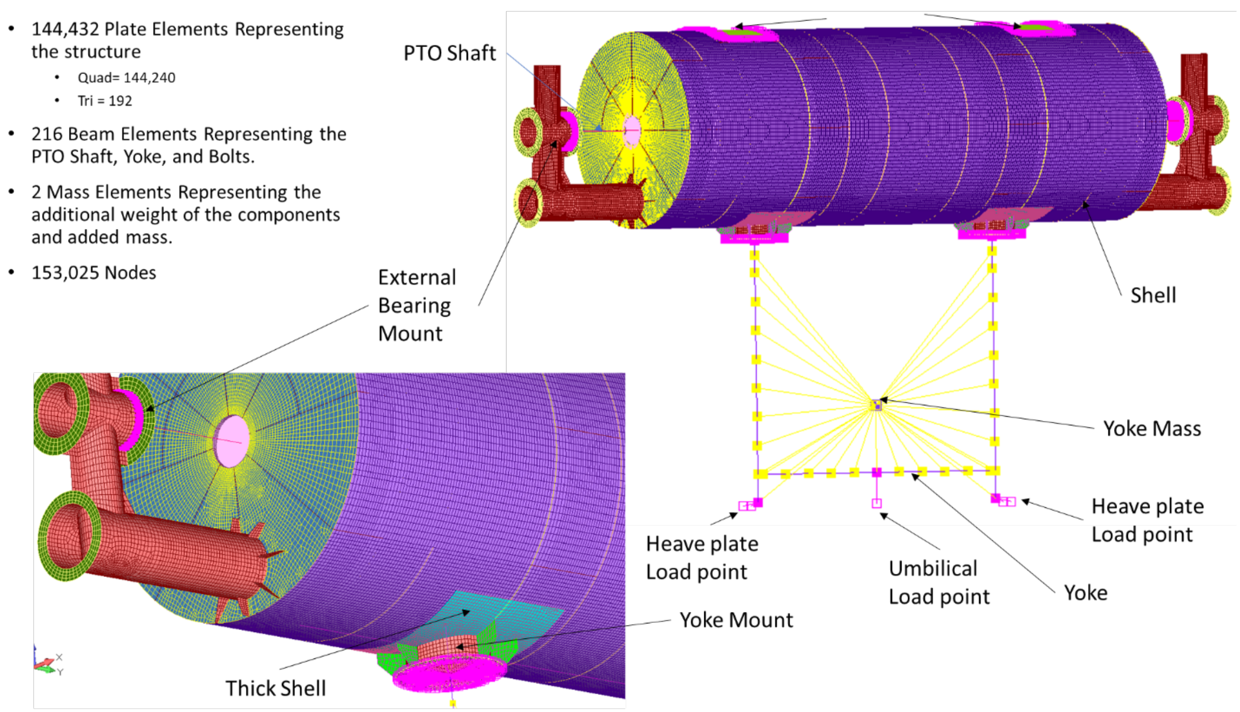


Figure 13 - Metallic FEM

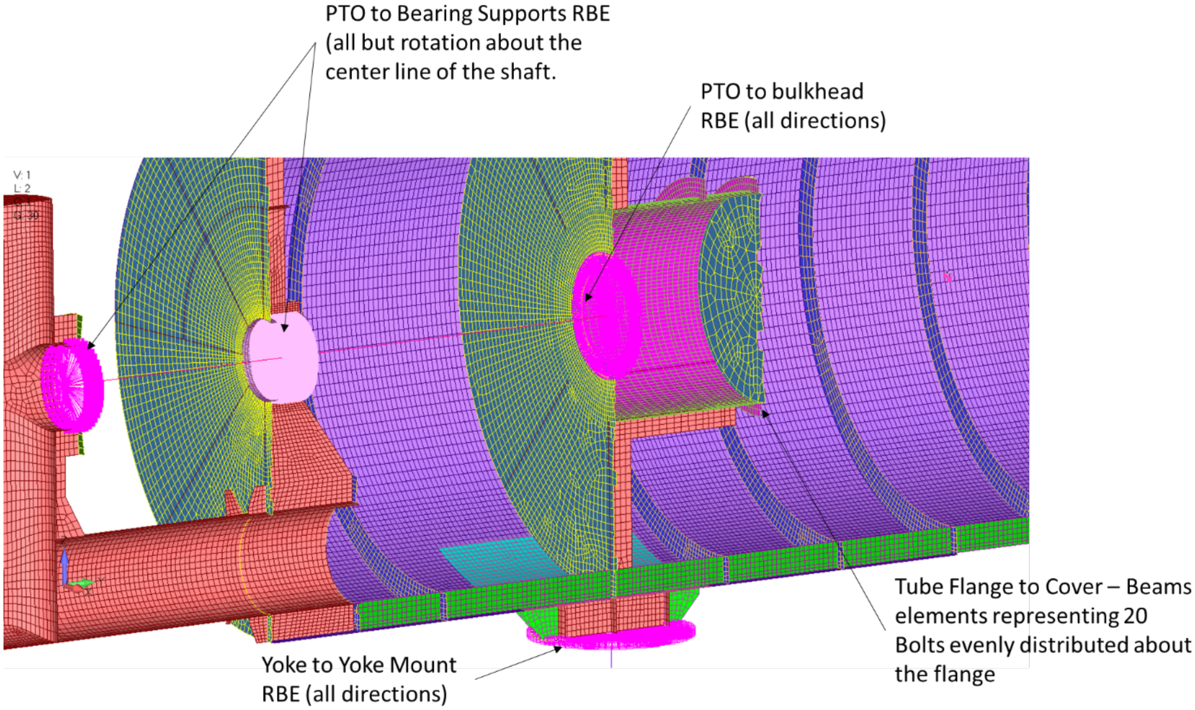


Figure 14 - Metallic FEM Continued.

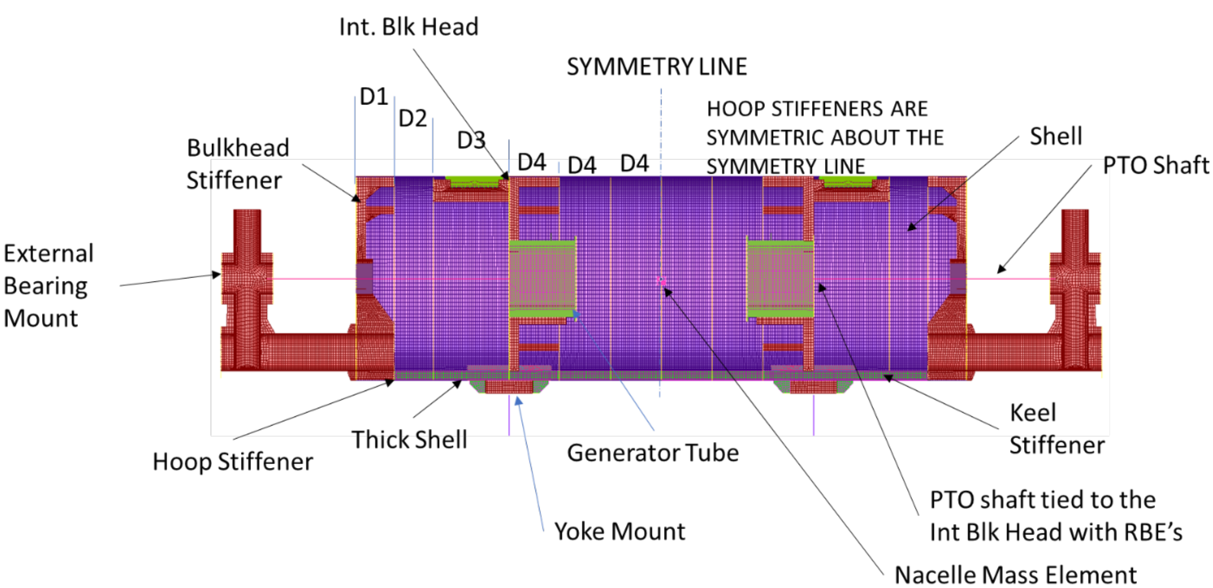


Figure 15 - Metallic Cross-Section and Layout

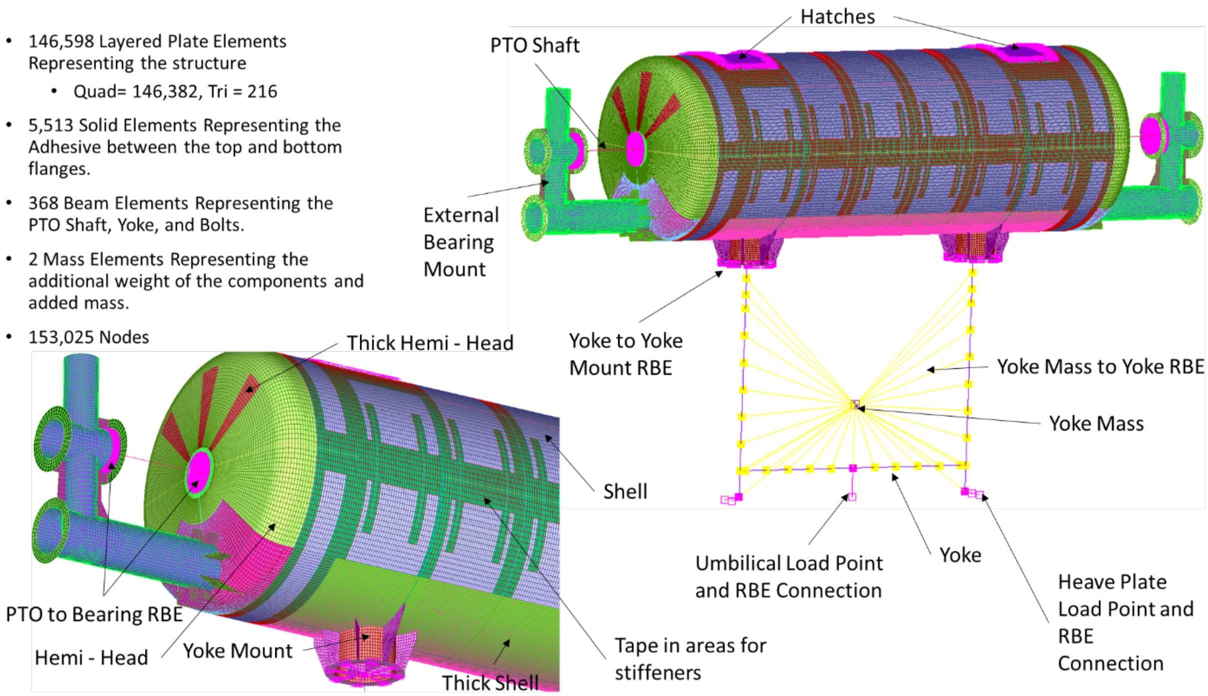


Figure 16 - Composite FEM

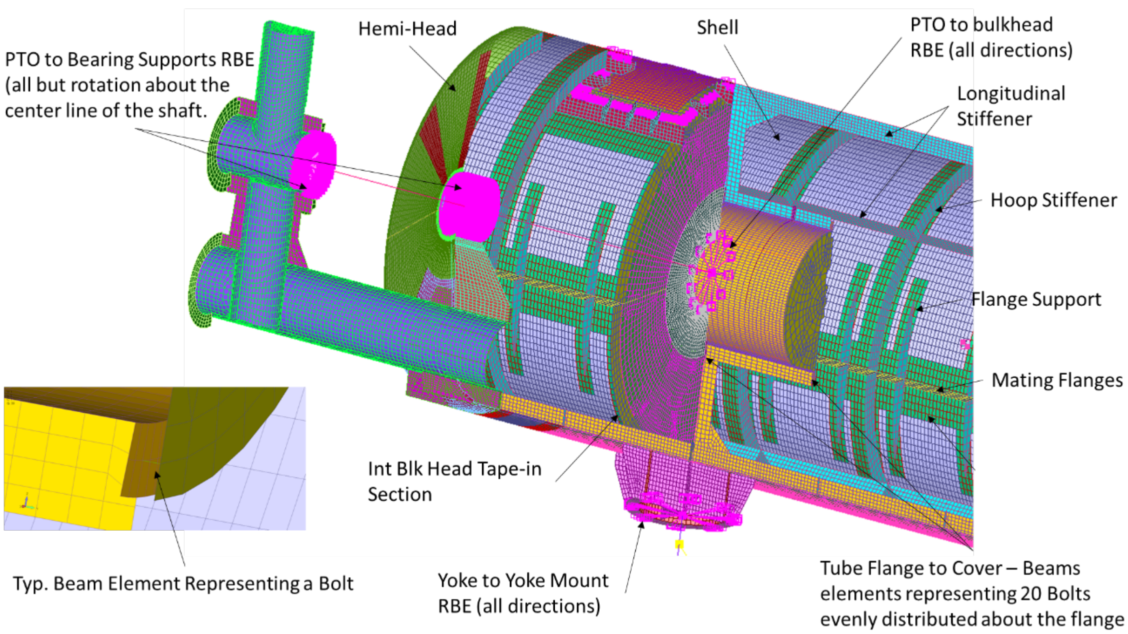


Figure 17 - Composite FEM Continued

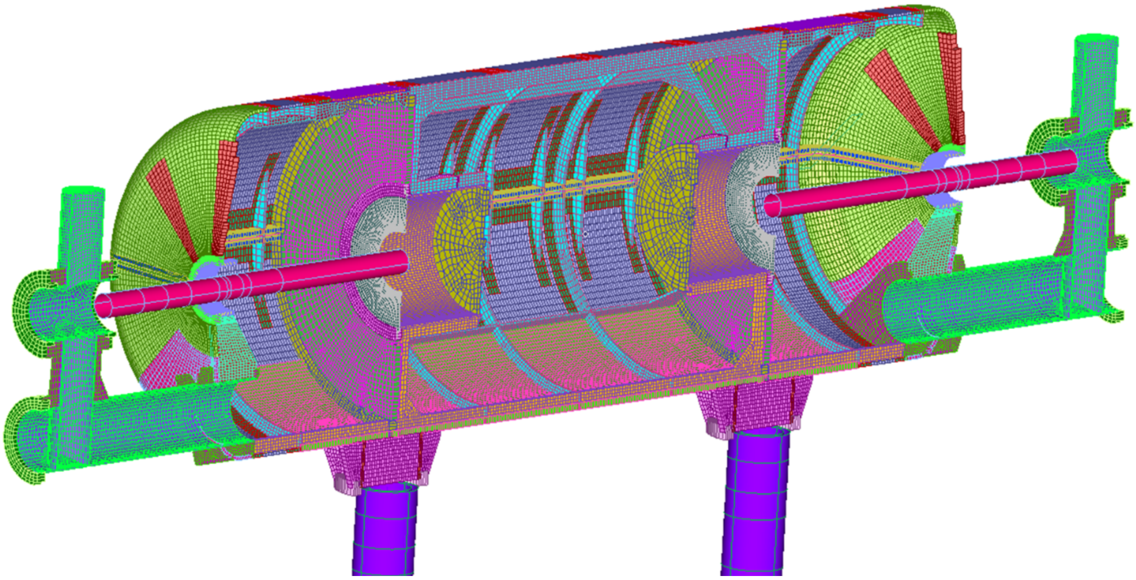


Figure 18 - Composite nacelle Cross-section Showing Plate thickness.

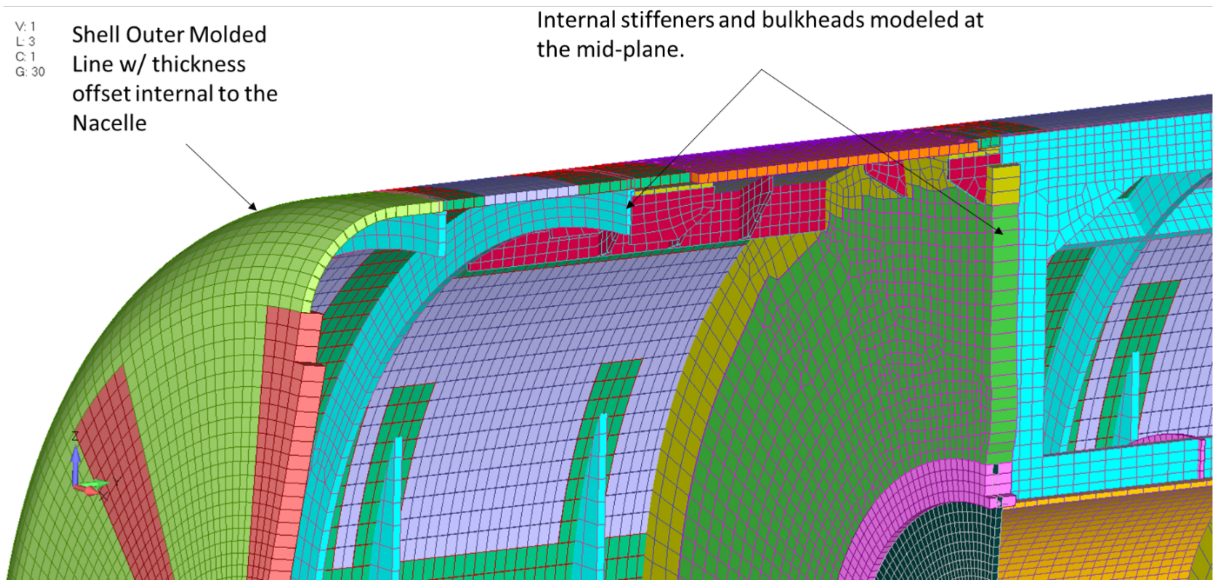


Figure 19 - Composite nacelle Detailed Cross-section Showing Plate thickness.

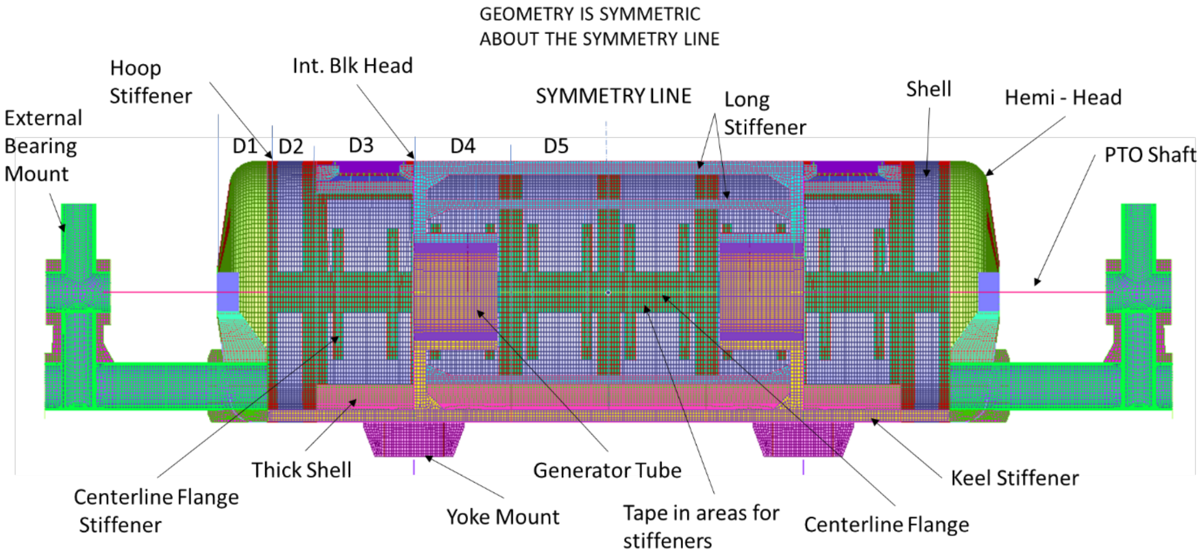


Figure 20 - Composite Cross-Section and Layout

Table 12 - Component Sizes and Overall Weights.

Component Description	units	NS	EHS	Al-5059	Composite
Shell thickness	in	0.25	0.125	0.5	0.698
Bottom shell thickened thickness	in	0.375	0.5	0.625	1.616
Thickened shell length and arc Covered	in, °	34.8, 60°	34.8, 60°	34.8, 60°	34.8, 90°
Hatch Cover	in	0.5	0.125	0.5	0.698
Ext Blk Head Thickness	in	0.25	0.125	0.5	0.786
Ext Blk Head Stiffeners Thickness	in	0.25	0.375	0.375	1.896
Number of Ext Blk Head stiffeners and angle	#, °	8, 45°	8, 45°	8, 45°	8, 45°
Number of Int Blk Heads	#	2	2	2	2
Int Blk Head Thickness	in	0.5	0.125	0.5	2.242
Number of Int Blk Head stiffeners and angle	#, °	8, 45°	8, 45°	8, 45°	8, 45°
Number of Hoop Stiffeners	#	9	9	9	7
Hoop Stiffener Thickness	in	0.25	0.125	0.25	0.646

Hoop Stiffener Height	in	4	4	4	4
Longitudinal Stiffener Thickness	in	0.25	0.125	0.25	0.646
Longitudinal Stiffener Height	in	4	4	4	4
Keel Stiffener Thickness	in	0.5	0.5	0.625	1.066
Keel Stiffener Height	in	4	4	4	4
Ext Bearing Support Tubes	in	0.25	0.125	0.5	0.356
Ext Bearing Support Gussets	in	0.25	0.125	0.5	0.566
Yoke Tube	in	0.35	0.35	0.35	0.495
Yoke Tube Gusset	in	0.5	0.5	0.5	1.614
Tube Bolt Flanges (Standard 250#)	in	1.5	1.5	1.5	3
Gearbox Tube	in	0.25	0.125	0.5	0.5
Gearbox Tube Diameter	in	31.43	31.43	31.43	31.43
Gearbox Tube Cover Plate	in	0.5	0.25	0.5	0.5
Gearbox Tube Length	in	27	27	27	27
PTO Shaft	in	2.95	2.95	2.95	2.95
Distance to 1st Hoop Stiff. D1	in	15.875	15.875	15.875	15.875
Distance to 2nd Hoop Stiff. D2	in	17	17	17	16
Distance to Bulkhead. D3	in	31.375	31.375	31.375	31.375
Distance to 3rd Hoop Stiff. D4	in	20.75	20.75	20.75	31.375
Distance to Center Hoop Stiff. D5	in				31.375
Weight	lbs	12,509	6,166	4,404	6,175

Mesh design, density and quality have been set to have high quality elements throughout the FEM. The mesh is quad dominant with an average element edge length of 1 inch. There are elements that do not meet all the mesh quality (<0.04%) and they are not in areas of high peak stress or gradient and therefore do not affect the analysis results. Representative mesh quality plots for the steel design are shown in Figure 21, Figure 22, and Figure 23.

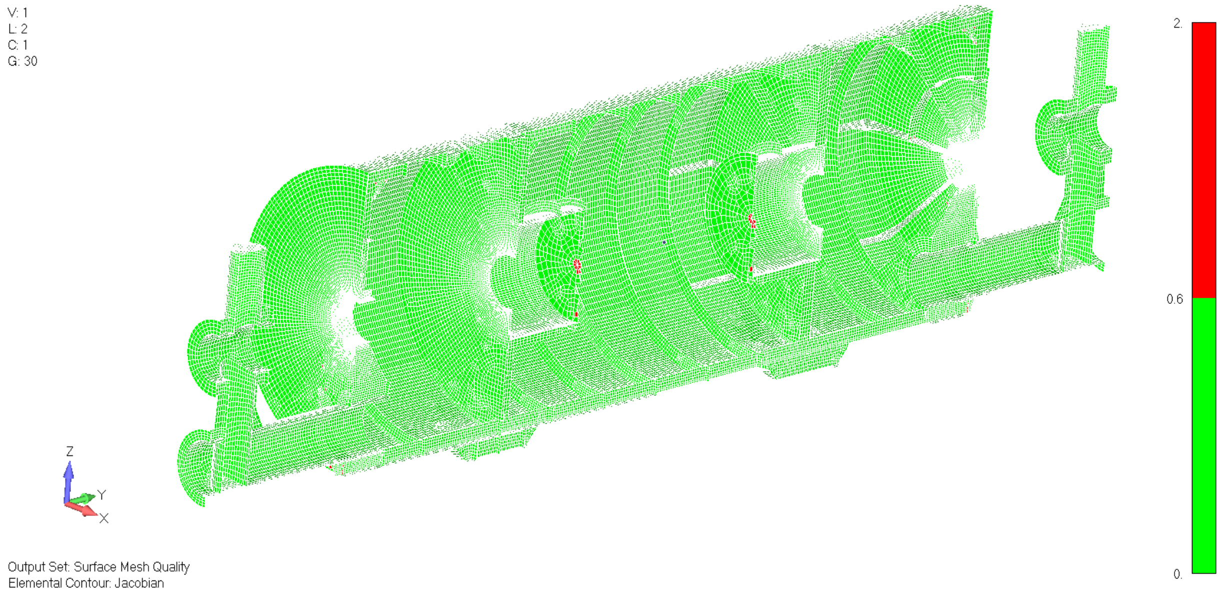


Figure 21 - Metallic FEM Jacobian Quality Check

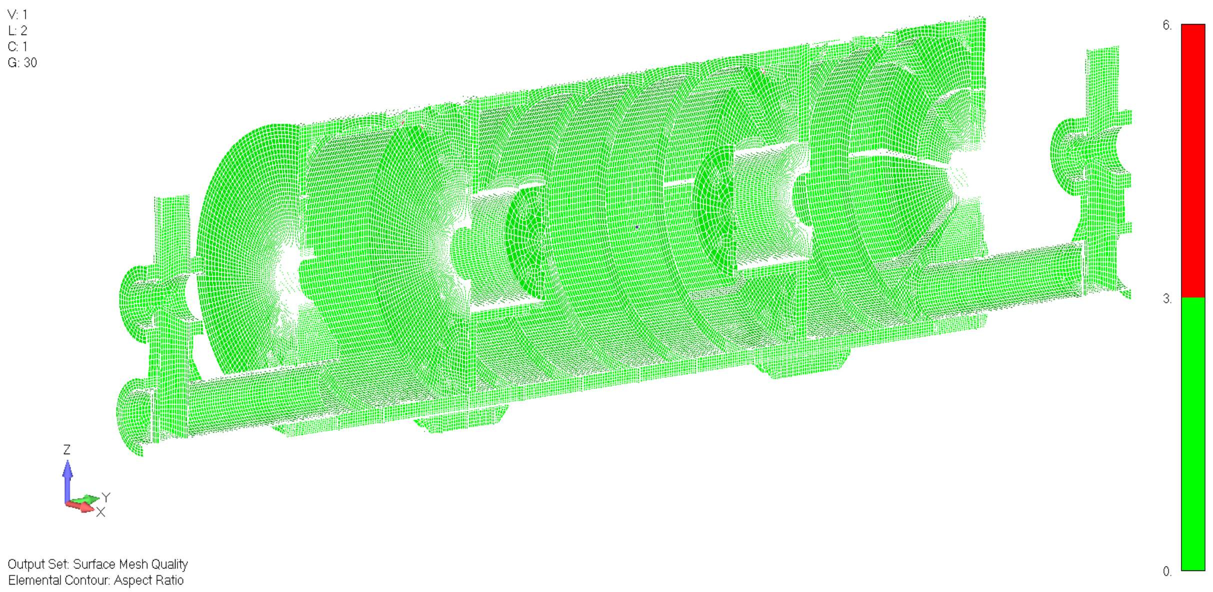


Figure 22 - Metallic FEM Aspect Ratio Quality Check

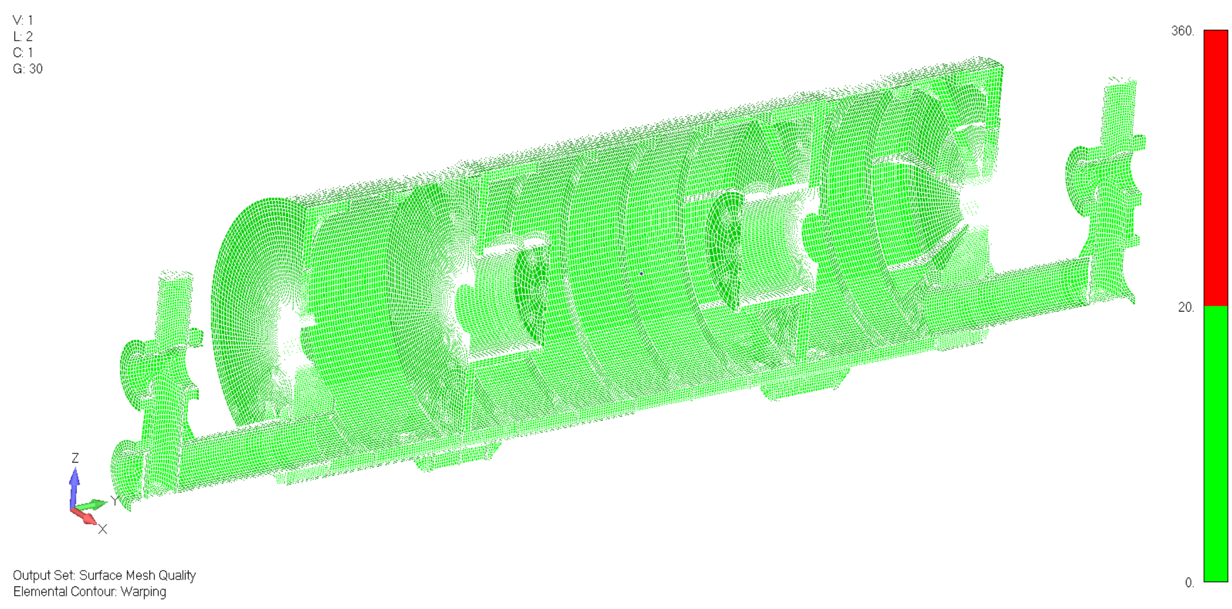


Figure 23 - Metallic FEM Warping Quality Check

7.1.2.5 Boundary Conditions and Loading

For all the operational load cases and linear buckling there are no fixed deflection boundary conditions and inertial relief is used to remove the rigid body movement in the same manner as the beam model. Peak loads from the beam models were used on the plate model as described in the earlier discussion of the loading. For the collapse and progressive ply failure analysis, constraints were placed to keep the system from having rigid body motion while allowing for maximum movement. The constraints are displayed in Figure 24, Figure 25, and Figure 26. Figure 26 is for the PPFA where a half symmetry model was used because the output file size for the full model was unmanageable. Note that the rigid links tying the mass elements to their respective components are not shown to make the illustration as clear as possible.

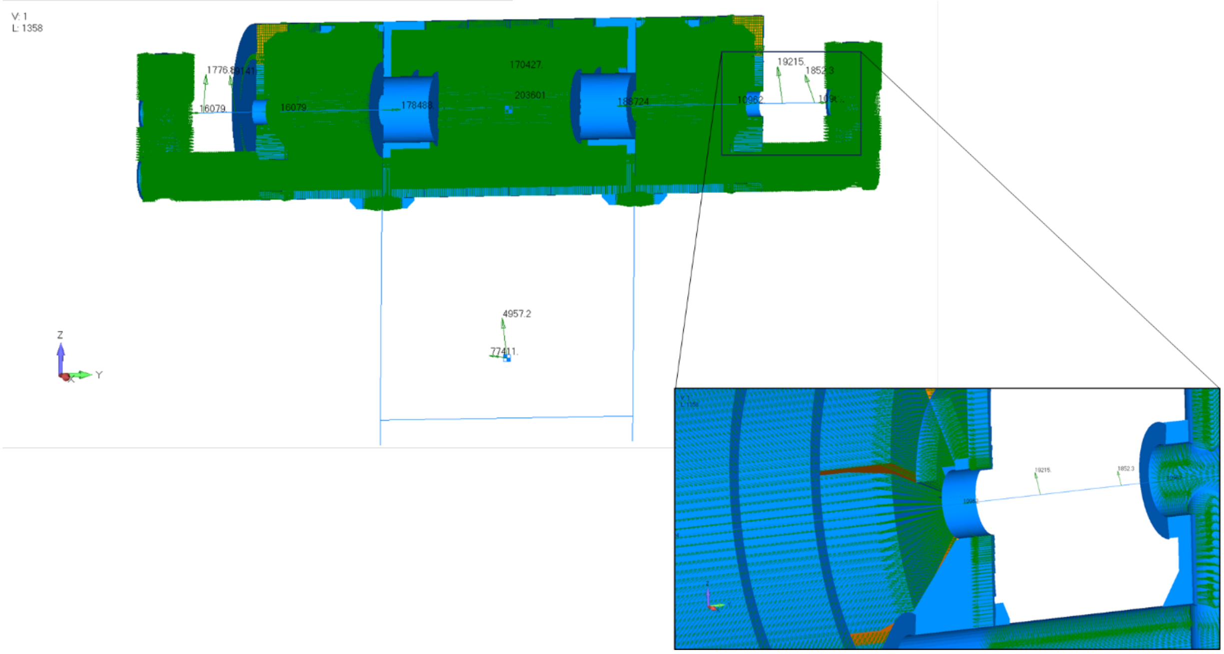


Figure 24 - Boundary Conditions and Loading for Operational Loading and Linear Buckling.

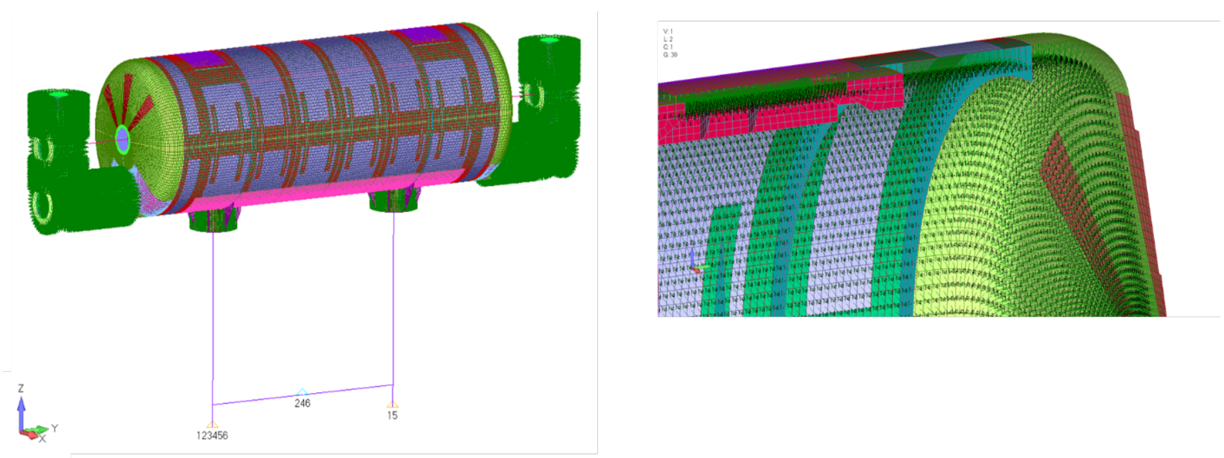


Figure 25 - Boundary Conditions and Pressure Loading for Collapse Analysis.

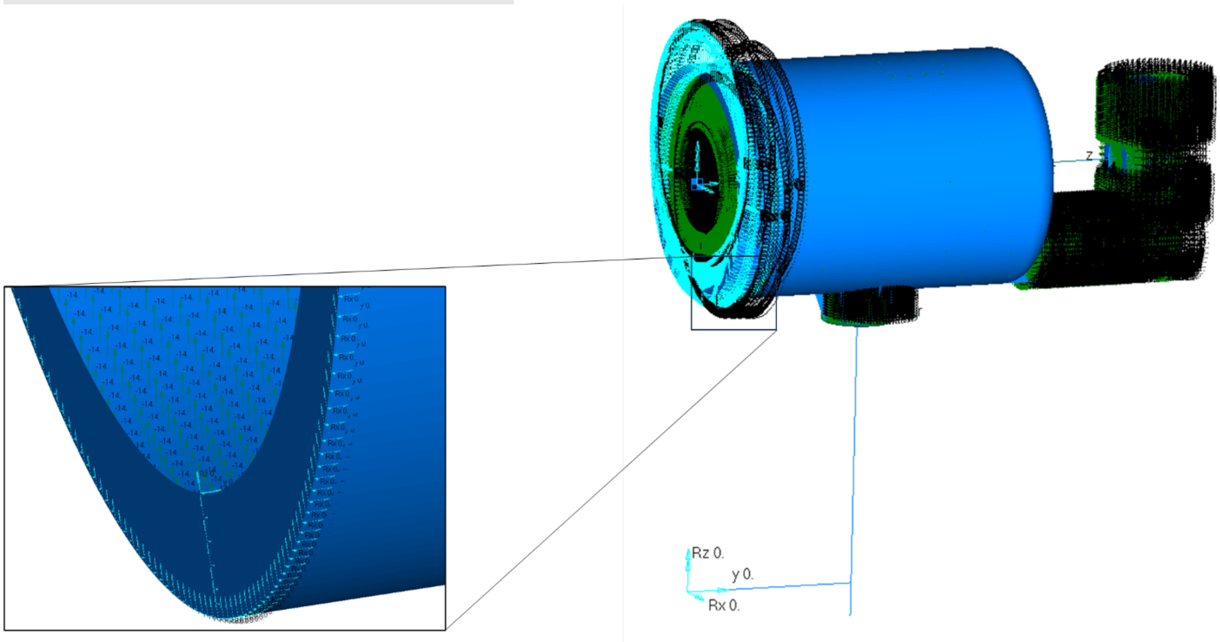


Figure 26 - Boundary Conditions and Pressure Loading for the ½ Symmetry PPFA.

The four material systems were run for operational loading, maximum submergence, and linear buckling. The NS steel design was used for the metallic collapse analysis and the composite design was run through the Progressive Ply Failure Analysis. The following sections illustrate the results of the analysis.

7.1.2.6 Finite Element Model Results

The NS steel design FEA results show that the limiting condition is the maximum external pressure of 14psi. The maximum stress of 30.1ksi, which is less than 37.3ksi, is in the exterior Bulkhead stiffener. This stress can be reduced by putting in a smooth radius or corner gusset to eliminate the sharp corner. The maximum deflection is 0.099 inches at the exterior bearing mount. Deflections were provided, but there is no limit on deflection and the displaced shapes are magnified to make it easier to see movement.

Table 13 summarizes the results from the metallic material system analysis and shows that all the material systems met their limits (Von Mises yield criterion). The metallic results are displayed in Figure 27 through Figure 42. Linear bifurcation buckling, Figure 35, was used as the initial assessment and then the final nonlinear collapse analysis was completed. The linear buckling shows a large margin of safety (6.11), and the nonlinear collapse analysis, Figure 36 and Figure 37, showed the nacelle was not near collapse as the deflection stayed linear as pressure was increased all the way to the 28psi (two times the value of the maximum submergence pressure). The collapse analysis was only done on the NS steel design to provide a baseline for the composite analysis and shows that the DNV closed form solution does produce a sound design. Note the assumption that geometric imperfections are within 10% of the nominal design allows them to be neglected in the collapse analysis per section 6 I408 of the DNV specification.

The rest of the metallic designs were assessed with the same loading cases and the maximum external pressure case proved to be the limiting case overall. Therefore, the maximum external pressure stresses and deflections for the designs are illustrated in Figure 38 through Figure 42.

Note that peak stresses at the intersection of beams and plates or rigid connections were not reported. This is due to the artificially high stress created by a point load.

Table 13 - Metallic Maximum Stress Summary

Load Case	Units	Max Von Mises Stress			
		NS Steel	EHS	AL-5059 non-Welded	AL-5059 Welded
TP 509 Max	psi	19,048	29,978	17,794	8,033
TP 1358	psi	25,483	28,008	21,239	11,818
TP 4055	psi	30,173	41,134	17,266	14,376
Max Pressure	psi	29,433	44,638	26,449	11,900
Material Limit	psi	37,311	57,805	27,221	16,291
Min MS		1.24	1.29	1.03	1.13
Linear Buckling Factor		6.11	1.71	3.4	-

The composite system results are summarized in Table 14 and plots illustrating the limiting stresses and Tsai-Wu Criterion are found in Figure 44 through Figure 83. The main failure criterion used for the composite structure is Tsai-Wu with the interaction factor set to -.5. Failure is noted when it exceeds 1. Materials that yield have a γ_{rd} = 1.0 compared to the characteristic yield strength of the material and must use the Von Mises yield criterion. Delamination happens after matrix cracking, so the conservative approach used is crack initiation. Matrix cracking is caused by shear traverse to the fibers and will be assessed using the shear12 limit to handle both delamination and leaking. Core wrinkling and shear crimping are handled by Equation 1 – 3 and the most limiting of the three results is output as core stability. Linear buckling analysis, Figure 84, shows a 3.39 margin to the maximum pressure load. The nonlinear progressive ply failure analysis, Figure 85, was completed and showed the structure maintains load carrying capability out to 1.0 times the maximum load which is much lower than the linear buckling load prediction. 1X the max load is the .5 load mark and after this point the maximum deflection becomes nonlinear, showing the loss of load carrying capability. Note that the assumption that geometric imperfections are within 10% of the nominal design allows them to be neglected in the PPFA per section 6 - I408 of the DNV specification.

One instance where the composite system didn't meet the material limits is at the adhesive shear stress at TP 4055. To remedy the adhesive short fall, an outer skin with the equivalent ply schedule as the shell skin is added. It covers the seam all around and on the inside of the flange a set of plies are clamping the top and bottom flanges together. This is a double strap joint and can be seen in the attached drawing (view 2-5G) for the composite geometry.

Table 14 - Composite Stress and Limit Summary

Load Case	Composite Stress Results															
	Max Tsai-Wu Failure Index	Min Tsai-Wu Failure Index	Bond Failure Index	Core Stability*	Max Normal Stess 1	Max Normal Stess 2	Max Shear Stess 12	Max Shear Stess 13	Max Shear Stess 23	Min Normal 1 Stress	Min Normal 2 Stress	Min Shear 12 Stress	Min Shear Stess 13	Min Shear Stess 23	Adheasive Tensile	Adheasive Compress	Adheasive shear
TP 509	0.39	0.08	0.31	0.35	5,463	3,244	2,371	425	780	8,556	3,212	2,371	2,521	768	3,667	6,270	2,072
TP 1358	0.81	0.16	0.918	0.56	12,926	9,520	2,238	1,514	2,308	13,061	9,519	3,206	655	2,172	4,299	6,432	2,953
TP 4055	0.74	0.11	0.51	0.31	10,687	7,804	2,889	802	1,286	1,807	4,082	2,901	615	1,141	11,735	2,922	3,367
Max Pressure overall	0.755	0.14	0.16	0.45	8,496	6,245	2,935	407	394	10,502	4,908	2,964	336	394	1,320	1,231	678
Max Pressure On Center Cylinder	0.977	0.35	0.284	0.25	8,079	3,379	2,863	138	714	15,404	6,939	2,864	234	712	5,512	5,512	277
Material Limit	1	1	1	1	90,871	9,631	3,356	4,641	3,395	56,876	9,631	3,356	4,641	3,395	7,500	11,500	4,000
Min MS	1.02	2.86	1.09	1.79	7.03	1.01	1.14	3.07	1.47	3.69	1.01	1.05	1.84	1.56	0.64	1.79	1.19

*Note: the Core Stability is the maximum of the wrinkling or crimpling and excluding the areas near bolts or Rigid Link attachment points

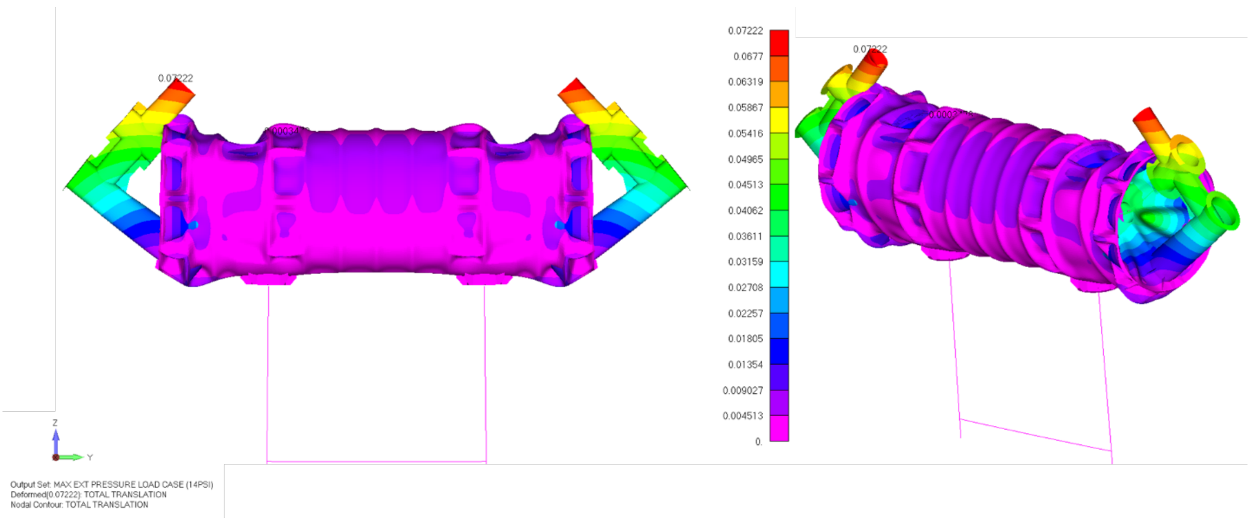


Figure 27 - NS Design Deflection - Maximum External Pressure.

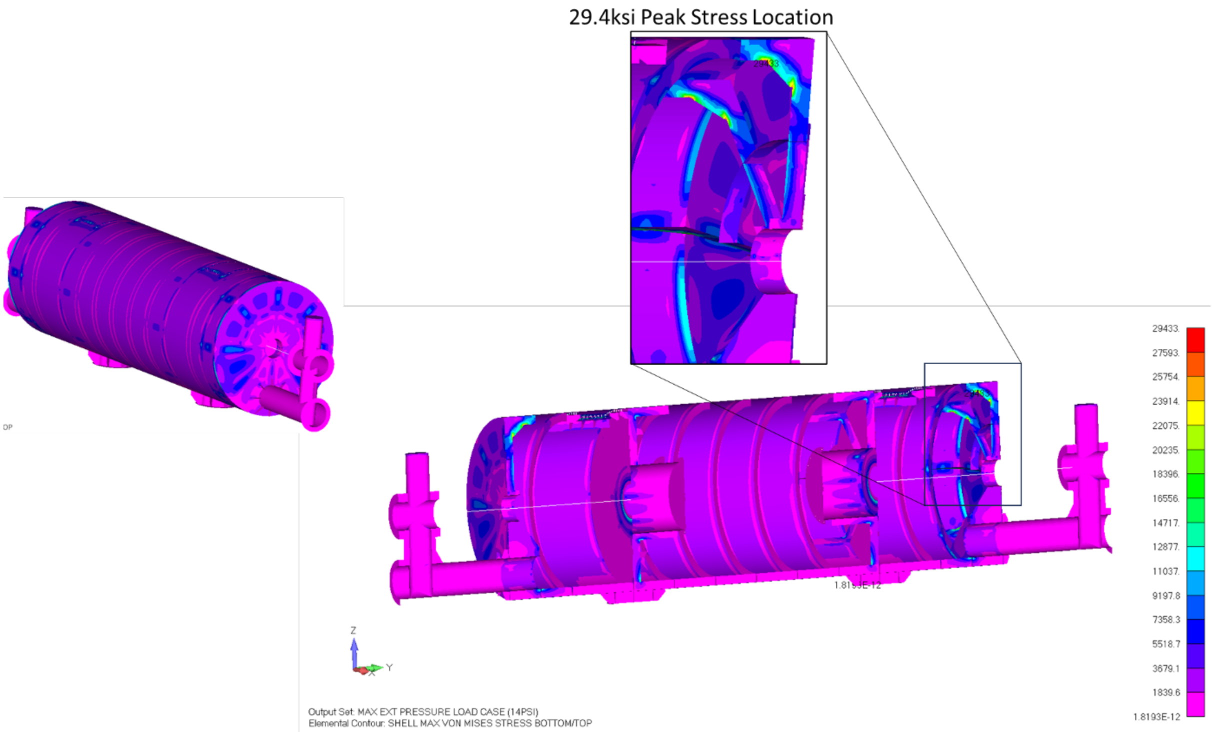


Figure 28 - NS Design Von Mises Stress - Maximum External Pressure.

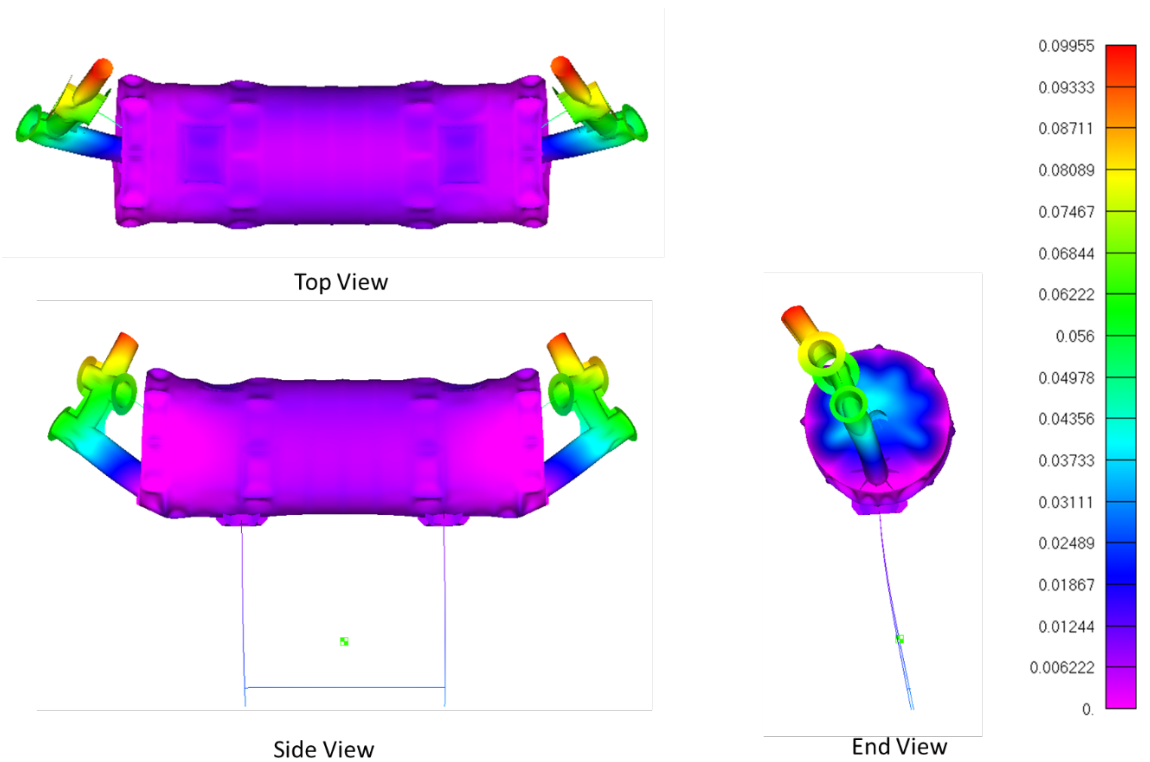


Figure 29 - NS Design Deflection -Time Point 509

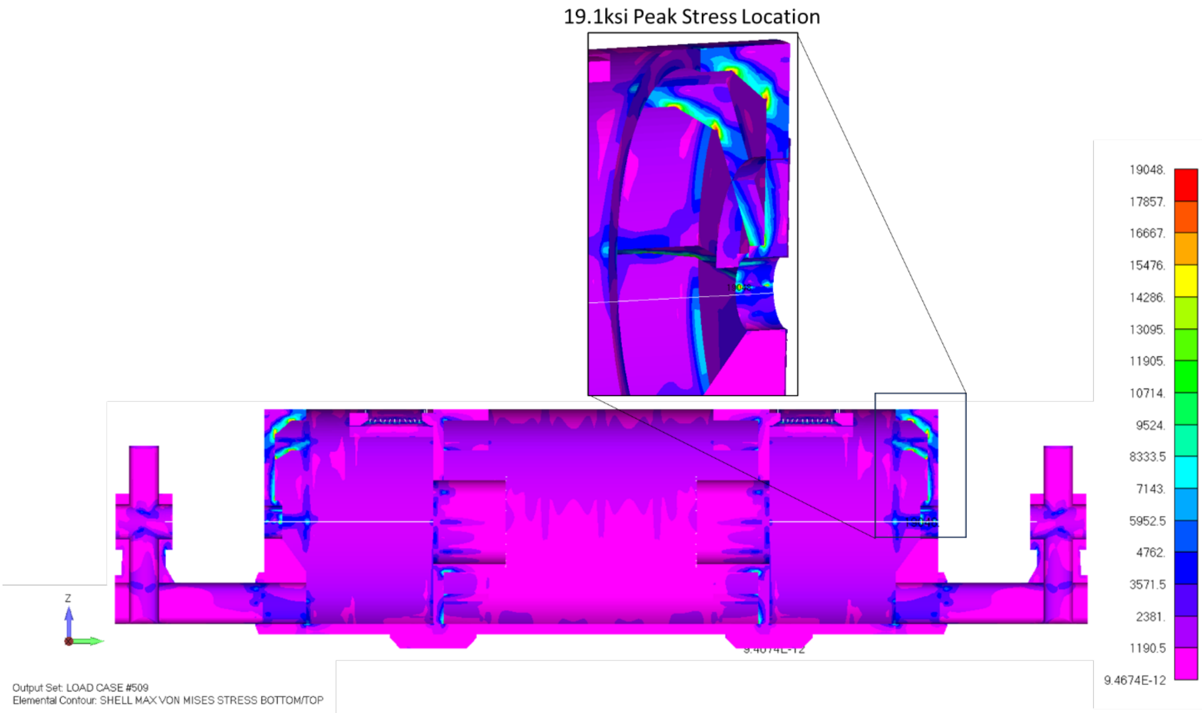


Figure 30- NS Design Von Mises Stress – Time Point 509

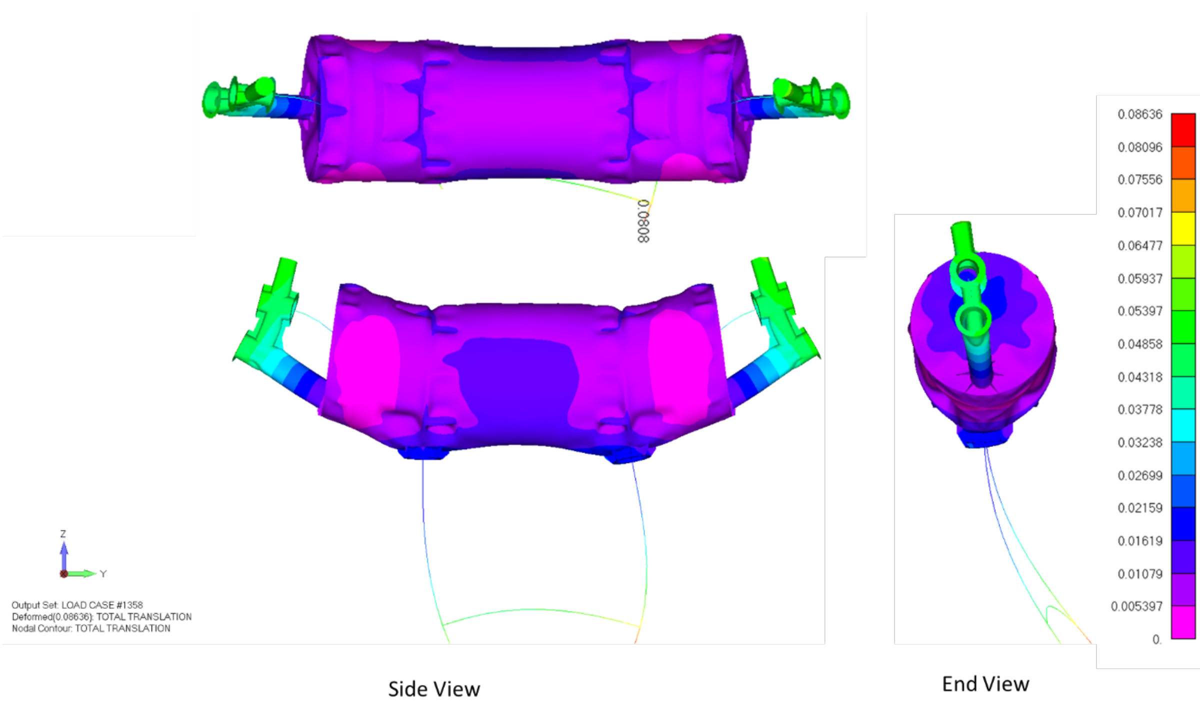
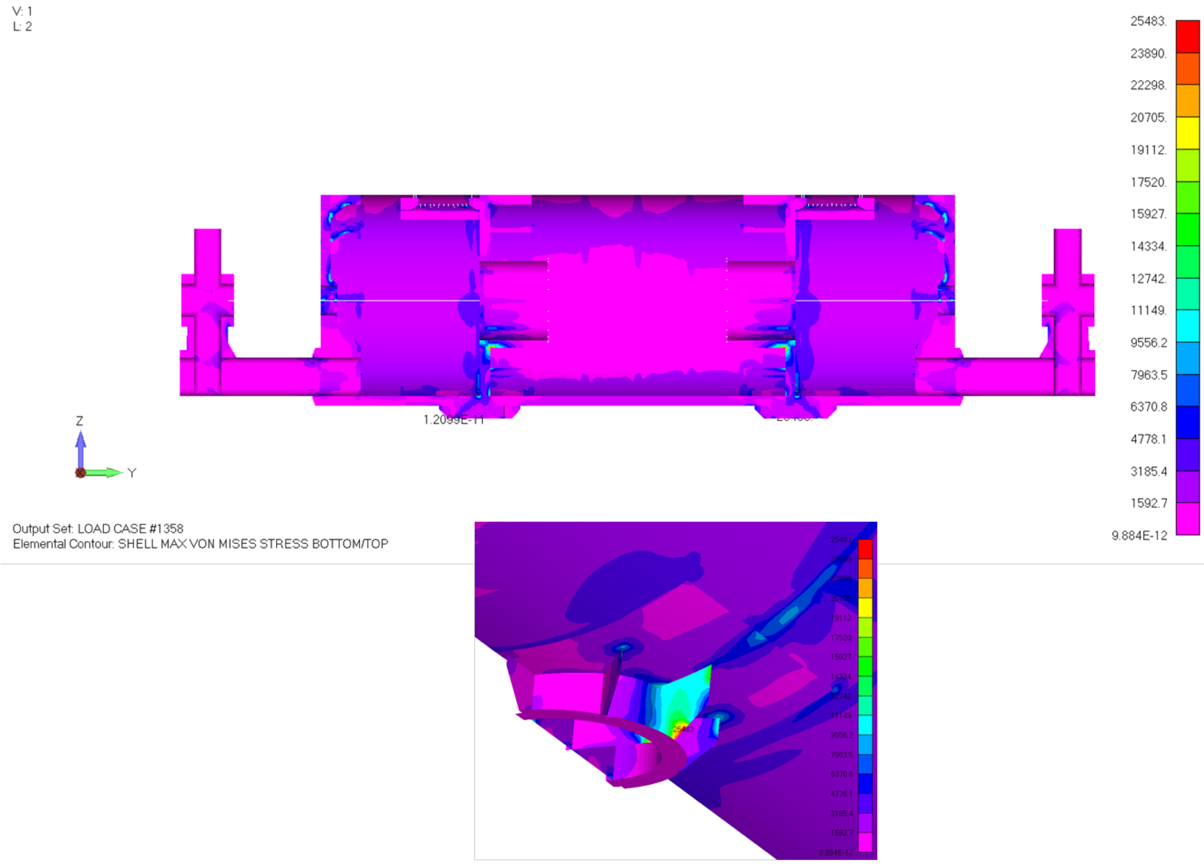


Figure 31 - NS Design Deflection -Time Point 1358



25.5ksi Peak Stress Location

Figure 32 - NS Design Von Mises Stress - Time Point 1358.

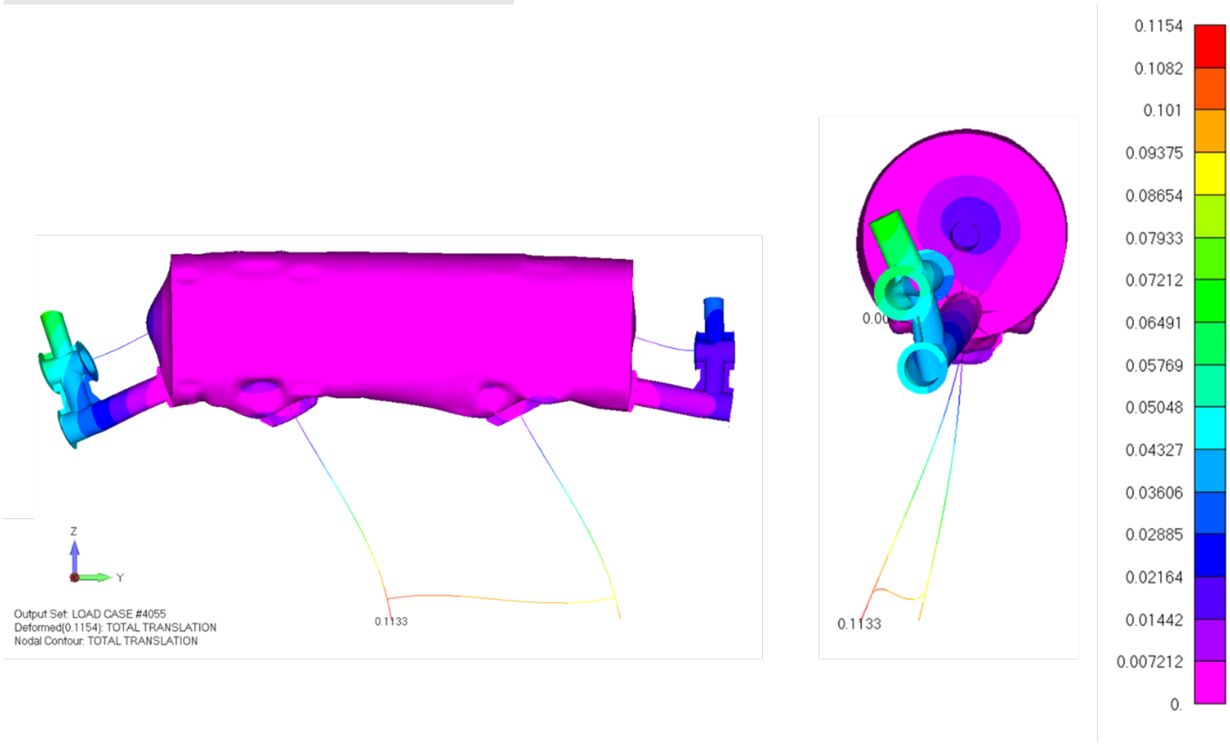


Figure 33 - NS Design Deflection -Time Point 4055

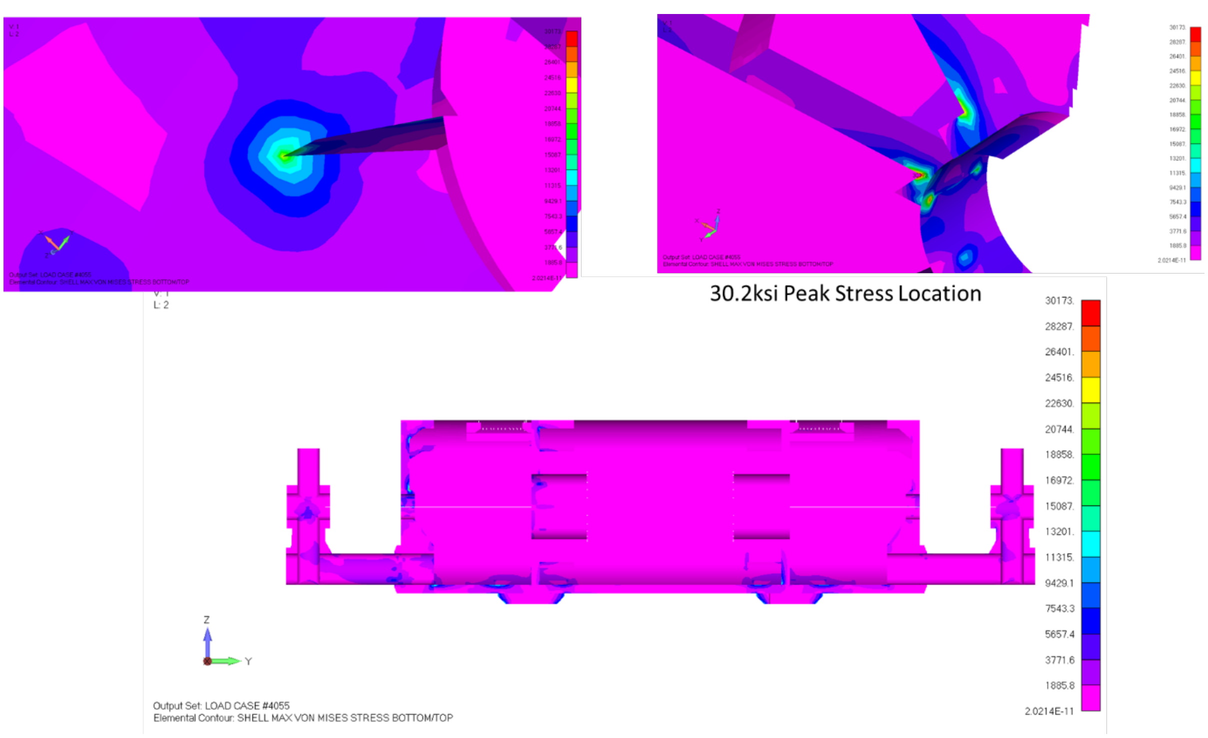


Figure 34 - NS Design Von Mises Stress -Time Point 4055

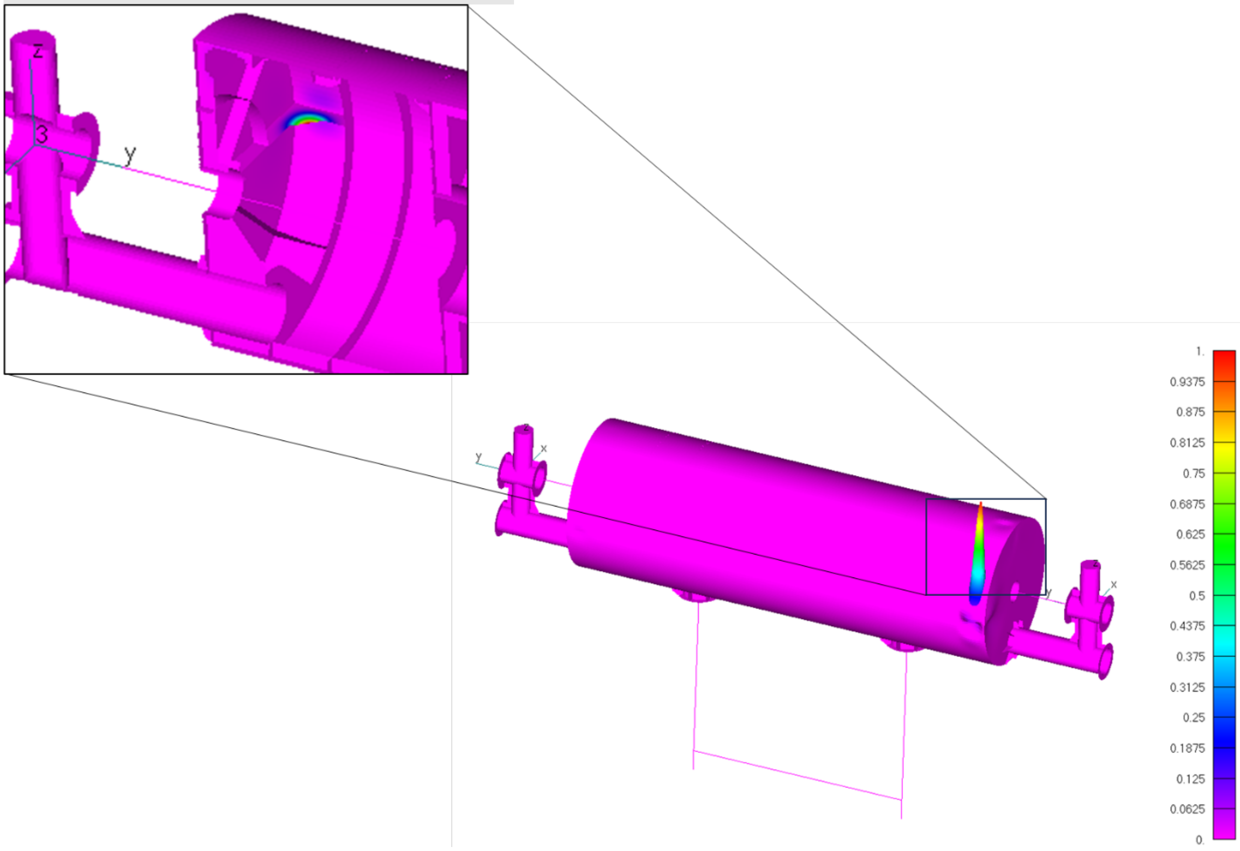


Figure 35 – NS Steel 1st Linear Buckling Mode.

NS NL BUCKLING/ COLAPSE Elastic Materials–

LOAD FACTOR OF 1 = 2X MAX PRESSURE

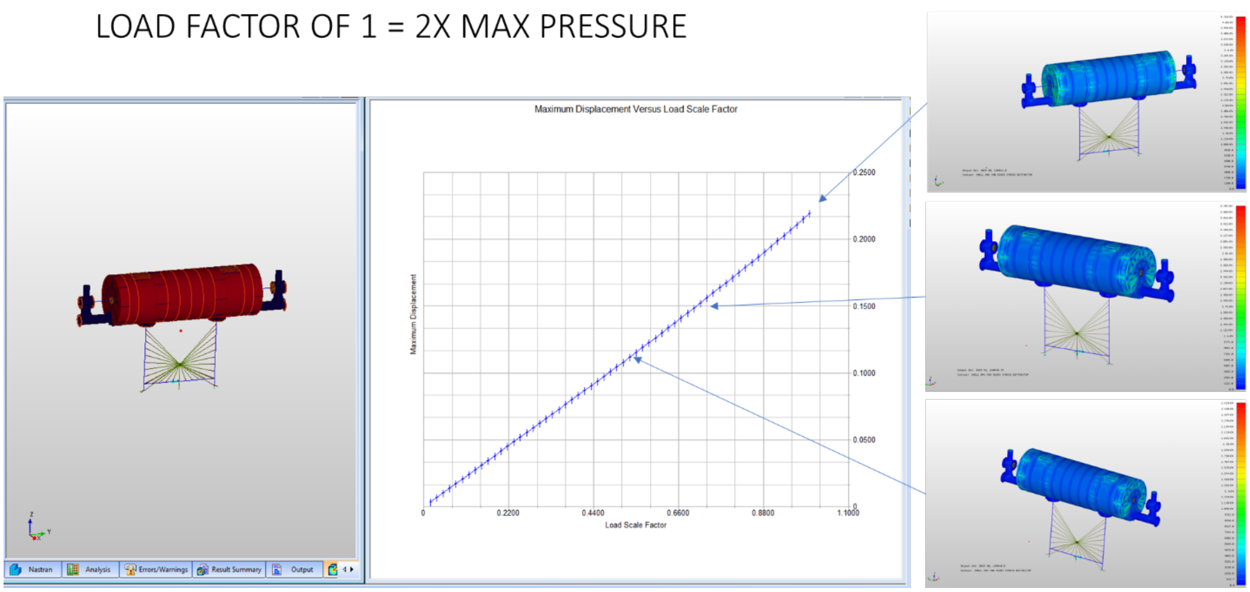


Figure 36 - NS Collapse Analysis with Elastic Materials.

NS NL BUCKLING/ COLAPSE Elastic-Plastic Materials– LOAD FACTOR OF 1 = 2X MAX PRESSURE

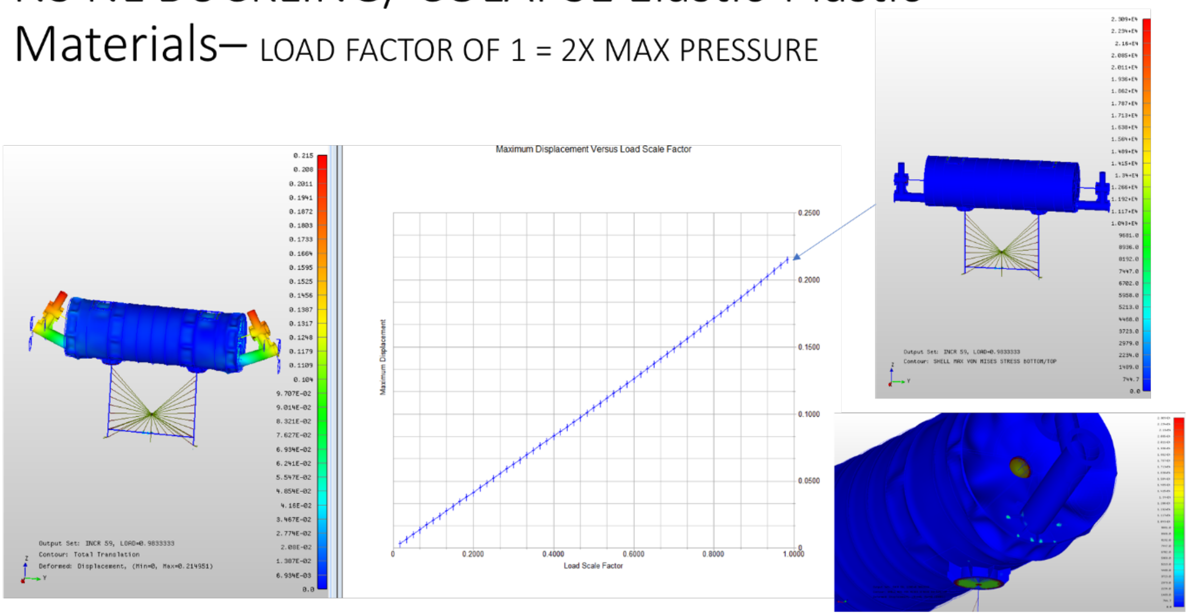


Figure 37 - NS Collapse Analysis with Elastic-Plastic Materials

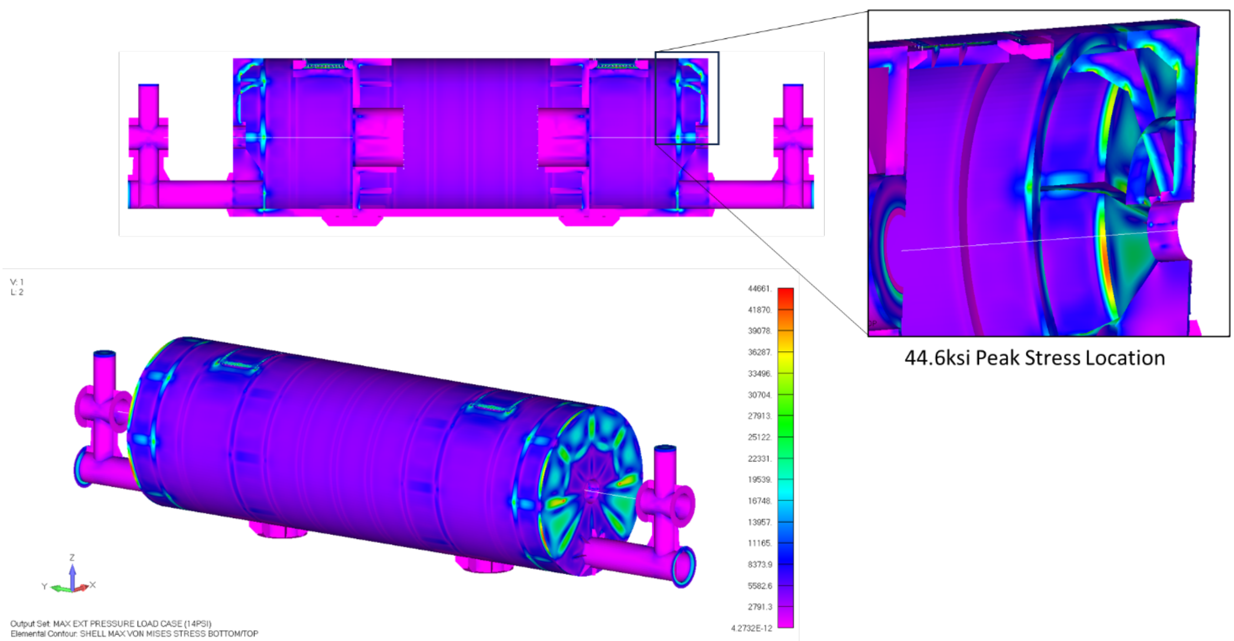


Figure 38 - EHS Maximum External Pressure Von Mises Stresses

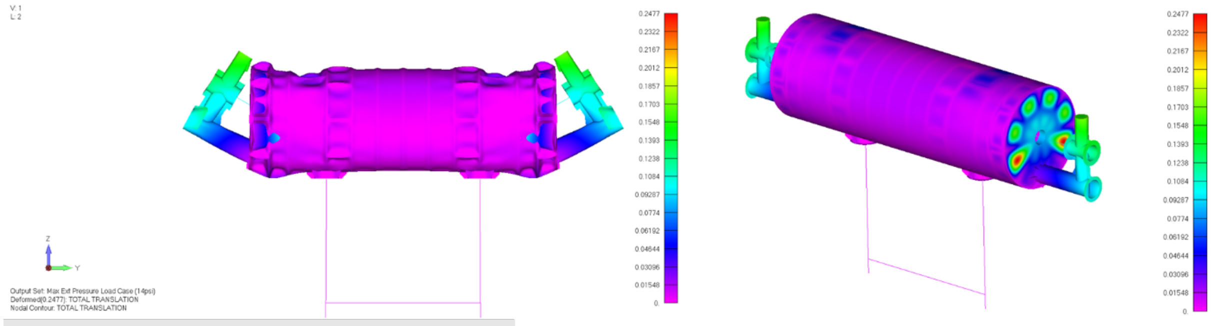


Figure 39 - EHS Maximum External Pressure Total Deflection

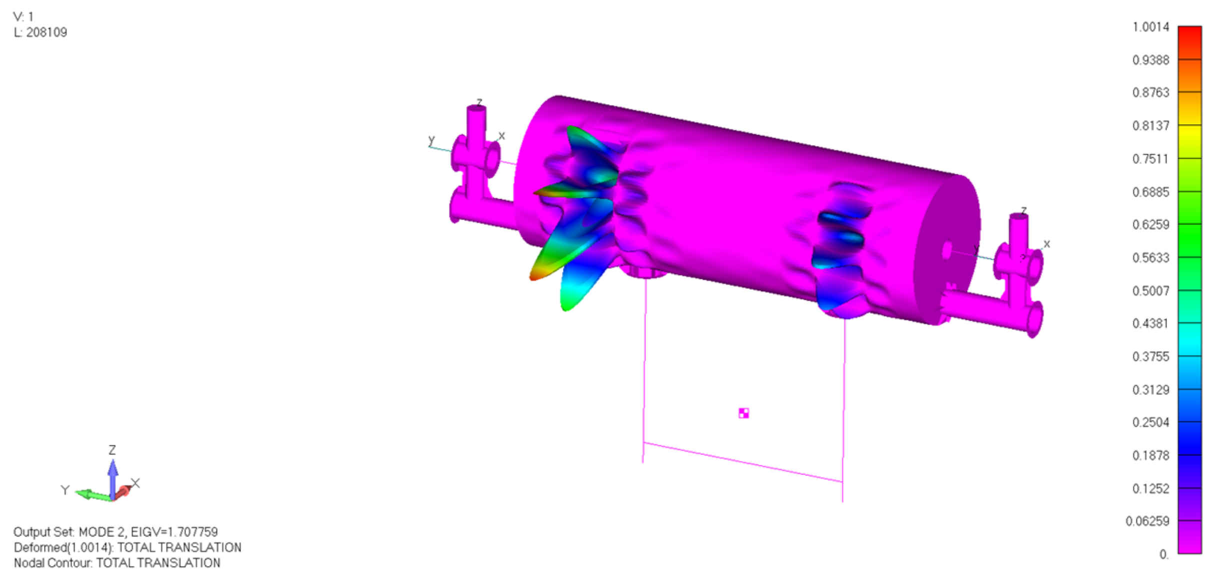


Figure 40 - EHS Max Pressure Linear Buckling

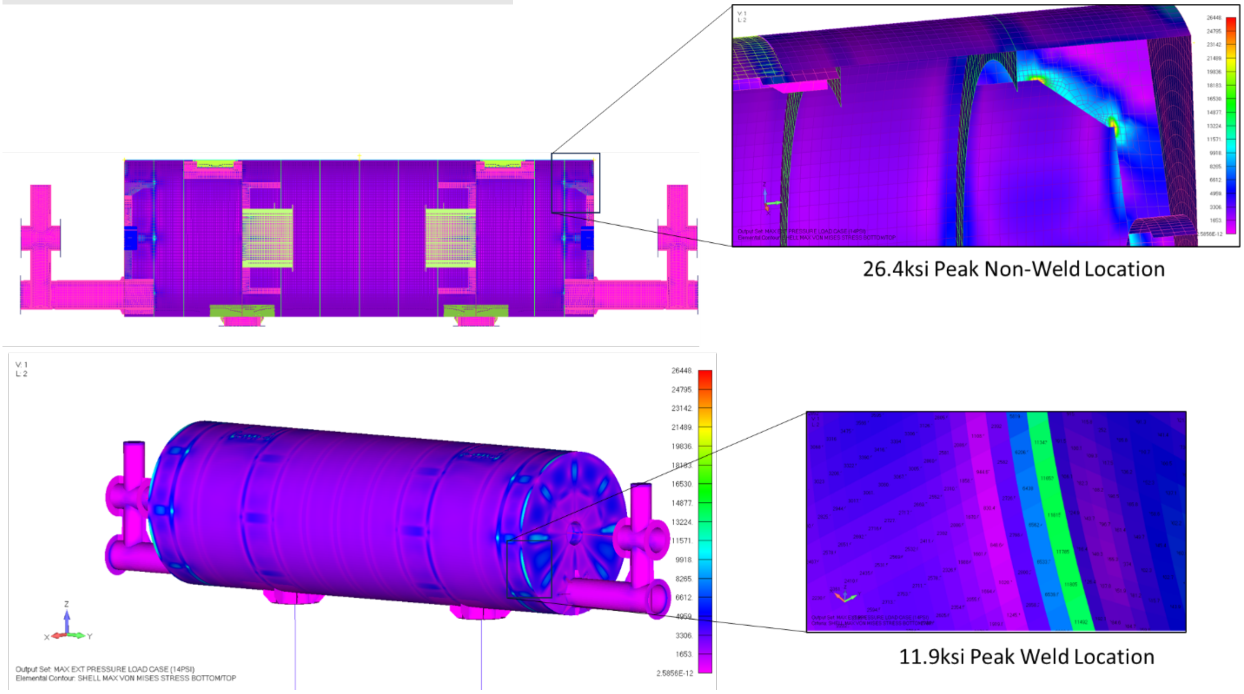


Figure 41 - AL5059 Maximum External Pressure Von Mises Stresses

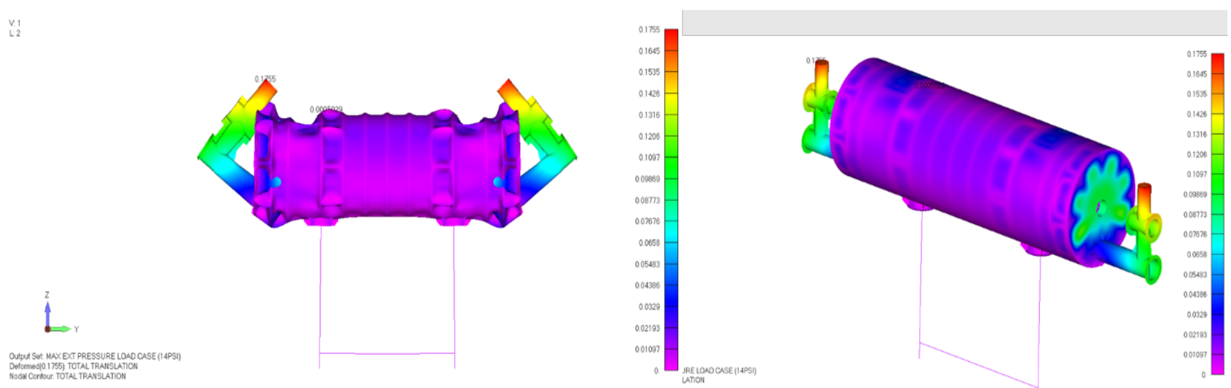


Figure 42 - AL5059 Maximum External Pressure Total Deflection

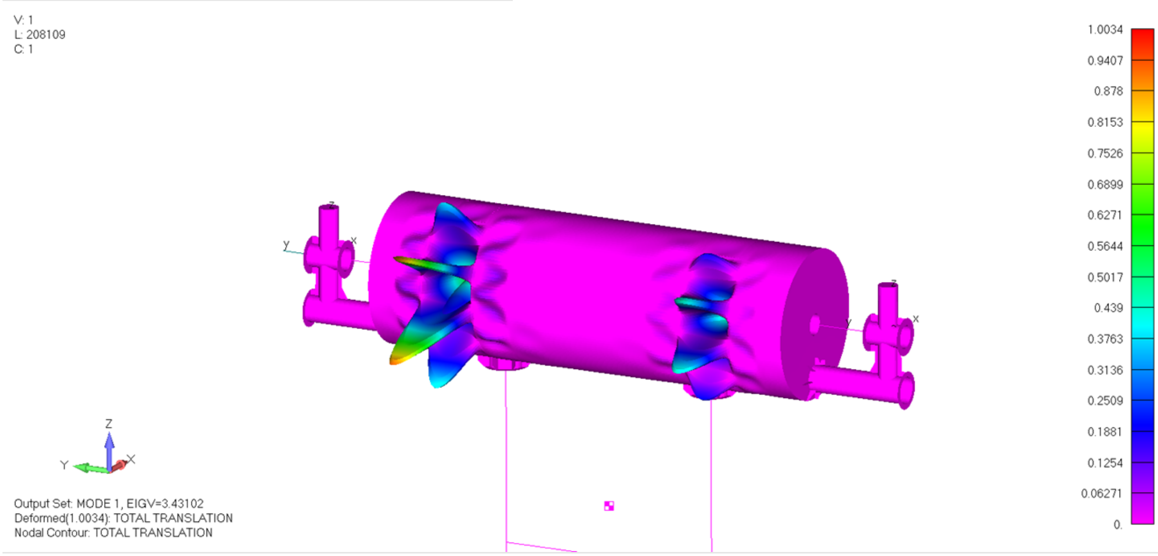


Figure 43 - AL-5059 Maximum Pressure Linear Buckling

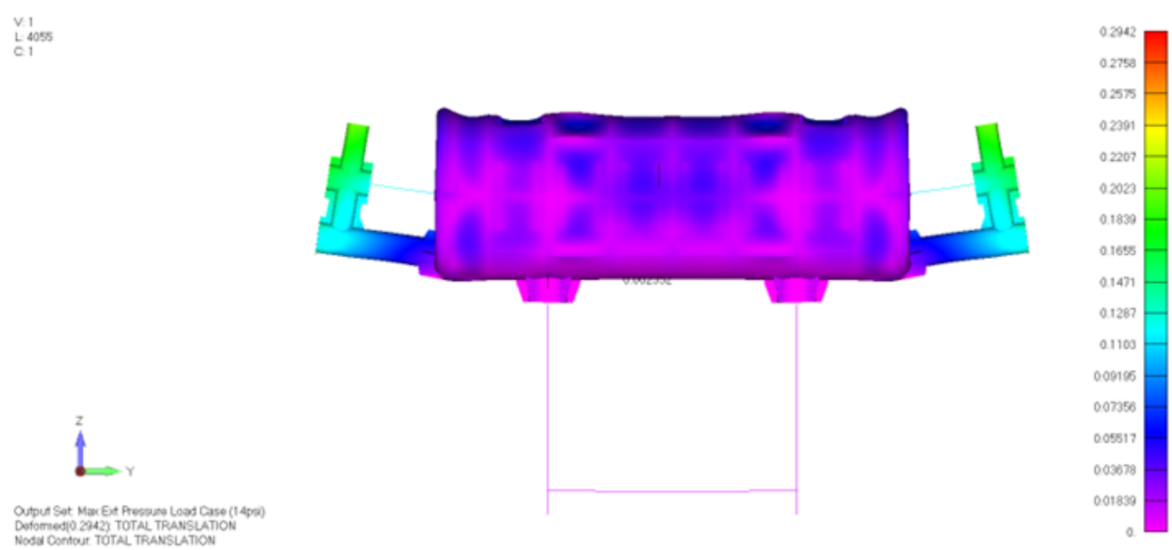


Figure 44 - Composite Maximum External Pressure Total Deflection

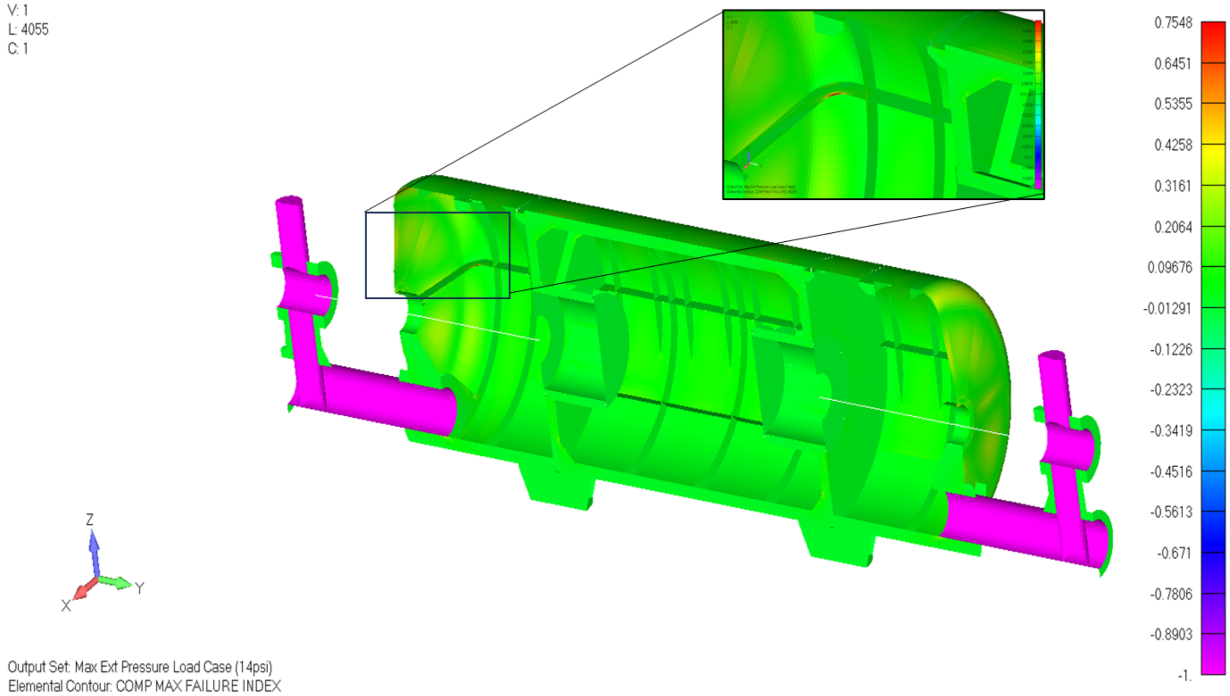


Figure 45 - Composite Maximum External Pressure Max Failure Index

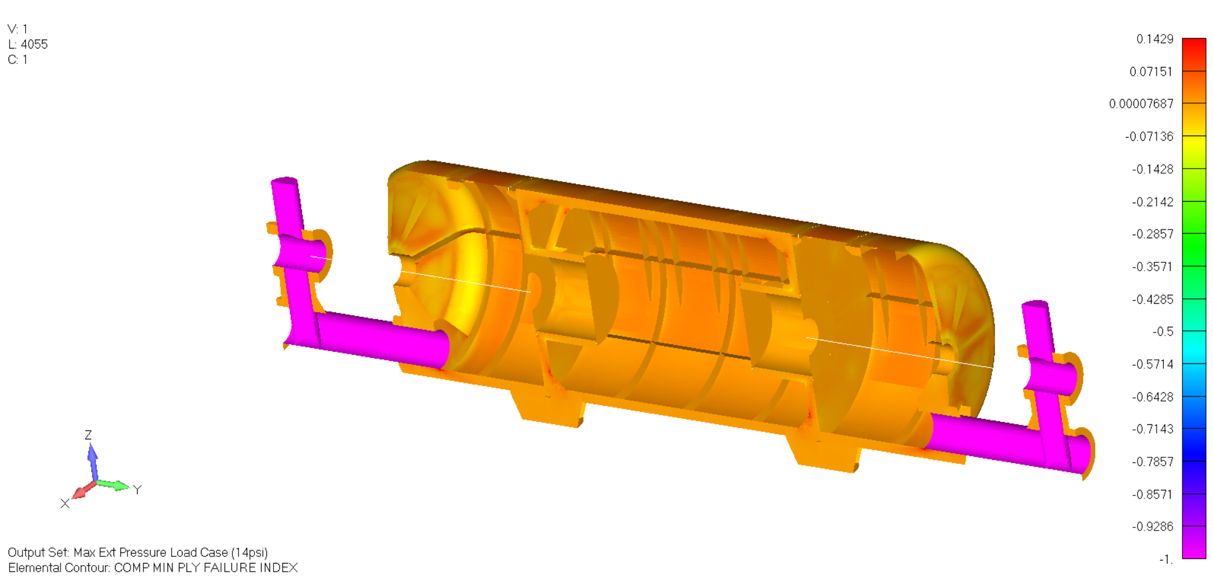


Figure 46 - Composite Maximum External Pressure Min Failure Index

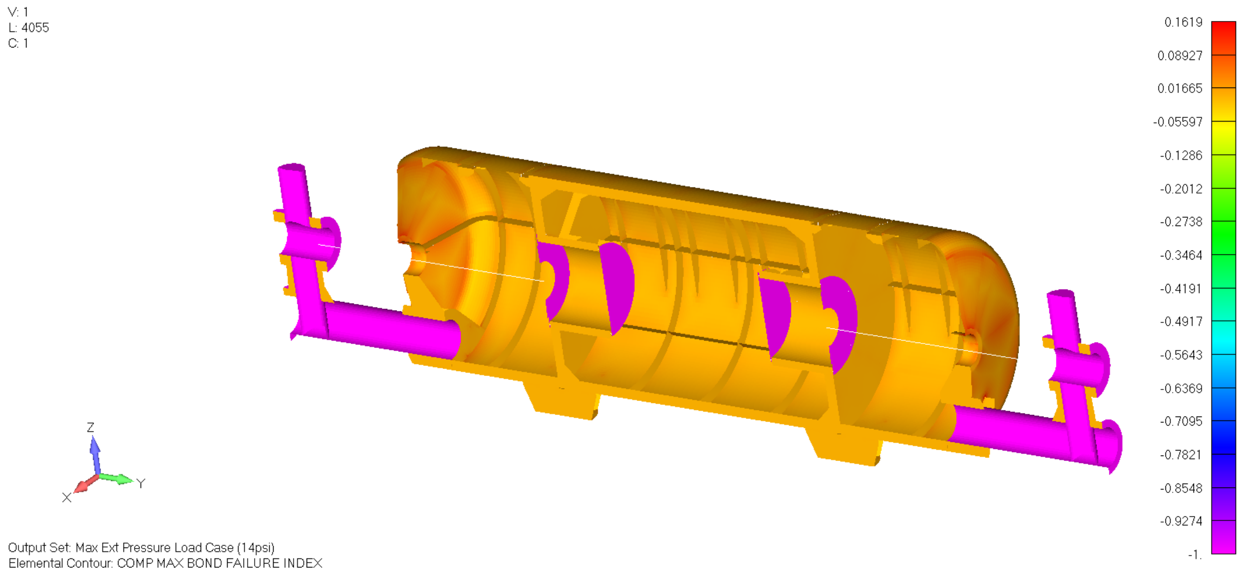


Figure 47 - Composite Maximum External Pressure Max Bond Failure Index

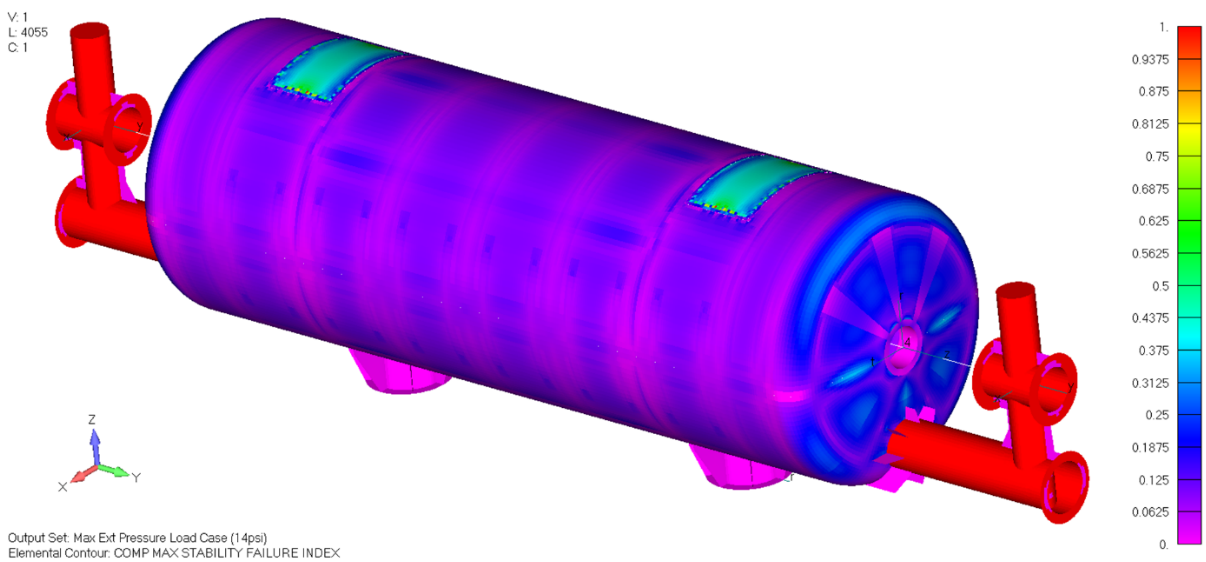


Figure 48 - Composite Nacelle Core Stability - Maximum Press Case

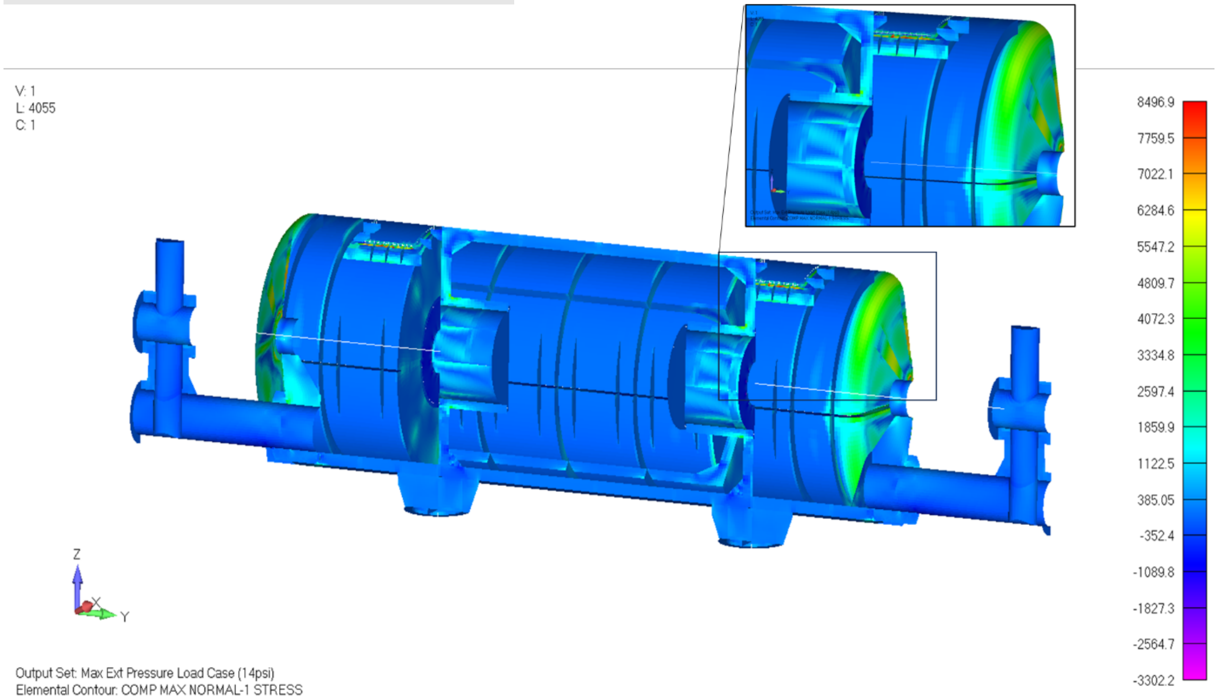


Figure 49 - Composite Nacelle Max Normal Stress 1 - Maximum Press Case

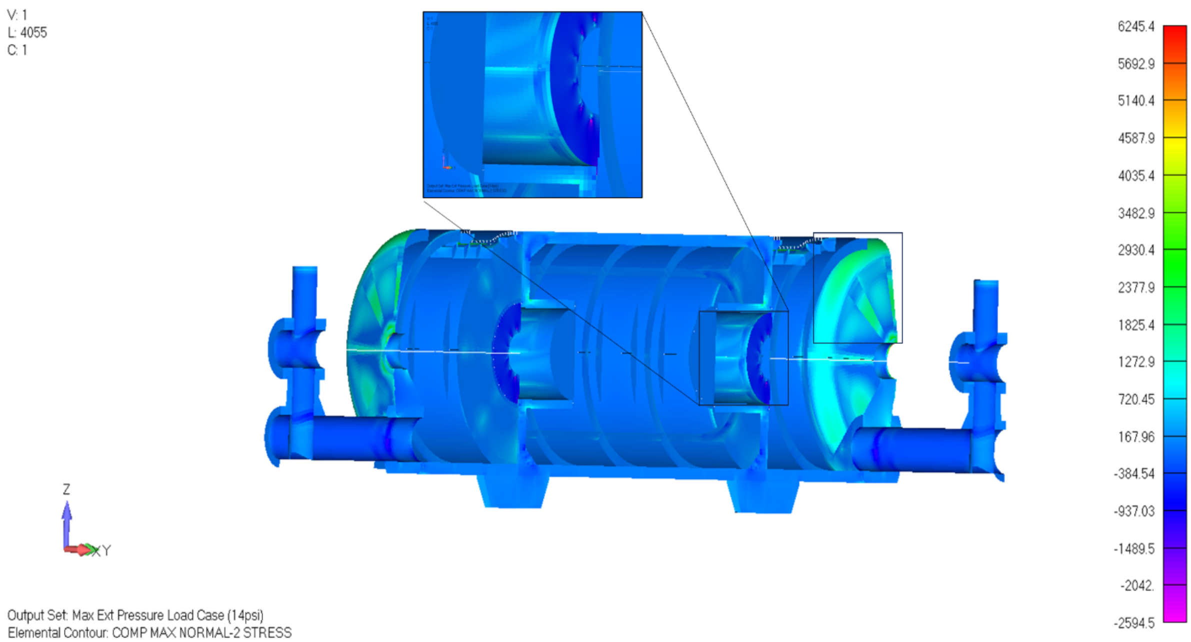


Figure 50 - Composite Nacelle Max Normal Stress 2 - Maximum Press Case

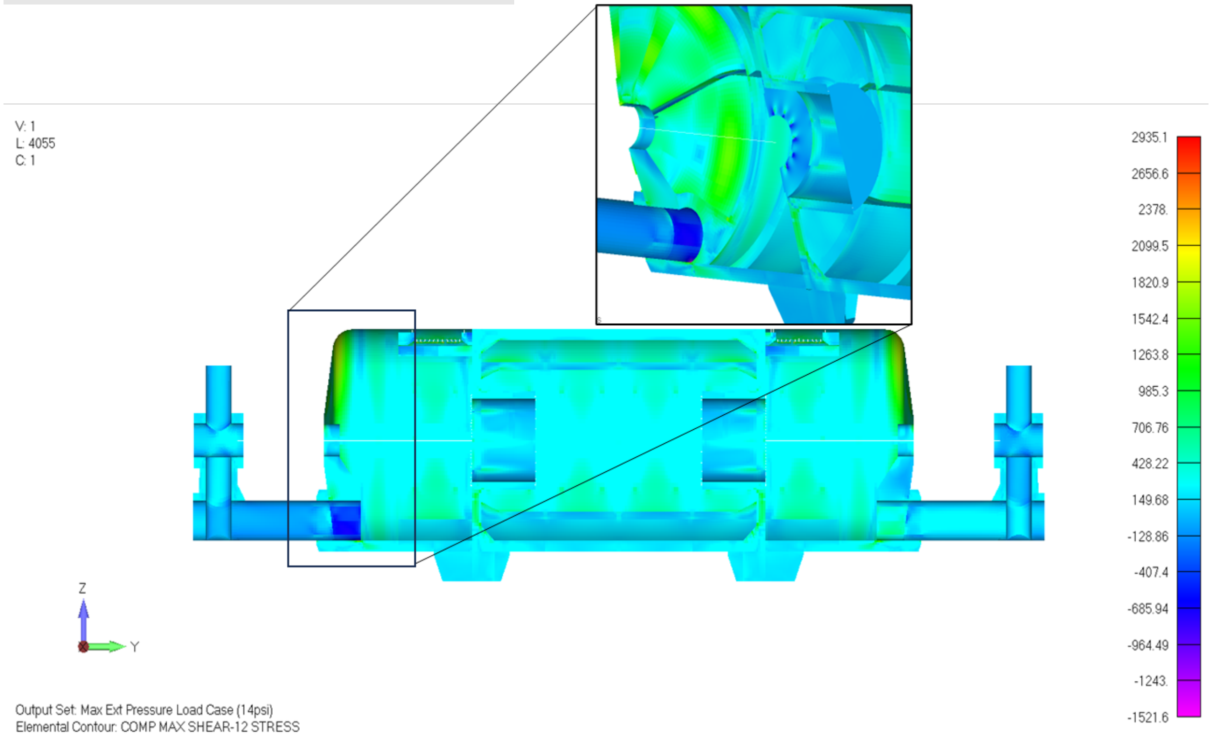


Figure 51 - Composite Nacelle Max Normal Shear Stress 12 - Maximum Press Case

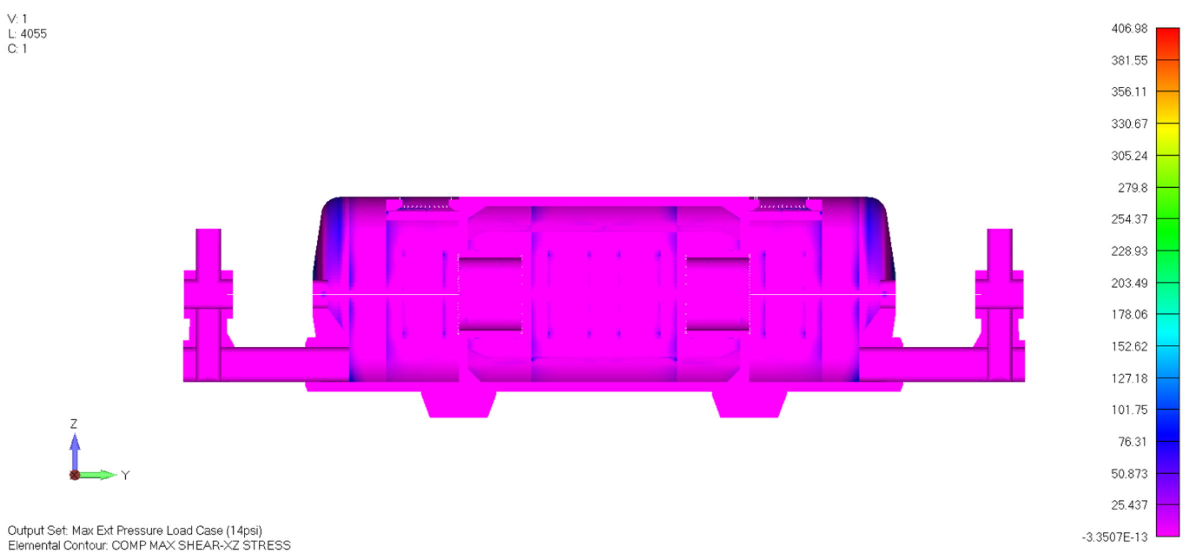


Figure 52 - Composite Nacelle Max Normal Shear Stress 13 - Maximum Press Case

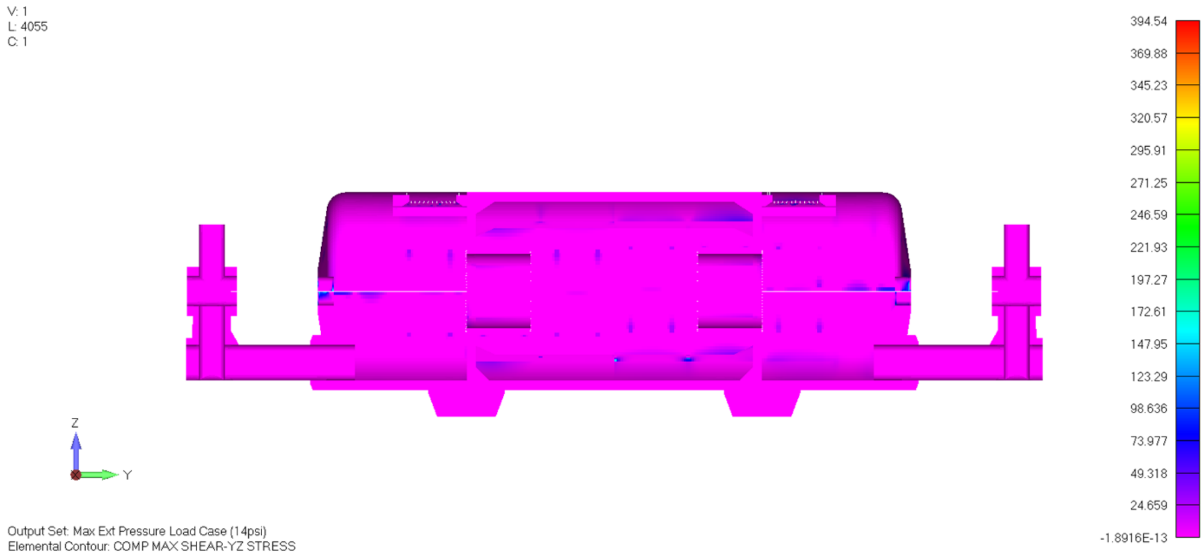


Figure 53 - Composite Nacelle Max Normal Shear Stress 23 - Maximum Press Case

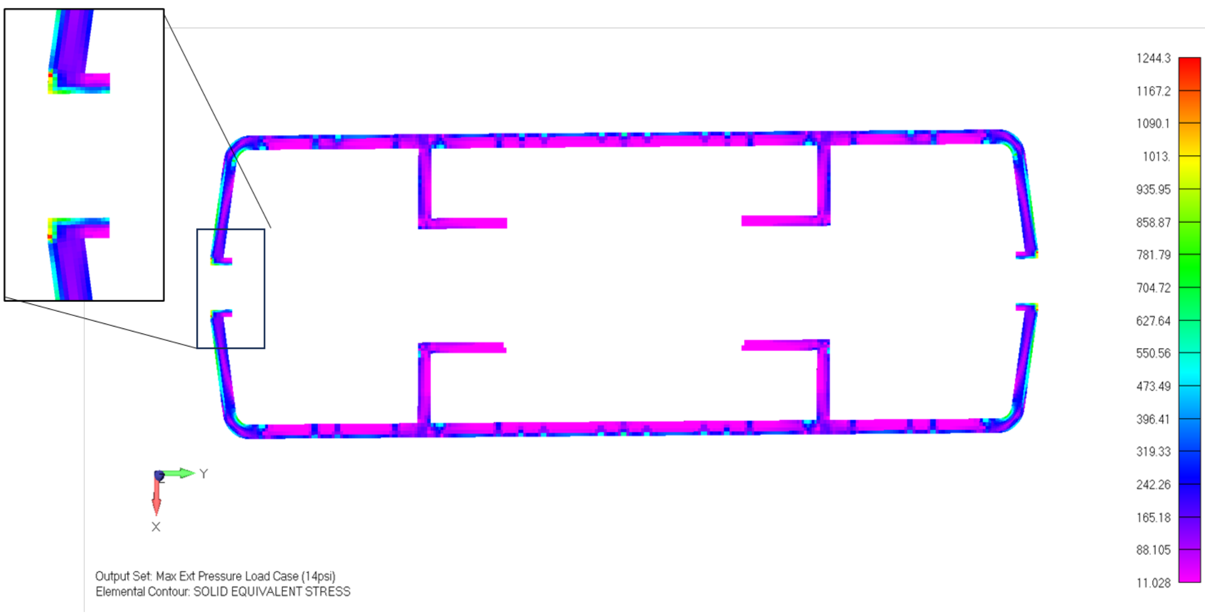


Figure 54 - Composite Nacelle Adhesive Von Mises - Maximum Pressure Case

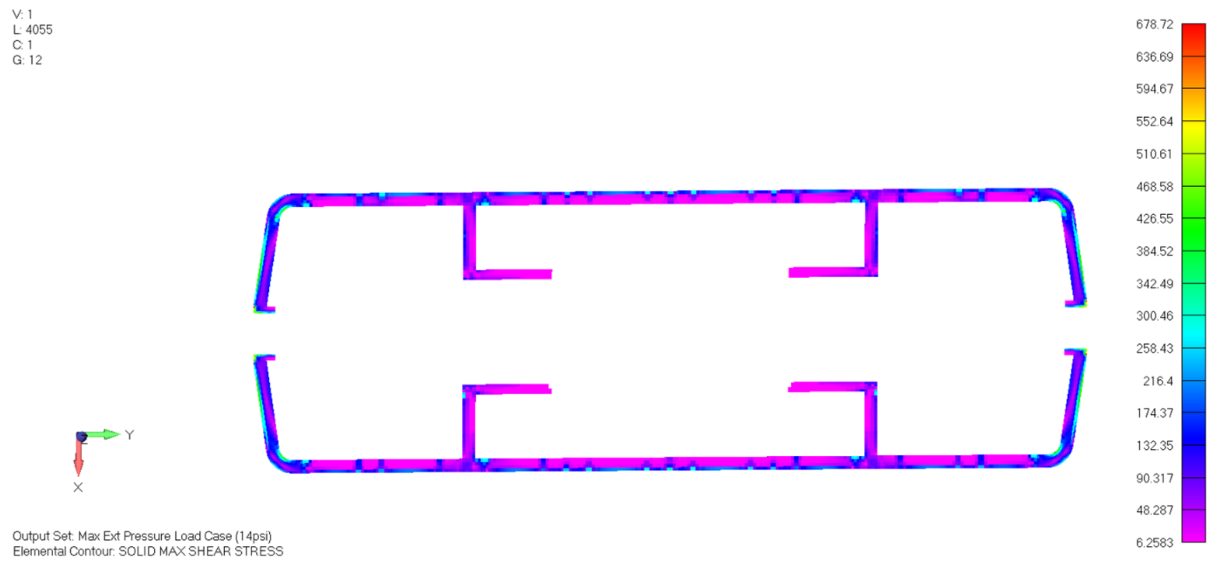


Figure 55 - Composite Nacelle Adhesive Max Shear - Maximum Press Case

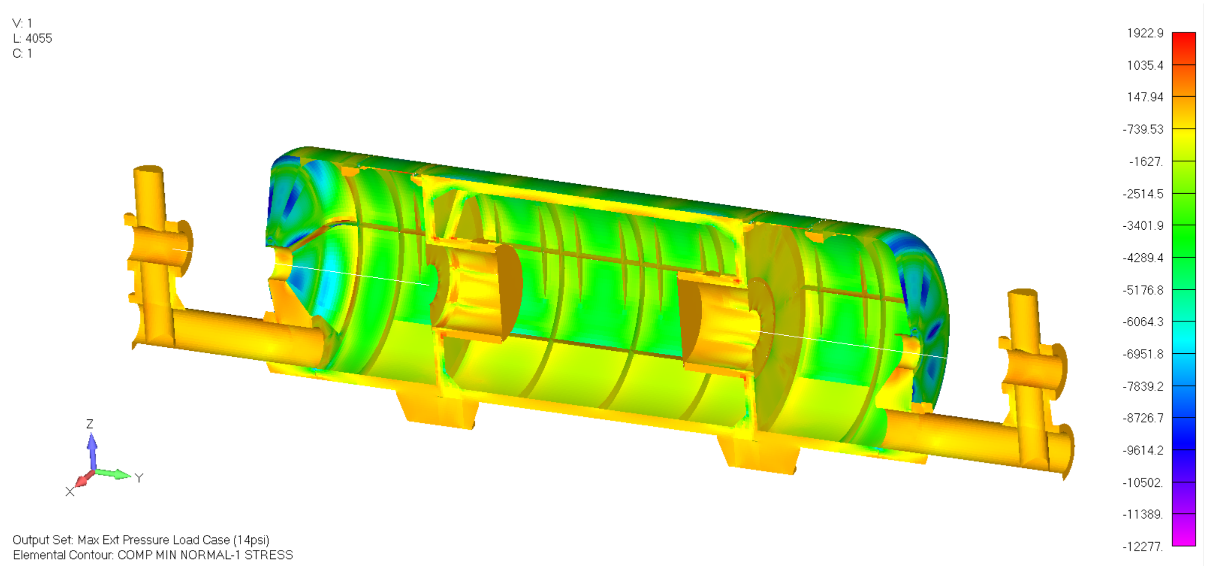


Figure 56 - Composite Nacelle Min Normal Stress 1 - Maximum Press Case

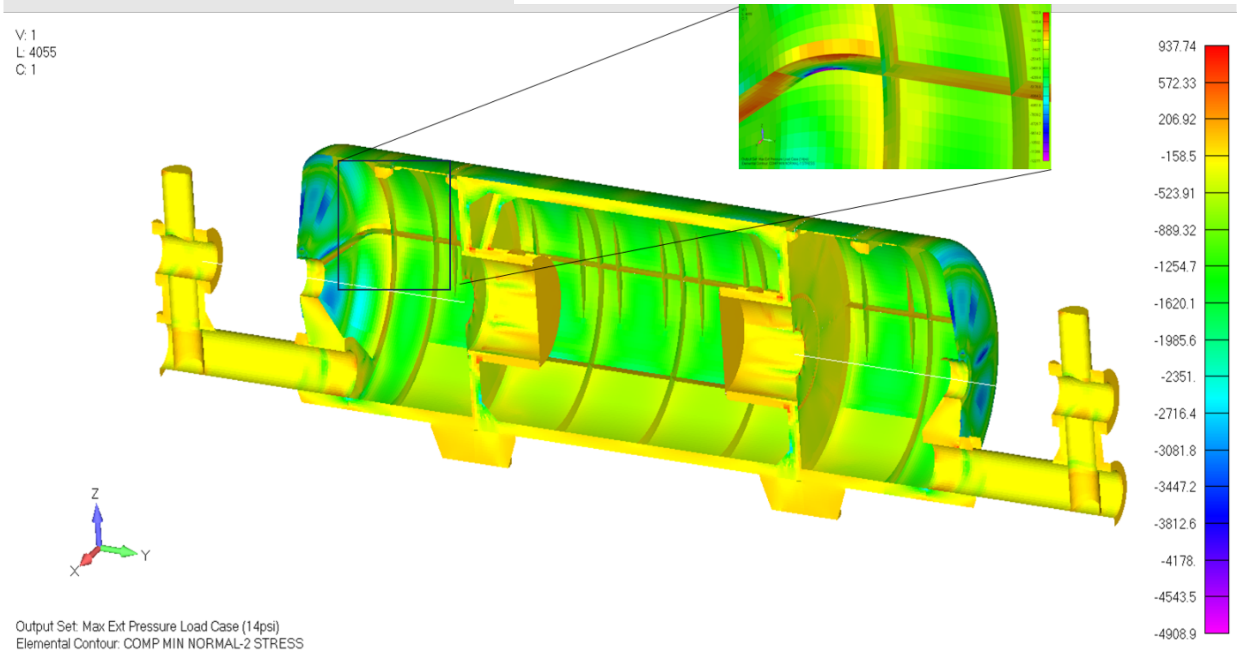


Figure 57 - Composite Nacelle Min Normal Stress 2 - Maximum Press Case

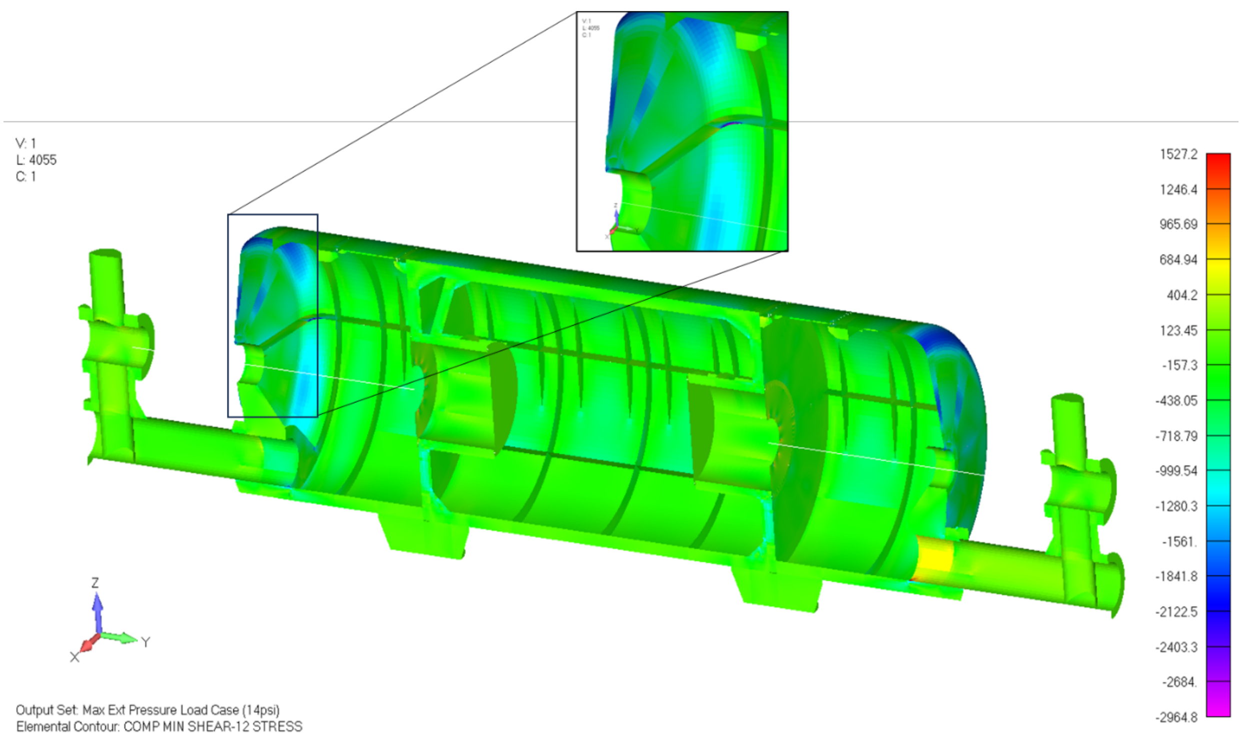


Figure 58 - Composite Nacelle Min Normal Shear Stress 12 - Maximum Press Case

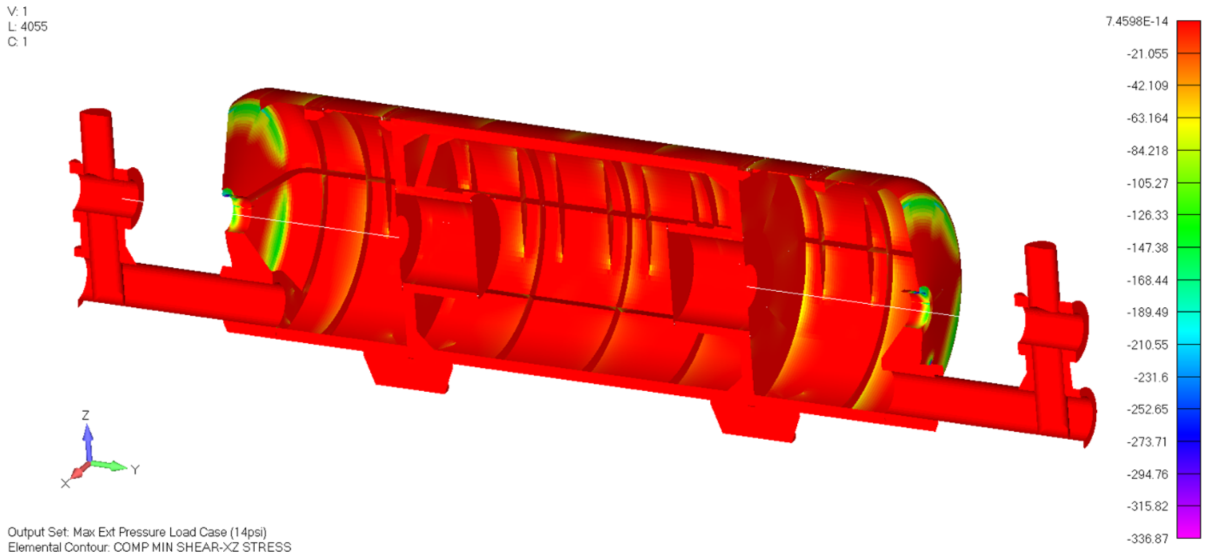


Figure 59 - Composite Nacelle Min Normal Shear Stress 13 - Maximum Press Case

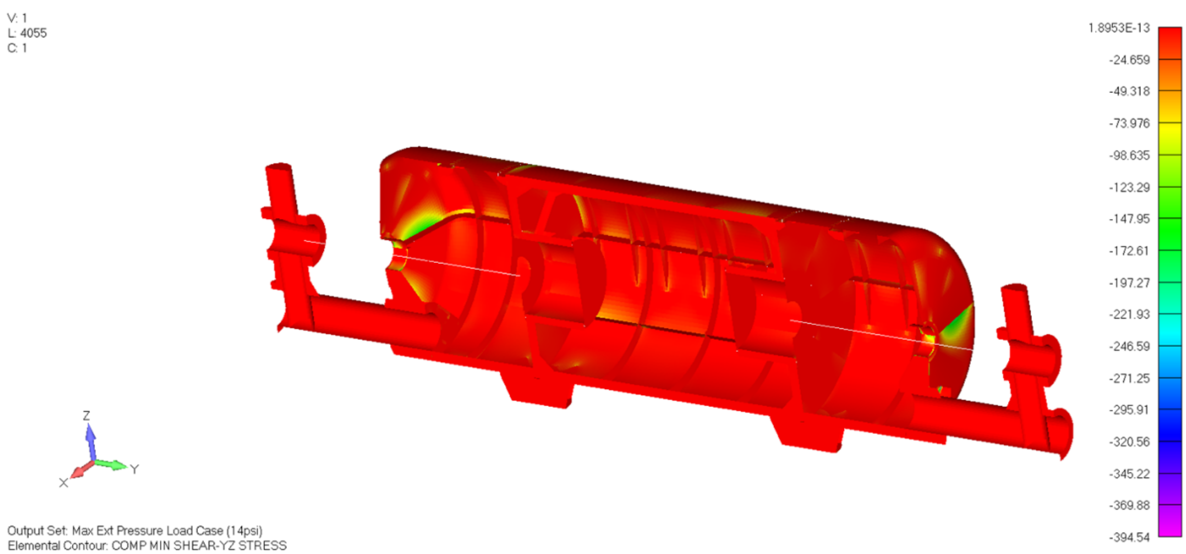


Figure 60 - Composite Nacelle Min Normal Shear Stress 23 - Maximum Press Case

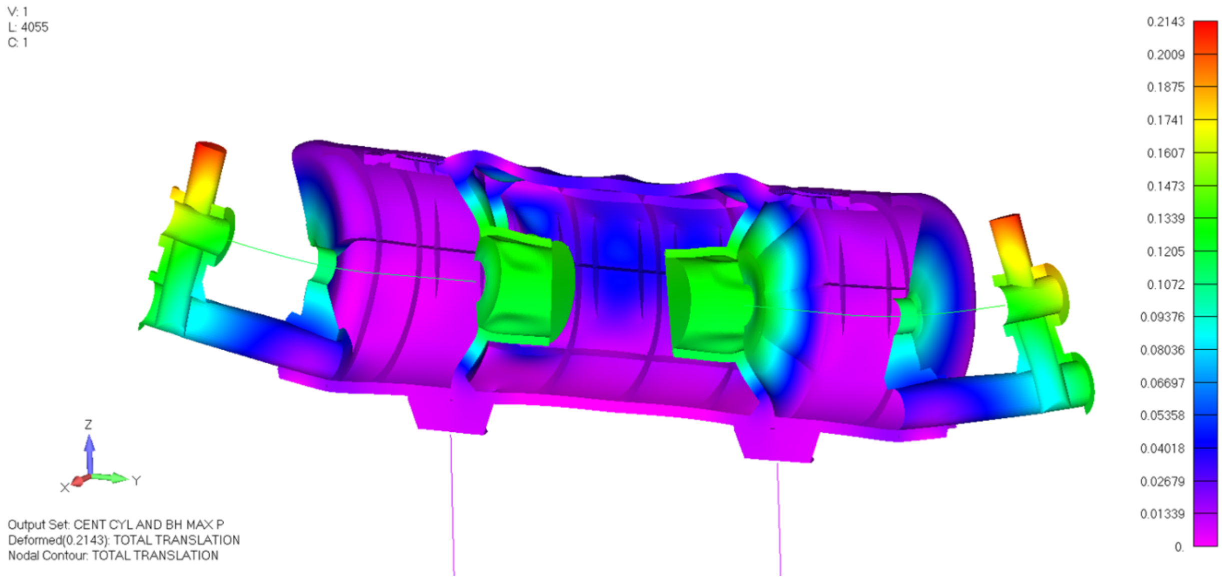


Figure 61 - Composite Nacelle Total Deflection - Maximum Press Case on Center Cylinder

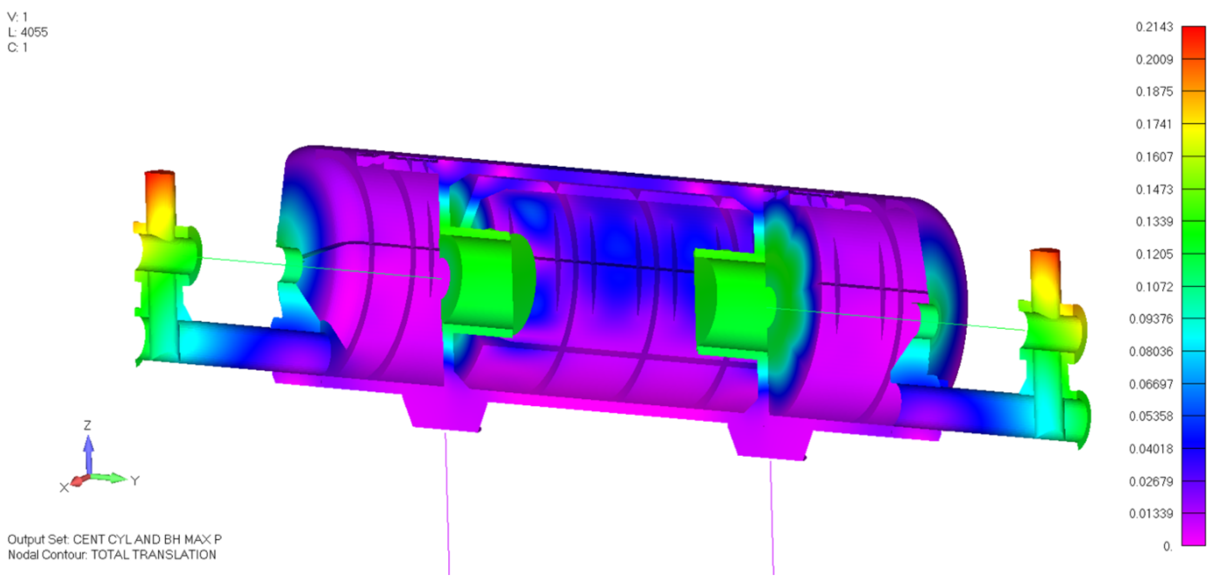


Figure 62 - Composite Nacelle Total Deflection Section - Maximum Press Case on Center Cylinder

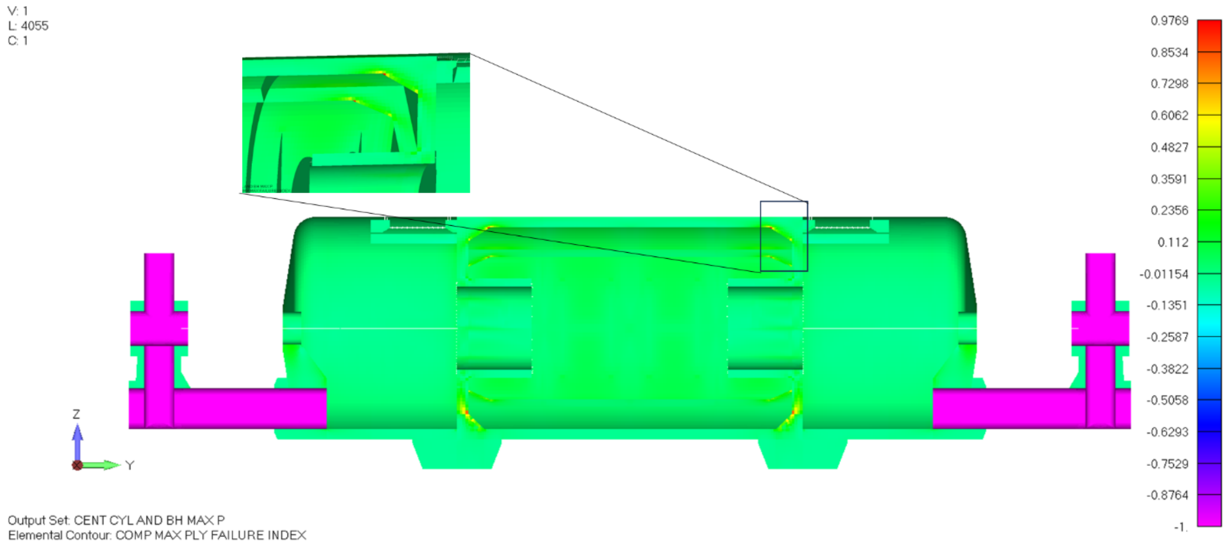


Figure 63 - Composite Nacelle Max Ply Failure Index - Maximum Press Case on Center Cylinder

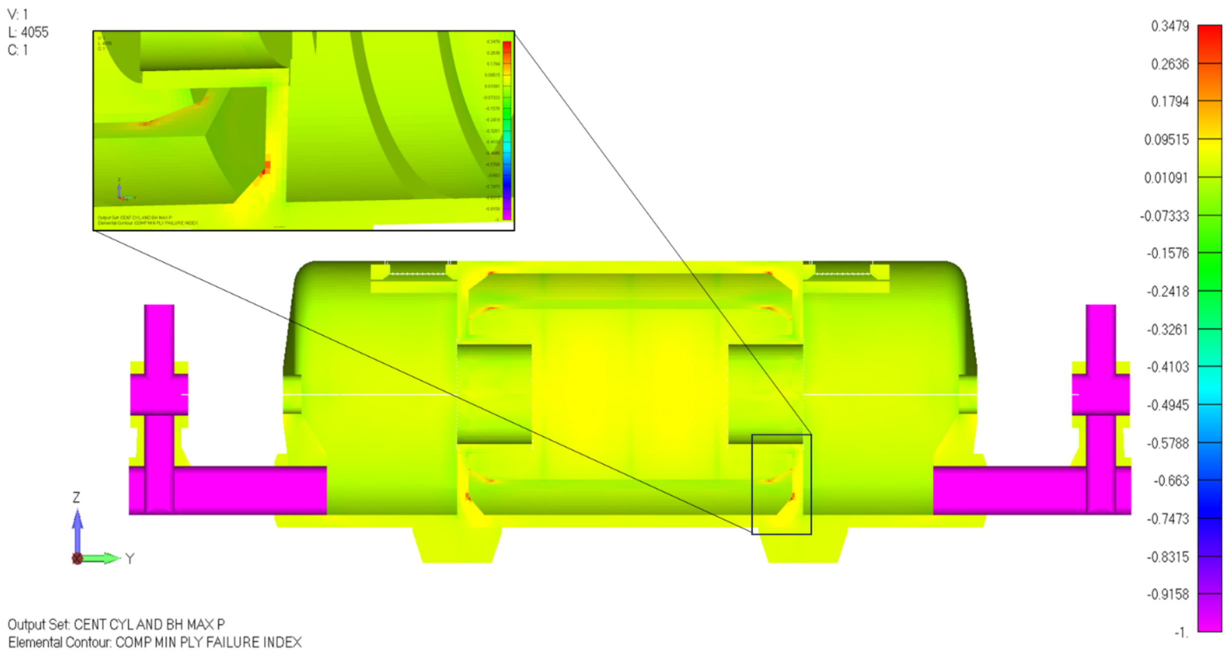


Figure 64 - Composite Nacelle Min Ply Failure Index - Maximum Press Case on Center Cylinder

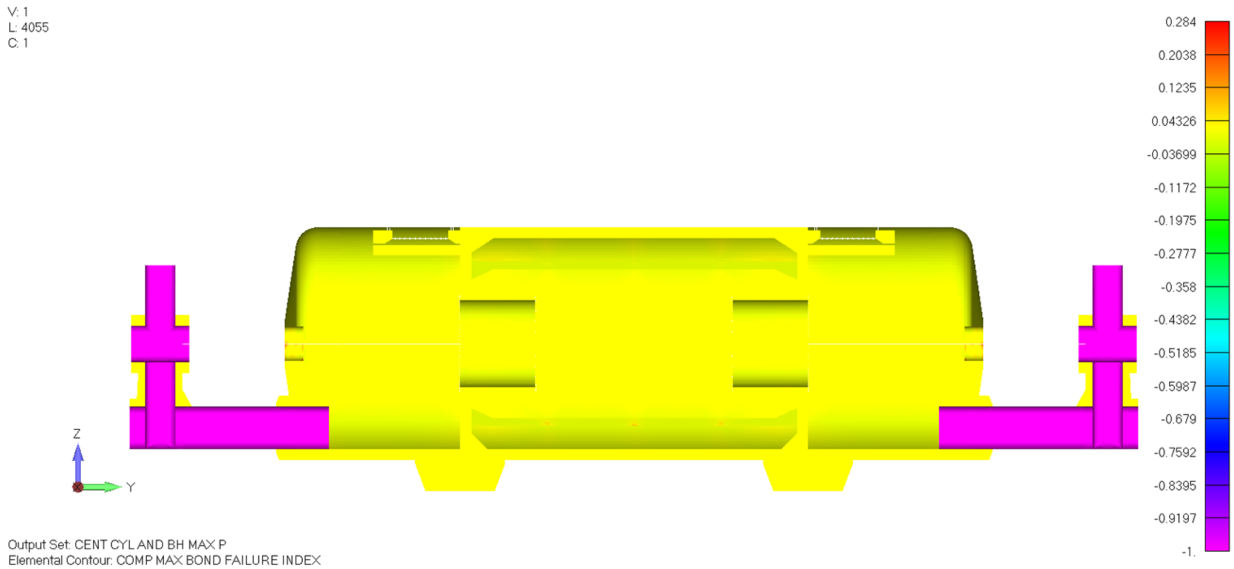


Figure 65 - Composite Nacelle Bond Failure Index - Maximum Press Case on Center Cylinder

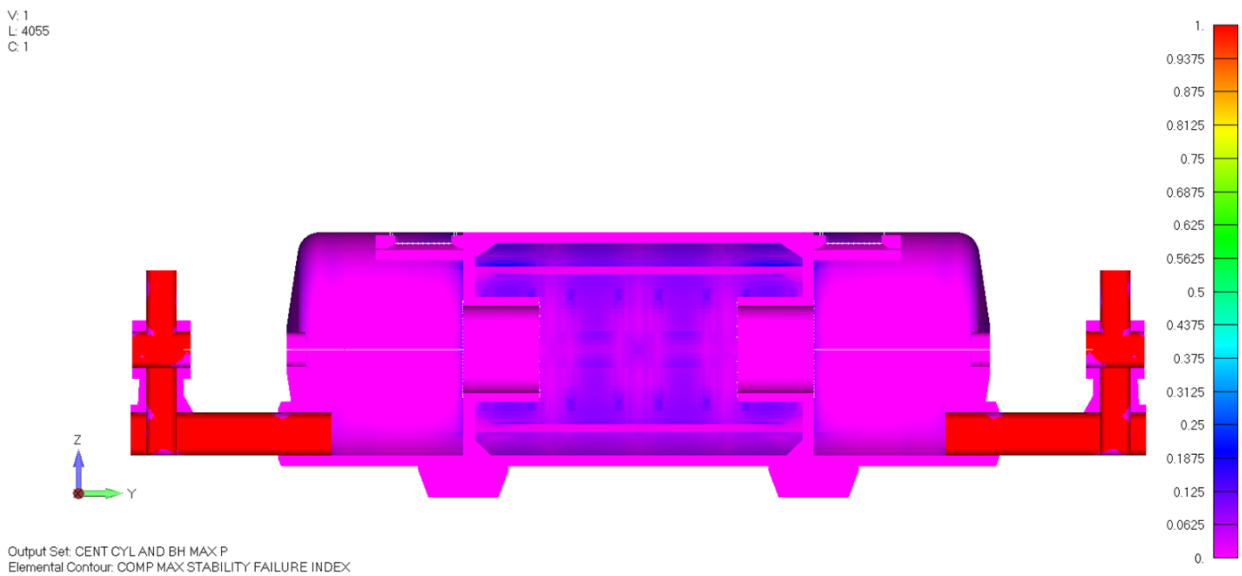


Figure 66 - Composite Nacelle Max Stability Failure Index - Maximum Press Case on Center Cylinder

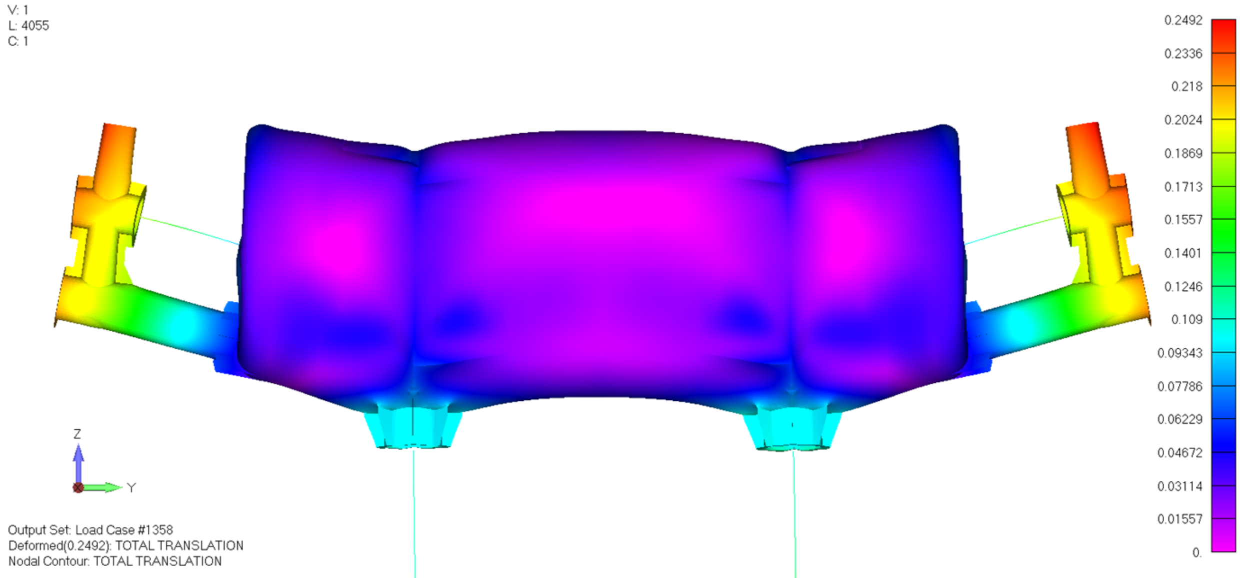


Figure 67 - Composite Nacelle Total Deflection – Time Point 1358

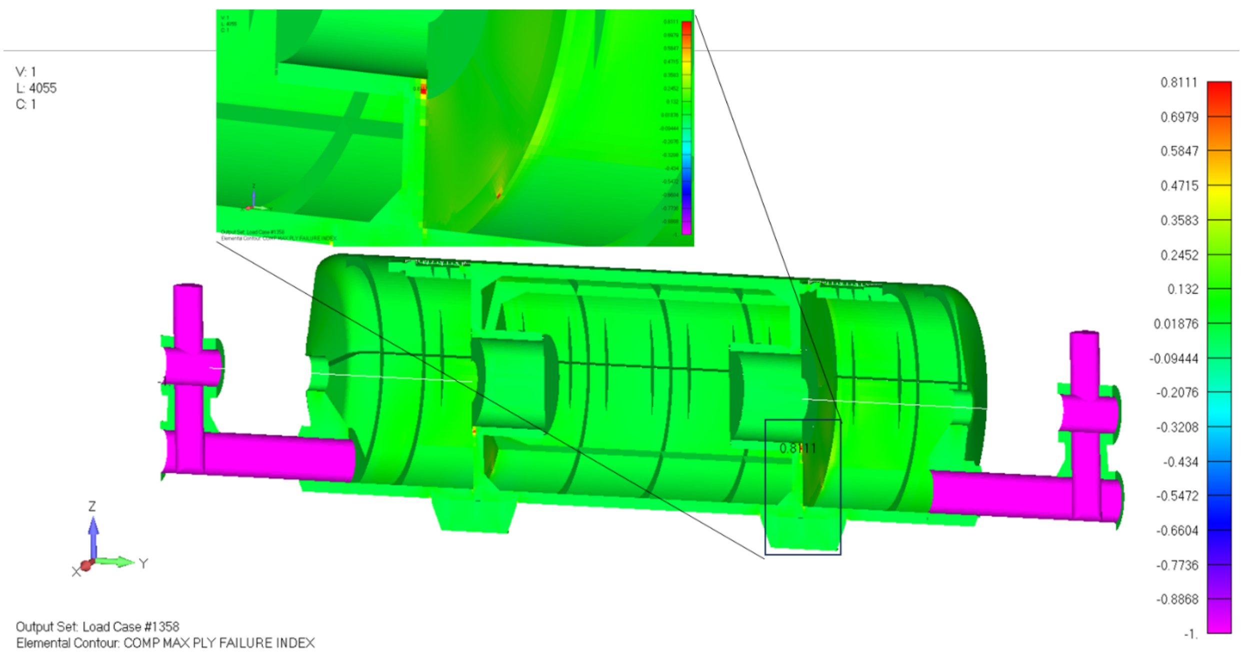


Figure 68 - Composite Nacelle Max Ply Failure Index – Time Point 1358

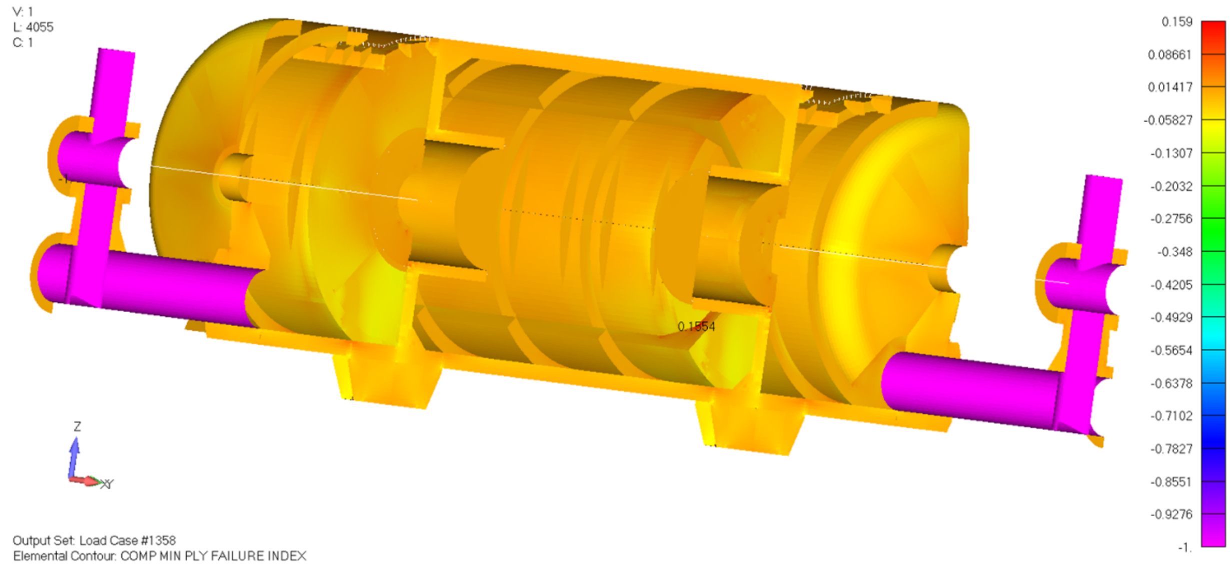


Figure 69 - Composite Nacelle Min Ply Failure Index – Time Point 1358

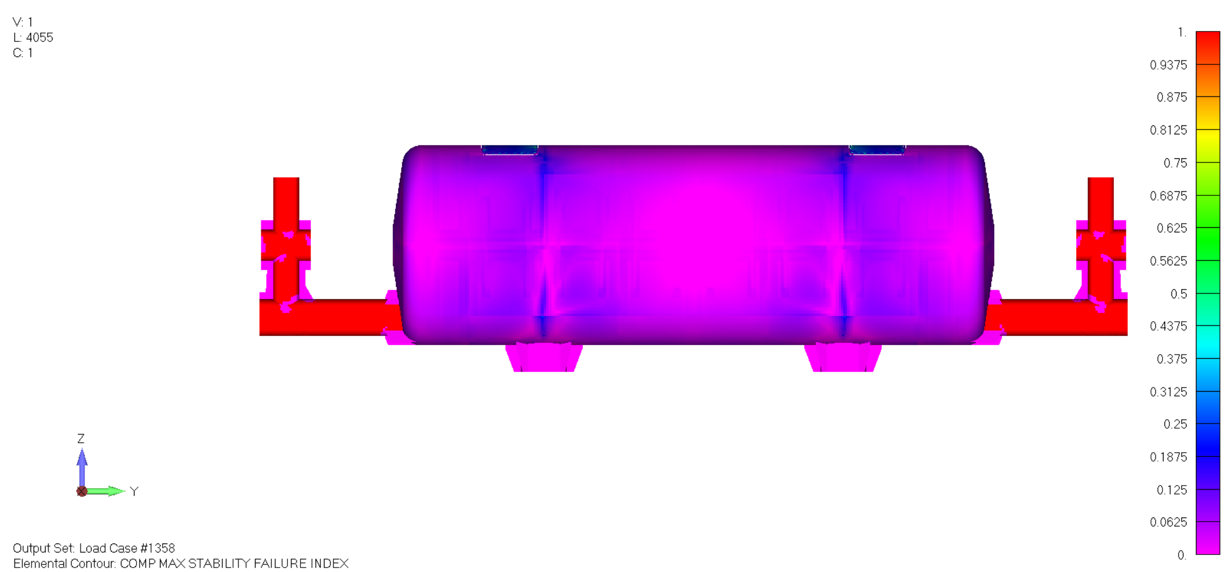


Figure 70 - Composite Nacelle Stability Failure Index – Time Point 1358

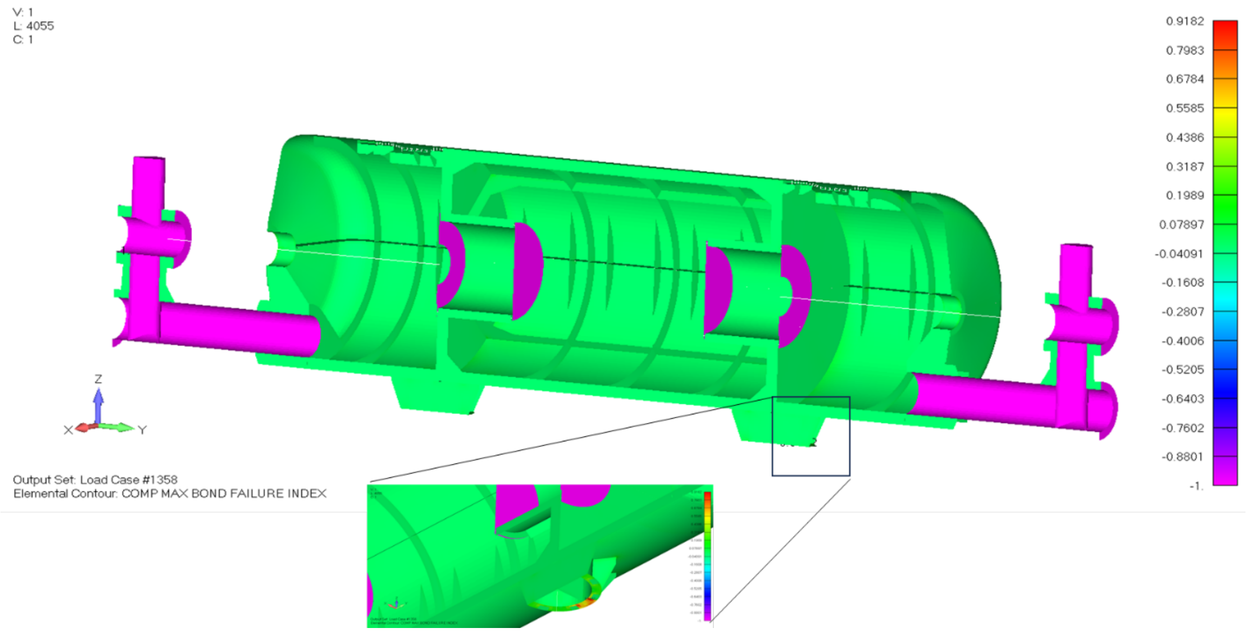


Figure 71 - Composite Nacelle Bond Failure Index – Time Point 1358

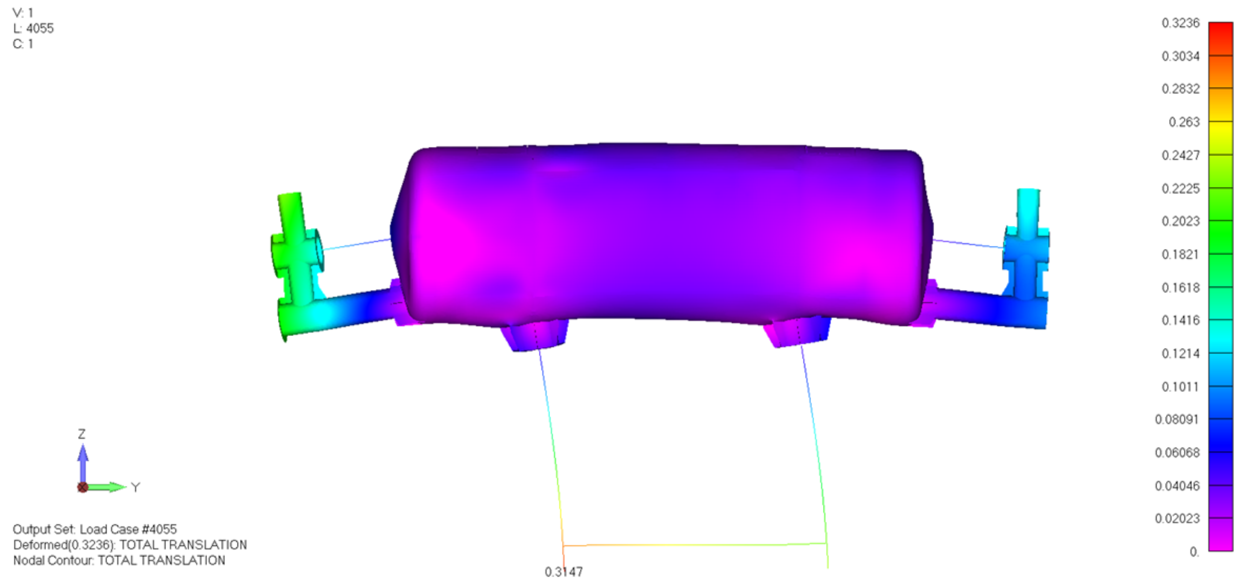


Figure 72 - Composite Nacelle Total Deflection – Time Point 4055

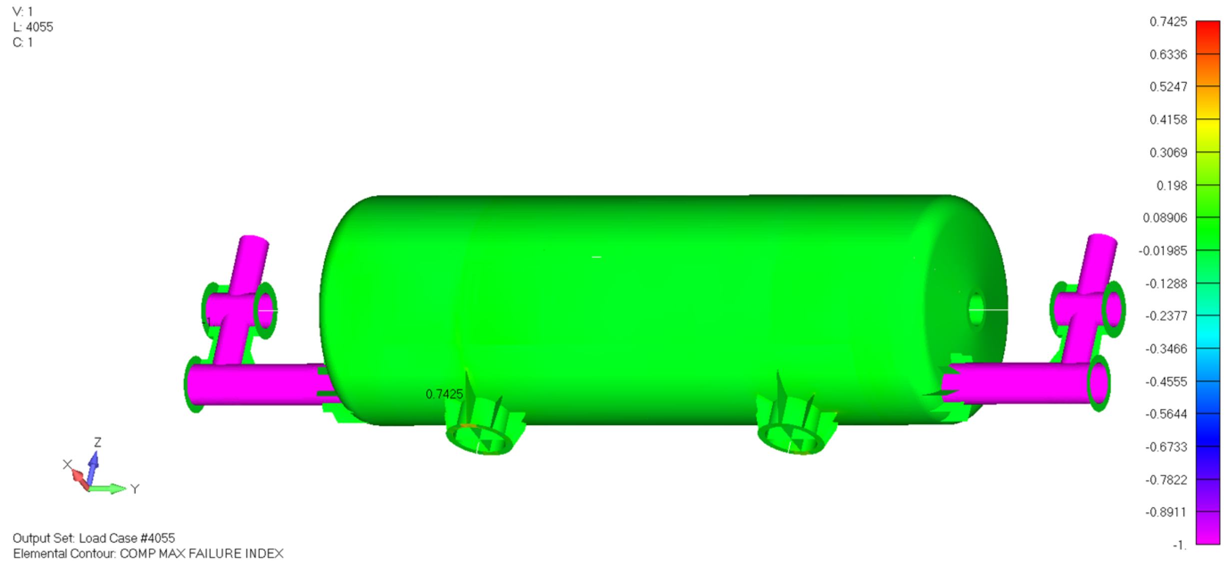


Figure 73 - Composite Nacelle Max Ply Failure Index – Time Point 4055

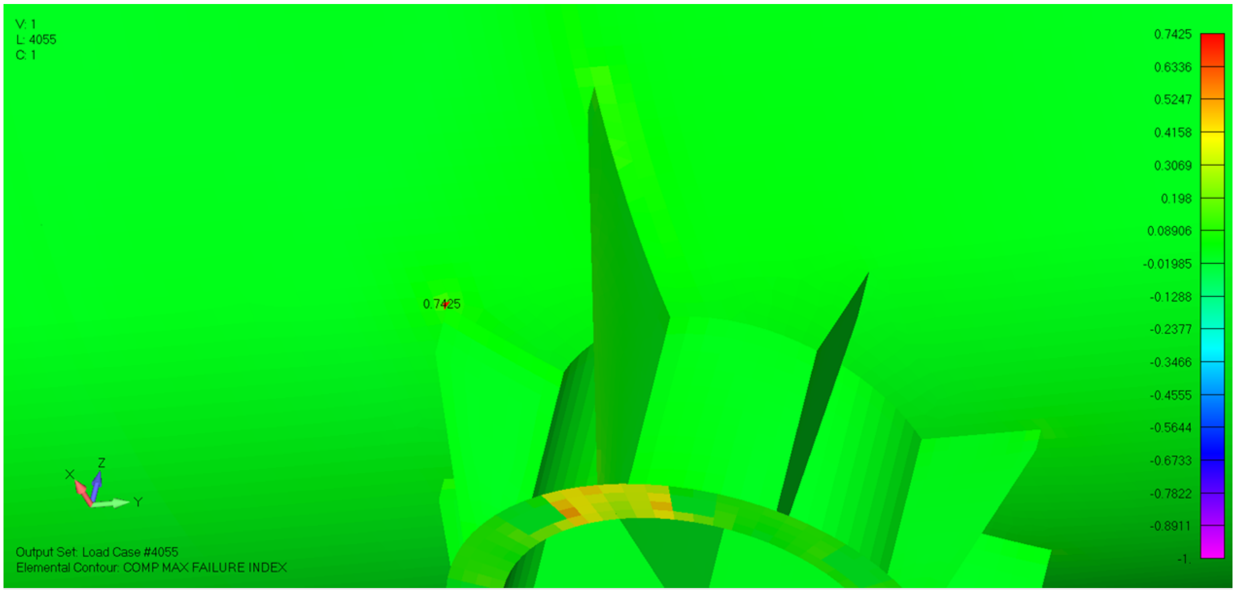


Figure 74 - Composite Nacelle Max Ply Failure Index Detail– Time Point 4055

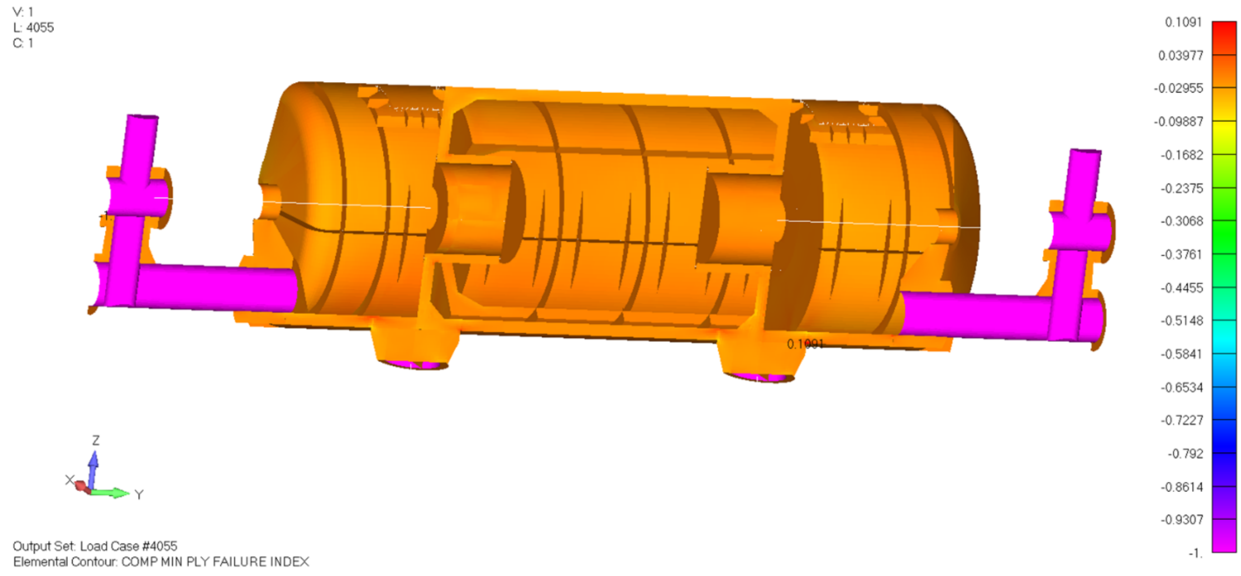


Figure 75 - Composite Nacelle Min Ply Failure Index – Time Point 4055

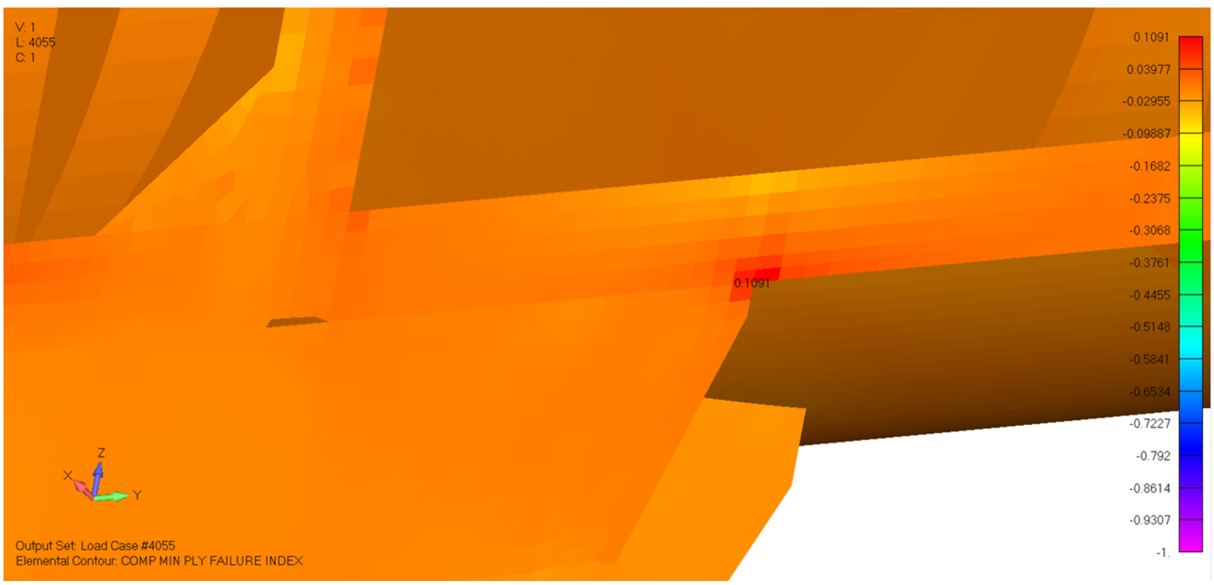


Figure 76 - Composite Nacelle Min Ply Failure Index Detail – Time Point 4055

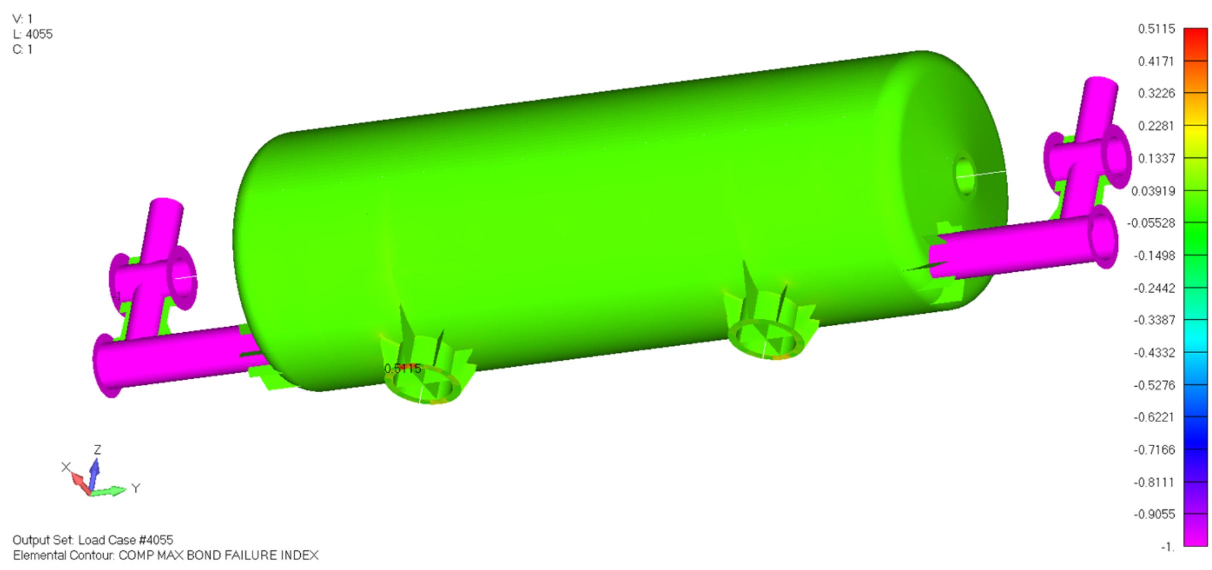


Figure 77 - Composite Nacelle Bond Failure Index Detail – Time Point 4055

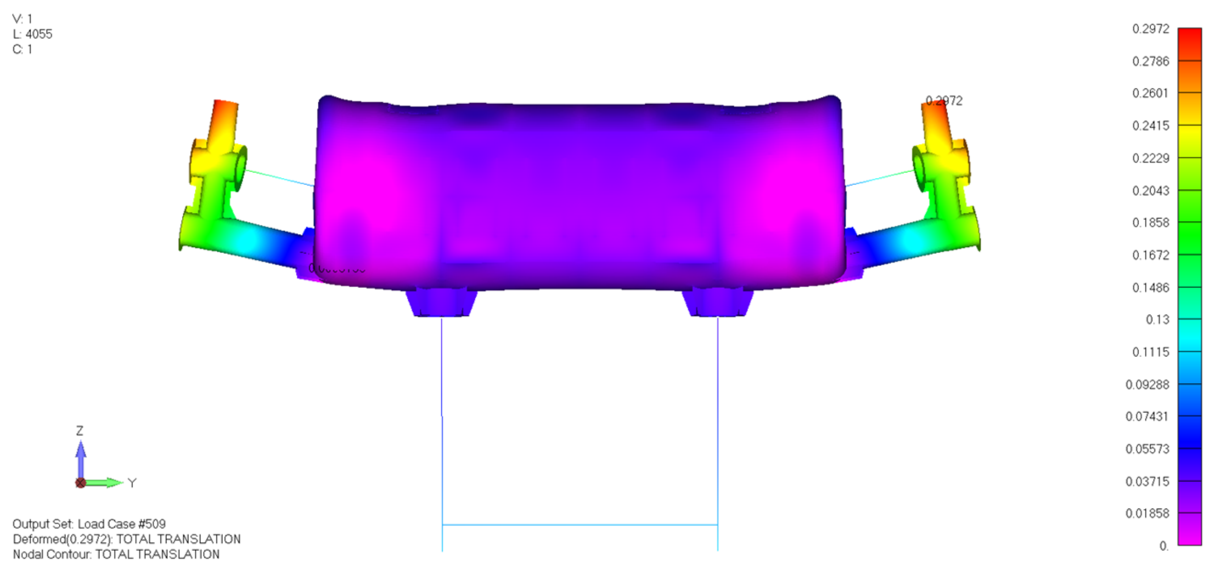


Figure 78 - Composite Nacelle Total Deflection– Time Point 509

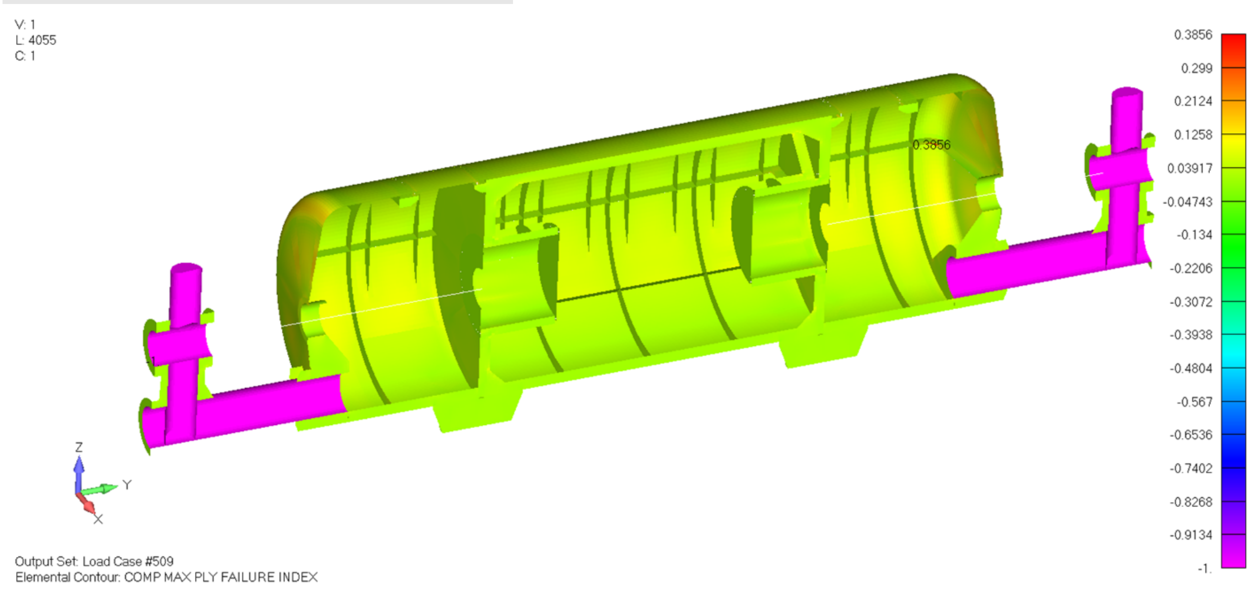


Figure 79 - Composite Nacelle Max Ply Failure Index – Time Point 509

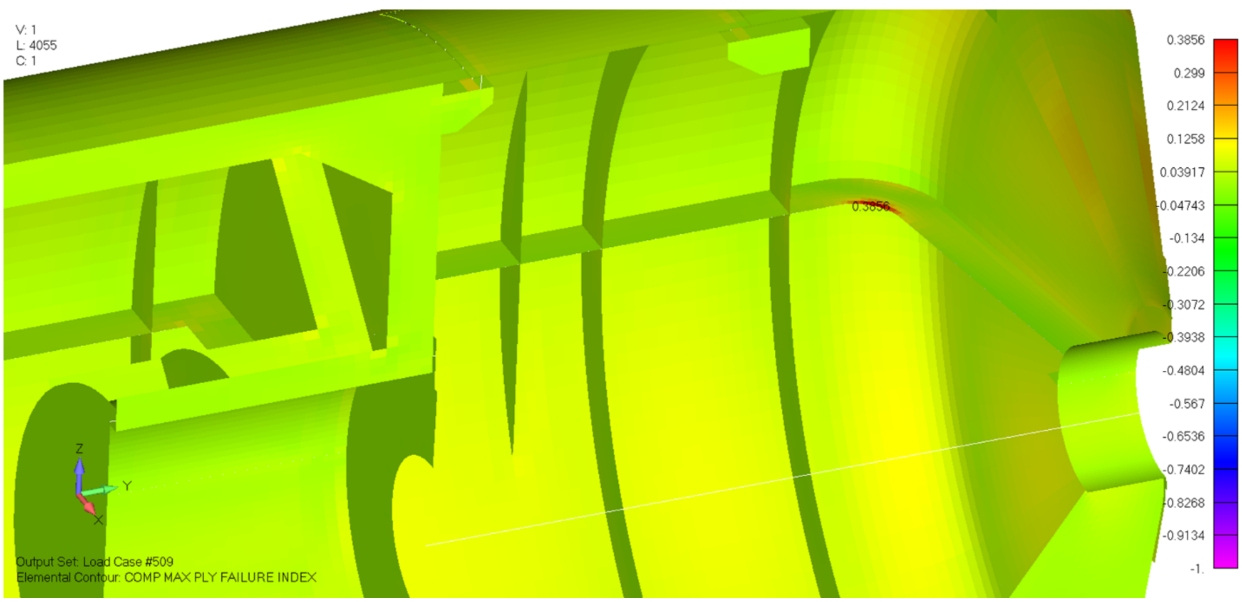


Figure 80 - Composite Nacelle Max Ply Failure Index Detail – Time Point 509

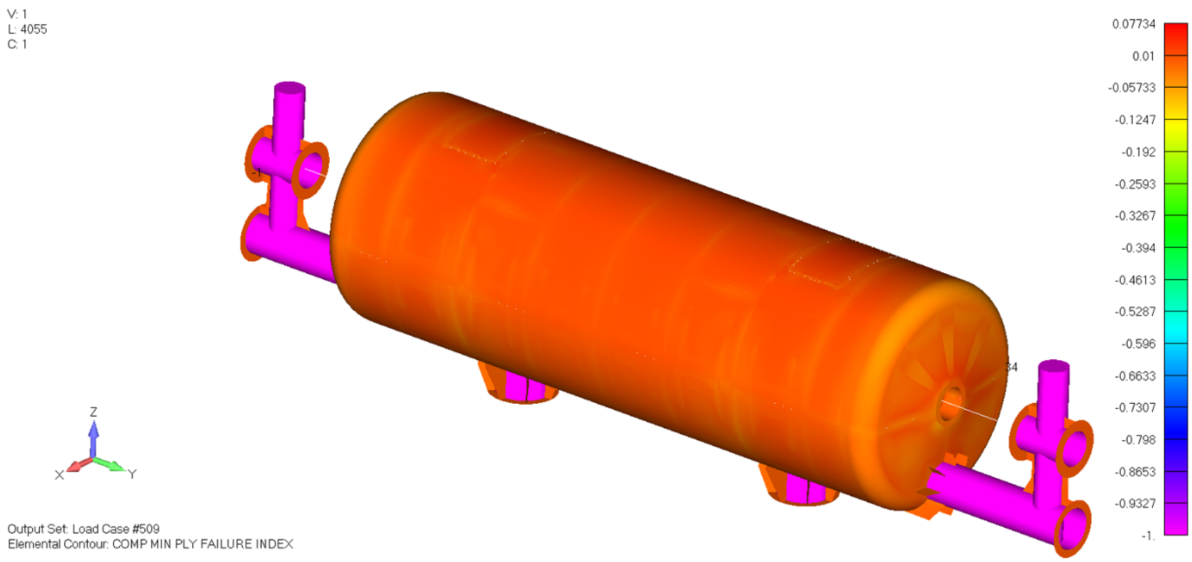


Figure 81 - Composite Nacelle Min Ply Failure Index – Time Point 509

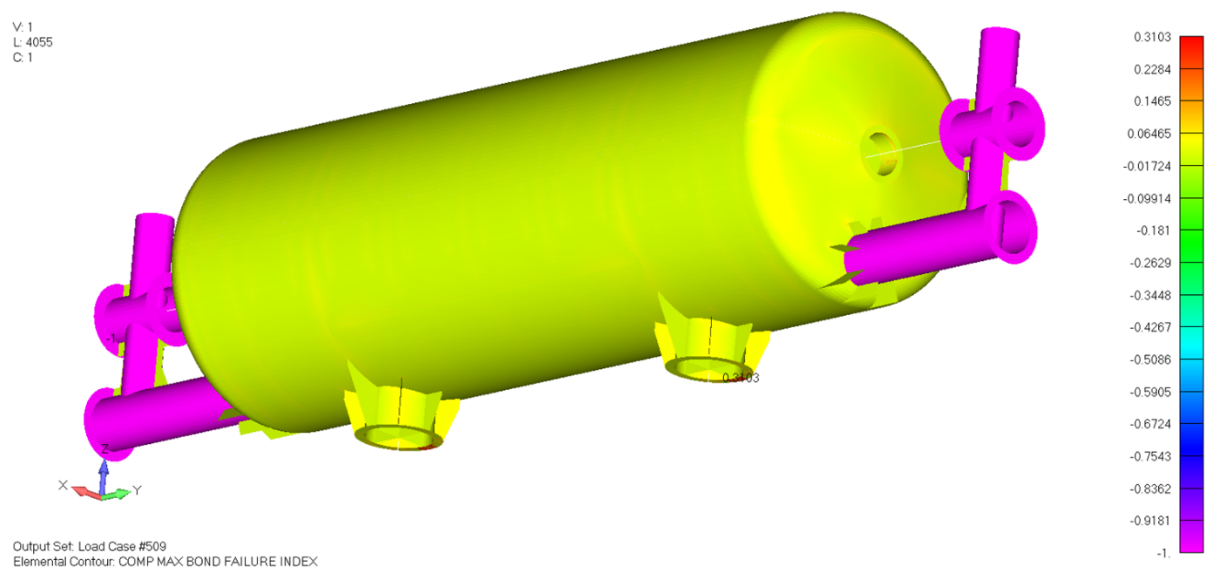


Figure 82 - Composite Nacelle Bond Failure Index – Time Point 509

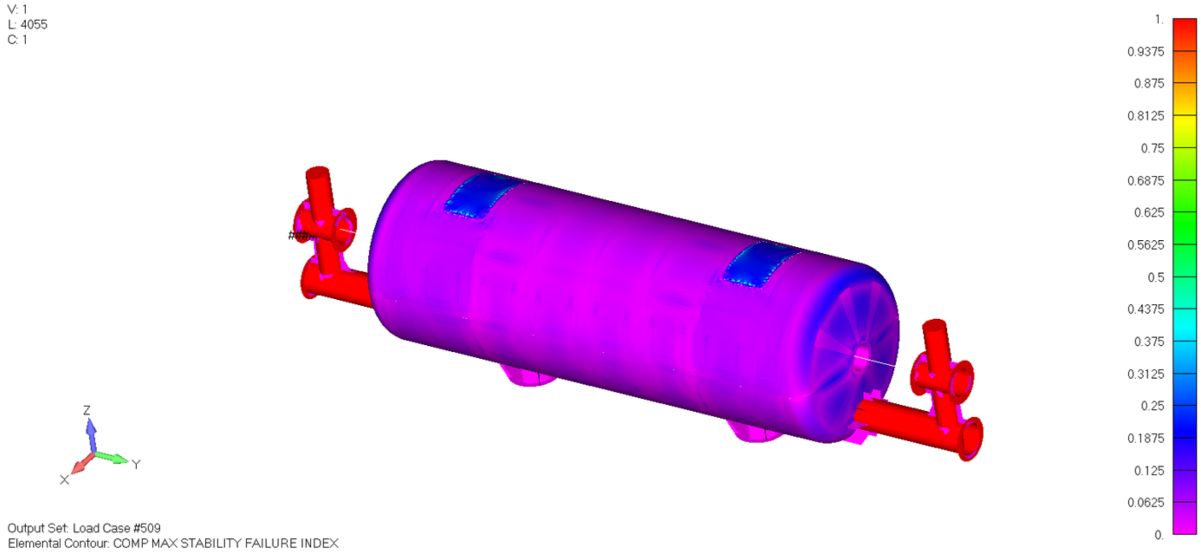


Figure 83 - Composite Nacelle Stability Failure Index – Time Point 509

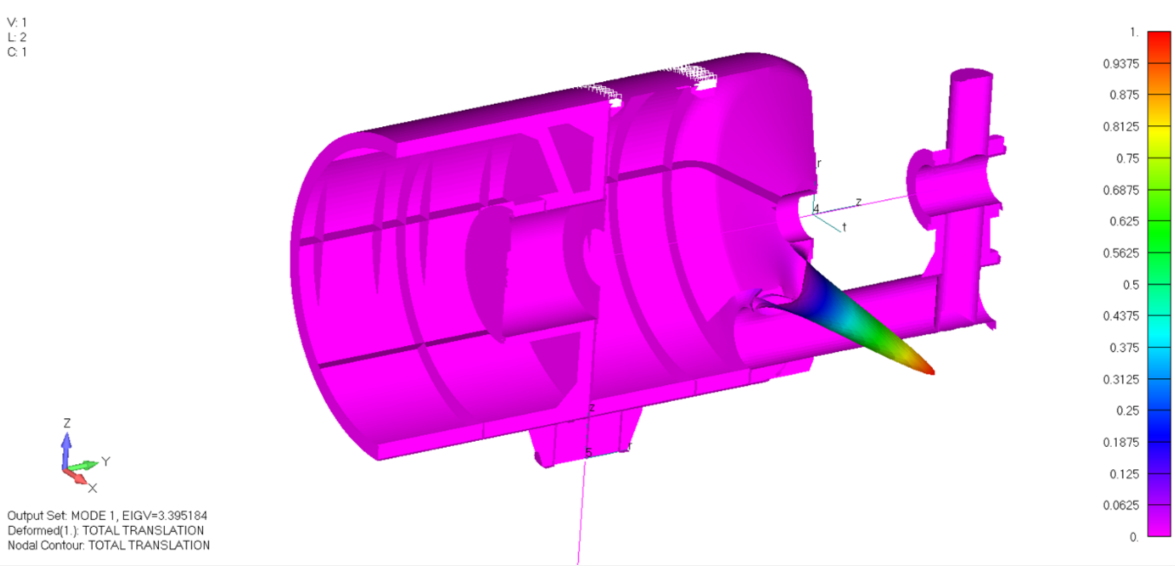


Figure 84 - Composite Linear Buckling

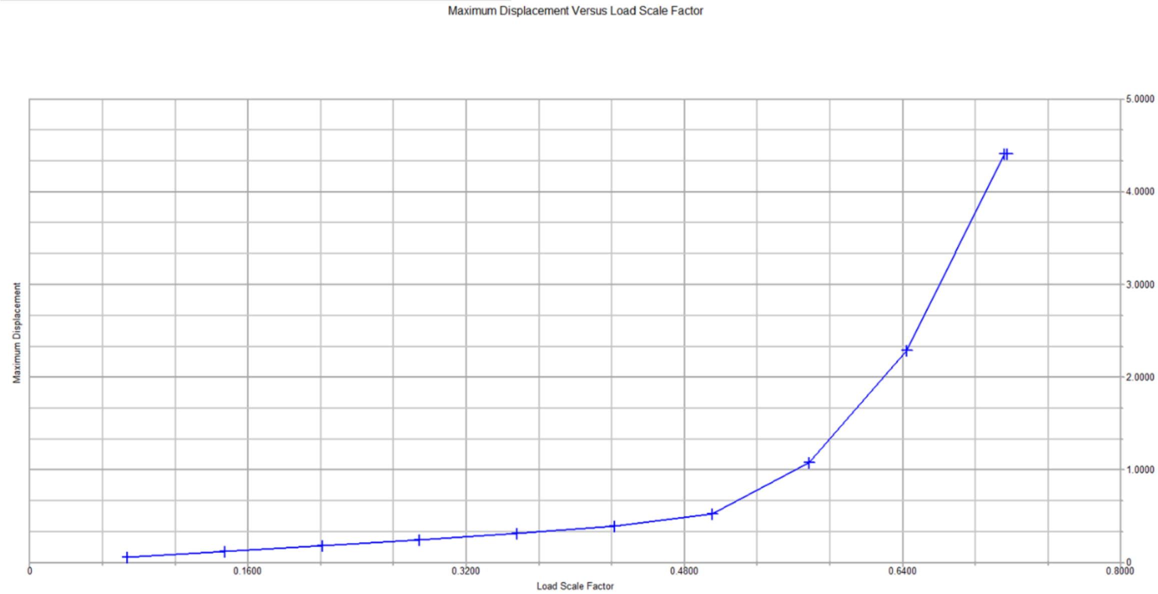


Figure 85 - Composite PPFA Maximum Deflection vs Load Factor

7.1.2.7 Composite Nacelle Geometry

The composite geometry is illustrated in Figure 86 and the details can be found in the attached drawing and solid model.

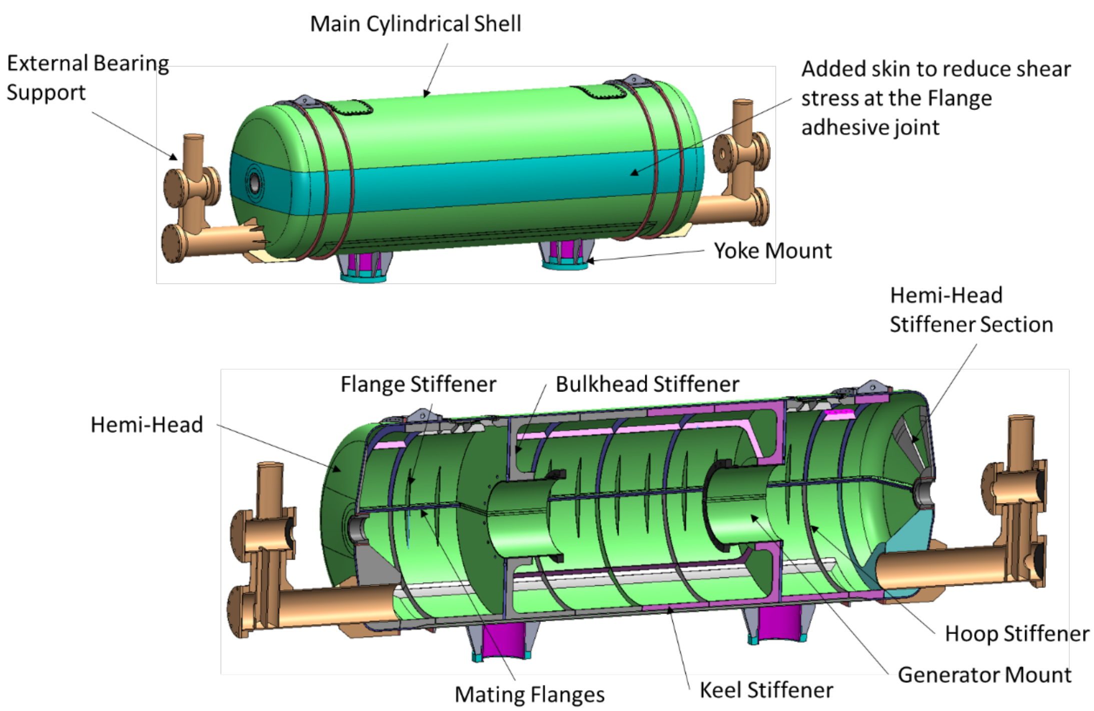


Figure 86 - Composite Nacelle Geometry.

7.1.2.8 Final Cost and Power-to-Weight Comparison

With the four material systems sized and analyzed, a cost and weight comparison was completed. The CAPEX consists of material costs and manufacturing costs and the OPEX consists of logistics and maintenance.

The CAPEX of the NS steel nacelle was estimated from a smaller nacelle built by C·Power. The fabrication cost was scaled up based on the increase in geometric size, 2.5X. The cost of the EHS steel and Aluminum were scaled up based on rule-of-thumb multipliers provided by fabricators. A 50% cost increase for EHS steel and 90% increase for the Al-5059 was used. The composite fabrication cost was based on an approximate order of magnitude estimation provided verbally by a capable manufacturer. The manufacturer estimated the design and construction of the mold to be approximately $125,000 and the manufacture of the first nacelle (to ABS standards) to be approximately $60,000. This manufacturer noted the build of a production run would bring the unit costs down due to volume and build efficiencies. The mold would be able to produce at least 100 units which would bring the cost of the mold to $12,500 per unit.

The OPEX is comprised of maintenance costs to keep the unit's operating efficiently, remove bio-growth, and service rusting components. A comparative data source for this information is weather buoys. Weather buoys are retrieved for maintenance approximately every two years, at a cost ranging from $25,000 to $170,000. Additionally, barnacle paint lasts between one (1) and three (3) years, which fits the two-year maintenance cycle. Based on this, it is assumed that WECs using any material system must be retrieved every two (2) years, stripped, and re-painted. The cost associated with corrosion can be considered based on when the nacelle would need to be replaced due to corrosion. When the corrosion impact is included, the composite material system has a clear advantage.

Table 15 - CAPEX, OPEX, and Power-to-Weight Summary

Description	units	NS	EHS	Al-5059	Composite
CAPEX					
Material Cost	$	$ 6,893	$ 22,129	$ 11,889	$ 12,913
Fabrication Cost	$	$ 96,107	$ 124,939	$ 172,992	$ 64,250
Total	$	$ 103,000	$ 147,068	$ 184,881	$ 77,163
OPEX					
WEC Retrieval Cost / 2 year	$	$ 25,000	$ 25,000	$ 25,000	$ 25,000
RE Paint /2 year	$	$ 1,000	$ 1,000	$ 1,000	$ 1,000
Maximum Potential Loss due to Corrosion	$	$ 103,000	$ 147,068	$ 184,881	$ -
Total	$	$ 129,000	$ 173,068	$ 210,881	$ 26,000
Power-to-Weight					
Hull Weight	kg	5,674	2,797	1,998	2,801
Power	kW	20.00	20.42	20.44	20.42
Power/Weight	kW/Kg	0.0035	0.0073	0.0102	0.0073
Power/Weight Inc.	%	-	107	190	107

7.2 Lesson Learned and Test Plan Deviation

There were no deviations from the approved test plan, however, there are lessons learned. During the execution of the plan, finding specific manufacturing data and details proved very difficult. Anecdotally, current manufacturing orders are maxing out production capacity at the limited number of commercial shipyards and composite component manufacturers that are thought to be capable of producing these components. When approached for detailed pricing information on materials and labor costs, several manufacturers refused to provide background unless presented with firm plans for a multi-unit order.

Gathering material and labor cost data has proved to be a challenge throughout this study. Cardinal Engineering and C·Power intend to engage manufacturers early on in any future design process and build relationships with manufacturers that will allow C·Power to incorporate manufacturing costs into comprehensive material trade studies.

8 Conclusions and Recommendations

The major conclusions that can be drawn from the analysis study are:

1. There is clear path to developing and certifying a multi-use heavy plate capable of towing a WEC to its deployment site and being used as an ISO shipping container for the WEC when being transported on land. Working with the certification organizations early in the process would be very helpful.
2. All of the material systems studied could be utilized for the nacelle to meet specifications.
3. Composites provide a very attractive alternative to metallic material systems for this application.

The composite nacelle would provide a reduction of CAPEX and OPEX with an increase in power-to-weight ratio. The cost reduction in OPEX could be significant. Based on an examination at the limit of design life, the replacement of the nacelle is estimated to be $129,000 for the baseline nacelle, compared to the refurbishment cost of $26,000 for a GRP design. When the corrosion reduction in OPEX is coupled with the estimated 25% CAPEX reduction and the 107% increase in power-to-weight ratio, the composite material system becomes a clearly superior alternative.

Another benefit to the weight reduction would be in shipping/handling of the WEC. The reduced weight would mean lower shipping costs and the opportunity to lower deployment costs by using a less capable work boat and smaller crew.

The project goals were achieved. However, the materials and manufacturing labor cost data was difficult to obtain.

It is recommended to continue the design and development efforts of the k20 nacelle, and other major WEC structural components with FRP material systems. Further analysis must be conducted to ensure compliance with all relevant load cases expected to be experienced by the WEC. Analyses should be further supported by physical testing, following DNV-OS-C501 Offshore Standard, *COMPOSITE COMPONENTS.* The specification lays out a specific plan to ensure a robust design. Following that, final updates to the FEM properties and construction should be assessed. Per the DNV specification, the manufacturer making the test pieces should be the manufacturer of the component, as consistency in the manufacturing process and workmanship are vital to the success of composite structures.

9 REFERENCES

Design and Analysis

a) DNV-OS-C501 Offshore Standard, COMPOSITE COMPONENTS, 2003
b) DNVGL-RU-NAVAL Rules for Classification Naval Vessels; Part 3, Chapter 1 – Surface Ships, Hull Structures and Ship Equipment, 2015
c) DNVGL-OS-B101 Offshore Standard, METALIC MATERIALS, 2015
d) NASA-RP-1351, Basic Mechanics of Laminated Composite Plates, 1994
e) NASA CR-1457, Manual for Structural Stability Analysis of Sandwich Panels, 1969
f) Eric Green Associates*, Marine Composites* 2nd Edition, 1999

Operation as a Shipping Bed

a) ISO 1496-5; Series 1 Freight Containers – *Specification and Testing – Platform and Platform-based Containers*
b) ISO 688; Series 1 Freight Containers – *Classification, Dimensions and Ratings*
c) ISO 10855-1; *Offshore Containers and Associated Lifting Sets – Design, Manufacture and Marking of Offshore Containers*

Operation as a Barge

a) DNVGL-RU-SHIP Rules for Classification of Ships; Part 1, Chapter 1 – *General Regulations*
b) DNVGL-RU-SHIP Rules for Classification of Ships; Part 1, Chapter 2 – *General Regulations*
c) DNVGL-RU-SHIP Rules for Classification of Ships; Part 3, Chapter 1 – *Hull General Principles*
d) DNVGL-RU-SHIP Rules for Classification of Ships; Part 5, Chapter 11 – *Non-Self-Propelled Units*
e) DNVGL-RU-SHIP Rules for Classification of Ships; Part 6, Chapter 7 – *Environmental Protection and Pollution Control*
f) DNVGL-RU-SHIP Rules for Classification of Ships; Part 7, Chapter 1 – *Survey Requirements for Fleet in Service*

Operation as a Heave Plate

a) IEC TS 62600-2 – Marine Energy – Wave, Tidal, and Other Water Current Converters; Part 2: *Marine Energy Systems Design Requirements*
b) IEC TS 62600-4 – Marine Energy – Wave, Tidal, and Other Water Current Converters; Part 4: *Specification for Establishing Qualification of New Technology*
c) IEC TS 62600-10 – Marine Energy – Wave, Tidal, and Other Water Current Converters; Part 10: *Assessment of Mooring System for Marine Energy Converters (MECs)*
d) DNV-OSS-312 Offshore Service Specification – *Certification of Tidal and Wave Energy Converters*

List of Acronyms

ABS	American Bureau of Shipping
AL	Aluminum
ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CAPEX	Capital Expenditures
CG	Center of Gravity
CoV	Coefficient of Variance
DDS	Design Data Sheet
DNV	Det Norske Veritas
EHS	Extra High Strength Steel
FEA	Finite Element Analysis
FEM	Finite Element Model
FRP	Fiber Reinforced Plastic
FVF	Fiber Volume Fraction
GRP	Glass Reinforced Plastic
IEC	International Electrotechnical Commission
IECRE	International Electrotechnical Commission-Renewable Energy
ISO	International Standardization Organization
LRFD	Load and Resistance Factor Design
MS	Margin of Safety
NS	Normal Steel
OPEX	Operational Expenditures
PPFA	Progressive Ply Failure Analysis
PTO	Power Take Off
PWS	PacWave South
RECB	Renewable Energy Certification Body
UD	Unidirectional
ULS	Ultimate Limit State
WEC	Wave Energy Converter

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11 Appendix

11.1 Design Parameters and Certification Requirements - Checklist

Applicable portions of the following governing standards are listed below:

11.1.1 Shipping Bed Certification: International Organization for Standardization (ISO)

- *ISO 1496-5; Series 1 Freight Containers – Specification and Testing – Platform and Platform-based Containers*

ISO characterization of mobile offshore floating structure/container:

Section 3 of ISO 1496 defines a *Platform* as a "Flat structure having no superstructure" and a *Platform-based container with incomplete superstructure* as a "Container which has no side walls but has a base similar to that of a platform container and a superstructure lacking any permanently fixed longitudinal load-carrying structure between the ends other than the base." The classification of the hybrid heave plate/barge/shipping bed is dependent upon the final design of the product when functioning as a shipping bed/container. Requirements for both classifications are given below, and it is noted when a requirement applies to only one of these classifications. Furthermore, the requirements listed below pertain to a *1BX freight container designation* per Table 2 of ISO 688 (maximum gross mass, R, is 34,480kg) given the condition that the hybrid heave plate/barge/shipping bed will need to be ≥20 feet long and support ≥12,000 kilograms. It is noted when a requirement is specific to this designation, so the specification can be changed accordingly if the length and capacity are altered.

Section 4 of ISO 1496-5 pertains to dimensions & ratings of freight containers:

☐ The overall top length of the container does not exceed 9,135mm in tare condition and is at least 9,105 mm when loaded. *These values are specific to a 1BX freight container designation* (Section 4.1.1).

☐ No part of the platform-based container shall project beyond the 9,125mm by 2,438mm by 2,438mm (LxWxH) overall external dimensions envelope. *These values are specific to a 1BX freight container designation* (Section 4.1.2).

Section 5 of ISO 1496-5 pertains to design requirements:

☐ The container meets the Annex A strength requirements for Stacking Test End Elevation, Stacking Test Side Elevation, Top Lift End Elevations, and Top Lift Side Elevations. *Values vary based on ("Platform/Platform-based") container classification* (Section 5.1.2).

☐ Corner fittings meet the positioning and strength requirements of ISO 1161 as applicable (Section 5.1.3, 5.3.1, 5.3.3, 5.4.1, 5.4.2.2).

☐ All parts with the potential to create a hazardous situation must be secured with a system that can provide external indication of the positive securement (Section 5.1.5).

☐ The container is capable of being supported only by load-transfer areas in its base structure and the transfer of load between rails and carrying vehicles is not envisaged. Load transfer area requirements are detailed in Sections 5.4.2.1-5.4.5 (Section 5.4.2).

☐ If the combined mass of the container and test load is equal to or greater than 54,864kg, no part of the base of the container deflects more than 6mm[4] below the plane located 12.5mm +5/-1.5mm[2] above the plane of the lower faces of the bottom corner fittings of the container (base plane), (Section 5.4.3).

☐ The sideway deflection of the top of the container with respect to the bottom of the container, at the time it is under full transverse rigidity test conditions, does not cause the sum of the changes in length of the two diagonals to exceed 60mm[4] (Section 5.5).

☐ The longitudinal deflection of the top of the container with respect to the bottom of the container, at the time it is under full longitudinal rigidity test conditions, does not exceed 42mm[4] (Section 5.6).

☐ In the absence of end walls, cargo must be secured to the base structure such that the cargo does not transmit longitudinal forces to the ends (Section 5.7).

☐ The base structure can withstand lateral forces and cargo is secured against later movement in accordance with Annex C (Section 5.4.4, 5.7.4).

☐ Fork-lift pockets may be provided on containers designated as "1BX" containers for empty handling only. The pockets must pass completely through the base structure with their bases near their ends, and decals indicating this condition must be applied near the pockets (Section 5.9).

Section 6 of ISO 1496-5 pertains to testing:

☐ The hybrid heave plate/barge/shipping bed withstands a stacking test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 and Table 3 of Section 6.3 (Section 6.2).

☐ The hybrid heave plate/barge/shipping bed withstands a top corner fitting lifting test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.3).

☐ The hybrid heave plate/barge/shipping bed withstands a bottom corner fitting lifting test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.4).

☐ The hybrid heave plate/barge/shipping bed withstands a longitudinal external restraint test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.5).

☐ For any end walls present in the design, the hybrid heave plate/barge/shipping bed withstands an end wall strength test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.6).

☐ The hybrid heave plate/barge/shipping bed withstands a floor strength test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.8).

☐ For any fork-lift pockets present in the design, the hybrid heave plate/barge/shipping bed withstands a fork-lift pocket lifting test in its operating condition as a shipping bed with its loading in accordance with Section 6.1 (Section 6.11).

☐ Following the completion of all structural tests, the hybrid heave plate/barge/shipping bed withstands a weatherproof test in its operating condition as a shipping bed (Section 6.1.1, 6.12).

Section 7 of ISO 1496-5 pertains to testing of folded platform-based containers with incomplete superstructure:

☐ For any folding ends present in the design, the hybrid heave plate/barge/shipping bed withstands a stacking test in its folded condition with its loading in accordance with Section 6.1 and Table 3 of Section 6.3 (Section 7.1, 7.2).

☐ For any folding ends present in the design, the hybrid heave plate/barge/shipping bed withstands an interlocked lifting test in its folded condition with its loading in accordance with Section 6.1 (Section 7.1, 7.3).

☐ For any folding ends present in the design that fold flush, the hybrid heave plate/barge/shipping bed withstands a top lifting test in its folded condition (Section 7.4).

- *ISO 10855-1; Offshore Containers and Associated Lifting Sets – Design, Manufacture and Marking of Offshore Containers*

  ISO 10855-1 presents overarching requirements for the design, manufacture, and marking of offshore containers with a gross mass less than or equal to 25,000kg. The hybrid heave plate/barge/shipping bed for the WEC meets the criteria of what this specification defines an *offshore service container* with an *open frame* while functioning as a shipping bed in that it is an offshore container built and equipped for a special service task. While the hybrid system will not serve precisely the same function as a traditional offshore shipping container, it will be subject to the same loading and unloading methods (and therefore types of pressure on the structure) as a traditional offshore shipping container and will be subject to the conditions of the sea, so it must be certified as such. The requirements detailed below primarily relate to the marking of offshore containers as it pertains to the certification requirements of a hybrid heave plate/barge/shipping bed. Critical elements of applicable design and manufacturing requirements are also highlighted, and direction to further details of these requirements is provided. When successfully certified, a certificate of conformity will be issued based on information included in an "as-built" dossier as detailed in Section 11.2 of this standard.

Section 5 of ISO 10855-1 pertains to design requirements:

☐ The container has minimal protruding parts, fittings, and guides that could snag on other structures (including the WEC), and protruding parts deemed necessary in the final design are protected so that they cannot catch the lifting set (Section 5.1.3).

☐ If the design contains exposed aluminum, the risk associated with sparks being generated by an impact with corroded steel is accounted for and the container is appropriately marked on all sides in letters at least 75mm high as required by Section 9.1 (Section 5.1.7).

☐ The required strength is found through calculations and verified through tests specified in Clause 7. The design satisfies applicable lifting load requirements (Section 5.2.2).

☐ Vertical impact tests, that comply with the requirements of Section 7.4, for impact on corners supplements static calculations. Static calculations are compliant with Section 5.2.3.2 and Section 5.2.3.3 (Section 5.2.3.1).

☐ The main frame structure is dimensioned to withstand a local horizontal impact force, combined with the listing stress as described in Section 5.2.3.2, acting at any point. Doors and hatches are designed for the same horizontal loads as the primary structure and are compliant with securement requirements (Section 5.4).

☐ The minimum material thickness requirements are satisfied (Section 5.2.5).

☐ Essential welded structural members have full penetration welds (Section 5.3).

☐ If fork-lift pockets are included, they are installed on the bottom structure IAW applicable requirements (Sec. 5.4.6) and the testing requirements detailed in Section 7.5.1 are met (Section 5.4.6).

☐ Adequate top protection, as is required for an open frame container, is provided (Section 5.4.7).

☐ Pad eyes are welded with full penetration welds and satisfy the applicable dimensional and alignment requirements (Section 5.4.8)

☐ The dynamic load factors given in Section 5.4.10 are used when evaluating force exposure to the equipment on container (Section 5.4.10).

Section 7 of ISO 10855-1 pertains to type testing:

☐ Lifting tests satisfying the requirements of Section 7.3, in compliance with Section 7.2, are performed.

☐ A vertical impact tests (drop test and lowering test) satisfying the requirements of Section 7.4, in compliance with Section 7.2 is performed.

Section 8 of ISO 10855-1 pertains to production requirements:

☐ Inspection certificates and test reports for the material used during construction are documented as required by Table 6 of Section 6.5. If markings identifying primary structure are not visible in the final product, a log of the components is available to ensure material traceability. *General material requirements for steel, aluminum, and non-metallics are detail in sections 6.1/6.2, 6.3, and 6.4, respectively* (Section 8.1.1).

☐ Non-destructive examination satisfying the requirements of Section 8.2.3.2 is performed after testing has concluded.

☐ All welding is performed in accordance with Section 8.2.2 and meets the acceptance criteria listed in Table 9 of Section 8.2.3.3 following the completion of examinations required by Section 8.2.3.

Section 9/10 of ISO 10855-1 pertain to marking requirements:

☐ Safety markings are compliant with Section 9.1.

☐ The container is given identification markings as required by Section 9.2

☐ The container is given mass and payload markings as required by Section 9.3

☐ A container data plate in compliance with Section 10 is attached to the exterior of the container.

☐ The documentation listed in Section 11.2 is collated in an as-built dossier.

ISO 1496-5; Series 1 Freight Containers – Specification and Testing – Platform and Platform-based Containers

ISO characterization of mobile offshore floating structure/container:

Section 3 of ISO 1496 defines a *Platform* as a "Flat structure having no superstructure" and a *Platform-based container with incomplete superstructure* as a "Container which has no side walls but has a base similar to that of a platform container and a superstructure lacking any permanently fixed longitudinal load-carrying structure between the ends other than the base." The classification of the hybrid heave plate/barge/shipping bed is dependent upon the final design of the product when functioning as a shipping bed/container. Requirements for both classifications are given below, and it is noted when a requirement applies to

11.1.2 Barge Certification: Det Norske Veritas (DNV)

- *DNVGL-RU-SHIP; Part 1, Chapter 1 – General Regulations*

Part 1, Chapter 1 of DNVGL-RU-SHIP presents overarching requirements for the Certification of any particular Class (assigned by DNV) of vessel. A general overview of the broad authority delegated to DNV and its affiliates in carrying out the Certification, as it pertains to the application of the Rules for the Class of vessel, is presented in Section 1.2.5. Additional detail is provided in Section 2.1.3. Specific Rules (specifications and design requirements) that a vessel is required to comply with are given in other portions of DNVGL-RU-SHIP. It is noted that "Compliance with the Rules does not imply that a vessel is considered seaworthy. The acceptance and commissioning of a vessel is the exclusive responsibility of the Owner" (Section 1.2.3.3). DNV may grant a Certificate confirming compliance with its Rules (which indicates that a vessel meets stringent industry standards) as applicable at the time of a survey but is not liable for the operation of a vessel. Statutory Certification may be issued, or alternative certificates may be accepted by DNV, if the requirements of Section 1.4 are satisfied. A type approval (a procedure for approval of standard designs to be used in DNV classed objects) can be applied to products, groups of products, and systems; it consists of a design assessment, initial survey, type testing, and issuance of a type approval certificate. Applicable procedural requirements to obtain a Certificate from DNV are outlined below.

Section 2 of DNVGL-RU-SHIP; Part 1, Chapter 1 pertains to Quality Control:

☐ Welding procedures and welding shops approved by DNV. Requirements are detailed in DNVGL-RU-SHIP Part 2, Chapter 4 (Section 2.1.2.3).

☐ The documentation (related to quality control, material handling, work environment, etc.) listed in Section 2.1.2.4 is available upon request. All revisions to drawings, plans, specifications, technical descriptions, calculations, and data are clearly marked (Section 2.1.4.1).

☐ Test program for harbor and sea trials is provided to DNV (Section 2.1.6.2).

☐ A maintenance system for the vessel has been implemented to inspect for defects in defined intervals and record corrective actions.

Section 3 of DNVGL-RU-SHIP; Part 1, Chapter 1 pertains to vessel Class:

☐ The customer obligations outlined in Section 3.1.2.1 (related to maintenance, handling, and vessel management) are fulfilled. DNV is to be notified prior to *any* drydocking of the vessel.

Section 4 of DNVGL-RU-SHIP; Part 1, Chapter 1 pertains to vessel Certification:

☐ Compliance with Rules for material, system and components is confirmed by the types of documents as defined in DNVGL-RU-SHIP Part 1 Chapter 3, Section 5 (Section 4.2.1.1).

☐ Material handling system is documented at all levels to ensure the product is free from asbestos and an "Asbestos Free Declaration" meeting the requirements of SOLAS Ch.II-1/3-5.2 is presented (Section 4.1.2.3).

☐ Type approval of standard system designs comply with the procedure detailed in DNVGL-CP-0338 (Section 4.2.3.2).

☐ Compliance with the approved design documentation and applicable requirements is documented by certificates which are available during Surveys (Section 4.2.4.1).

- *DNVGL-RU-SHIP; Part 1, Chapter 2 – General Regulations*

  Part 1, Chapter 2 of DNVGL-RU-SHIP presents general requirements for the Certification of any class of vessel, class notations, and guidance to the associated technical requirements. Specific Rules (specifications and design requirements) that a vessel is required to comply with are given in other portions of DNVGL-RU-SHIP. As it is intended to operate, the hybrid heave plate/barge/shipping bed may be subject to the requirements of both a barge and a semi-submersible heavy transport vessel (without propulsion). Applicable requirements pertaining to barges are listed in the ***DNVGL-RU-SHIP; Part 5, Chapter 11 – Non-Self-Propelled Units*** section of the checklist. Applicable requirements pertaining to semi-submersible heavy transport vessels are listed in the ***DNVGL-RU-SHIP; Part 5, Chapter 10 – Vessels for Special Operations*** section of the checklist. The ballast system will require the hybrid heave plate/barge/shipping bed to have an additional class notation; requirements for the class notation are listed in the ***DNVGL-RU-SHIP; Part 6,***

Chapter 7 – Environmental Protection and Pollution Control section of the checklist. Additional general requirements and applicable procedural requirements to obtain a Certificate from DNV are outlined below.

☐ The design requirements of DNVGL-RU-SHIP Part 6, Chapter 7, Section 1 (checklist included below) are met such that the additional notation "BWM" can be assigned (Section 4.8).

☐ A request for descriptive notation that characterizes the operation of the WEC has been submitted to DNV (Section 6.1).

Section 5 of DNVGL-RU-SHIP; Part 1, Chapter 2 pertains to Service Area Notation:

☐ Service area restriction/notation, assigned in accordance with Table 1 of Section 5.1.1.1, is clearly identified (as it will be included in the appendix to the class certificate).

- *DNVGL-RU-SHIP; Part 3, Chapter 1 – Hull General Principles*

Part 3 of DNVGL-RU-SHIP contains all the *design* requirements that the WEC and hybrid heave plate/barge/shipping bed must satisfy prior to classification. This checklist is intended to present *certification* requirements for the hybrid heave plate/barge/shipping bed (in its function as a barge). General requirements for certification/classification are briefly referenced in Part 3, Chapter 1 of DNVGL-RU-SHIP, and applicable portions of these requirements are listed below.

Section 3 of DNVGL-RU-SHIP; Part 3, Chapter 1 pertains to Verification of Compliance

☐ All applicable certification requirements of Table 2 of Part 1, Chapter 3 are present (Section 3.1.2).

☐ Proof that the structural safety of the novel hybrid heave plate/barge/shipping bed is equivalent or better than the design rules in Part 3, Chapter 1 is submitted to DNVGL (Section 3.4.2.2).

- *DNVGL-RU-SHIP; Part 5, Chapter 10 – Vessels for Special Operations*

Part 5, Chapter 10 of DNVGL-RU-SHIP presents requirements for vessels with special operations. The hybrid heave plate/barge/shipping bed will operate as a semi-submersible ship which is considered a vessel for special operations. The associated requirements for such a vessel are listed below. Transporting the WEC will require an additional notation of "Strengthen (DK)" (mandatory for all semi-submersible heavy transport vessels). The requirements for this notation are given in the DNVGL-RU-SHIP; Part 6, Chapter 6 section of the checklist.

Section 5 of DNVGL-RU-SHIP; Part 5, Chapter 10 pertains to Semi-Submersible Heavy Transport Vessels:

☐ The design requirements of DNVGL-RU-SHIP Part 6, Chapter 1, Section 2 are met such that the additional notation "Strengthened (DK)" can be assigned (Section 1.3.1).

☐ Boundaries are capable of withstanding sea pressure at the maximum submerged draft (Section 2.1.2) and a sea trial to maximum submerged draft (including function testing of all submersion equipment) is performed (Section 1.4.1).

☐ Vertical wave bending moments have been determined through direct wave load analysis (Section 2.1.1).

☐ Vertical wave shear forces have been determined through direct wave load analysis (Section 2.1.1).

☐ The moment of inertia satisfies the requirements of DNVGL-RU-SHIP Part 3, Chapter 5, Section 2 over a quarter length of the vessel centered at midship (Section 2.1.4).

☐ High-pressure ballast tanks satisfy the requirements of Section 2.3.1 (permissible stresses listed in DNVGL-RU-SHIP Part 3, Chapter 6, Section 4 and 5) and the boundaries of all ballast tanks are designed in accordance with DNVGL-RU-SHIP Part 3, Chapter 4, Section 6 (Section 2.2.4).

☐ A strength assessment of the cargo (WEC) area has been completed in the form of a partial structural analysis, with the loading conditions specified in Section 2.4.2, in accordance with DNVGL-RU-SHIP Part 3, Chapter 7, Section 3 (Section 2.4.1).

☐ A buckling capacity calculation of the deck plate panels, using normal stresses and shear stresses from the aforementioned partial structural analysis (corrected in accordance with DNVGL-RU-SHIP Part 3, Chapter 8 and DNVGL-CG-0128), is completed (Section 2.4.3).

☐ Two independent remote sounding systems for the ballast tanks are present *if* the tanks are not always accessible for checking of level (Section 2.4.3).

☐ The stability requirements of The International Code on Intact Stability (2008 IS Code) Part A, Chapter 2 (or alternative criteria for maximum righting lever in explanatory notes to IMO 2008 IS Code) are satisfied (Section 4.1.1). The buoyancy of the WEC may be included if the watertight integrity of the WEC is considered as part of the calculations (Section 4.1.3).

☐ The additional intact stability criteria for the submerged condition of Section 4.2 is met.

☐ Damage stability meets the requirements of SOLAS Chapter 2, Section 1 or ICLL 1966 Reg, 27, including IACS UI LL65 (Section 2.1.1).

☐ The additional damage stability criteria for the submerged condition of Section 4.3 is met.

☐ Freeboard compliance for watertightness, in accordance with ICLL 1966, is documented with a freeboard plan (Section 5.1.1).

☐ Reserve buoyancy at the maximum draft condition satisfies the requirements of Section 5.3.

☐ Watertight integrity at the maximum draft condition satisfies the requirements of Section 5.4.

☐ Adequate fire extinguishing equipment is present onboard the vessel (Section 6.1).

- *DNVGL-RU-SHIP; Part 5, Chapter 11 – Non-self-propelled units*

Part 5, Chapter 11 of DNVGL-RU-SHIP presents the rules for vessels intended to be operated as barges, which the hybrid heave plate/barge/shipping bed will be held to (in part) for DNV certification per Part 1, Chapter 1 of DNVGL-RU-SHIP (DNV classification of "Barge"). The portion of the system that will act as a barge must meet the applicable strength, stability, system operation, and procedural requirements outlined below. The requirements below do not concern the transport of personnel given the condition that the mobile offshore floating structure/container is not intended to carry personnel, although safety requirements for barges intended to carry personnel are included in this portion of the standard should they become applicable.

Section 1 of DNVGL-RU-SHIP; Part 5, Chapter 11 pertains to notation and documentation:

☐ Towing arrangement and towing equipment supporting structures are submitted to DNV (Section 1.4.1.2).

Section 2 of DNVGL-RU-SHIP; Part 5, Chapter 11 pertains to the barge hull:

☐ The barge has compliant watertight and collision bulkhead arrangements (Section 2.1.1, Section 10.1.1).

☐ The barge has compliant bottom structure arrangement (supported by the bulkheads). If a double bottom arrangement is used, it follows the requirements of DNVGL-RU-SHIP Part 3, Chapter 3, Section 3 (Section 2.2.1).

☐ Hull material satisfies the requirements of DNVGL-RU-SHIP Part 3, Chapter 3, Section 1 (Section 3.3.1.1).

☐ Plans are submitted to DNV showing the arrangement, position, magnitudes, and dynamics of loads (Section 3.3.2.1).

☐ Wave loads, compressed tank air over pressure, and section moduli are compliant with DNVGL-RU-SHIP Part 3, Chapter 4, Section 2 and DNVGL-RU-SHIP Part 3, Chapter 5, Section 2 (Section 4.1, Section 4.3, Section 5.1).

☐ Buckling capacity calculations are compliant with DNVGL-RU-SHIP Part 3, Chapter 8 and DNVGL-CG-0128 Section 3 (Section 7).

☐ Fatigue strength calculations are compliant with DNVGL-RU-SHIP Part 3, Chapter 9 (Section 8).

☐ Bow impact and bottom slamming calculations are compliant with DNVGL-RU-SHIP Part 3, Chapter 10 (Section 9).

☐ Towing equipment has been proven capable of withstanding the breaking load of the towline in compliance with DNVGL-RU-SHIP Part 3, Chapter 11 (Section 9.3).

☐ Structural members are compliant with DNVGL-RU-SHIP Part 3 (Section 10.3.1).

☐ Wave-induced loads were determined according to accepted theories, model tests or full-scale measurements. Wave conditions were based on expected service area of North Atlantic eave statistics (Section 10.4.2).

☐ If a pusher is used, the stress values at the connection to the barge do not exceed those listed in Section 10.4.3. Deflections of the structural parts in the connection structure are submitted (Section 10.4.5).

Section 5 of DNVGL-RU-SHIP; Part 5, Chapter 11 pertains to stability & openings/closings:

☐ The vessel meets the intact stability requirements of DNVGL-RU-SHIP Part 3, Chapter 15 *or* the stability criteria of 2008 IS Code Part B Chapter 2.2.1 (Section 1.1.2).

☐ Drainage facilities for cargo holds, watertight compartments, and tanks are provided in an arrangement that allows for drainage to be performed in loaded conditions (Section 2.1.6).

☐ Deck openings and hatches are compliant with DNVGL-RU-SHIP Part 3, Chapter 12 (Section 2.2.2).

- *DNVGL-RU-SHIP; Part 6, Chapter 7 – Environmental Protection and Pollution Control*

Part 6, Chapter 7 of DNVGL-RU-SHIP presents requirements for additional class notations regarding environmental protection and pollution control. The heave plate portion of the hybrid heave plate/barge/shipping bed will require a ballast system. Any vessel with a ballast system must receive an additional class notation for ballast waste management. Most ports require vessels to carry out ballast water exchange or ballast water treatment, in addition to fouling and sediment management. There are separate class notations for ballast water exchange (*BWM(E[m])*) and ballast water treatment (*BWM(T)*). The requirements listed below pertain to ballast water exchange class notation and must be satisfied to obtain a "certificate of compliance ballast water exchange"; ballast water exchange at sea will be proposed as a process in lieu of treatment of ballast water. Since the hybrid heave plate/barge/shipping bed is considered a semi-submersible ship, uptake and discharge is done at the same location during loading/unloading of the ship, and there is no transport of species to be considered from one location to another. Untreated water and sediments in the ballast tank must be considered as a potential contamination source in the next location.

Section 1 of DNVGL-RU-SHIP; Part 6, Chapter 7 pertains to Ballast Water Management (BWM):

☐ A piping diagram and ballast water management plan for the ballast system are submitted to DNVGL (Section 2.2.1).

☐ There is a ballast water record book and a copy of the approved ballast water management plan aboard the vessel (Section 2.2.4).

☐ Ballast water management operations do not adversely impact the strength and stability of the vessel. (Section 2.3.1.1).

☐ The foundation of the ballast water management system has its own support structure (Section 4.5.1).

☐ The visibility requirements of SOLAS Chapter 5, Reg. 22 are satisfied during ballast water management operations (Section 2.3.3.1).

☐ The ballast arrangement is such that sediment is clear from the ballast tanks (Section 4.4.3).

☐ Detailed sediment management procedures, which comply with Section 4.5.3.1 of Part 6, Chapter 7 and follow the guidance given in MEPC.209(63) 2012 Guidelines on Design & Construction to Facilitate Sediment Control on Ships (G12), are included in the ballast water management plan (Section 4.3.1.3).

☐ Ballast water management operations are controlled from a central ballast control station (Section 4.4.4.1).

☐ The ballast water system includes sampling facilities that comply with G2 guidelines. (Section 4.5.2.1).

☐ A description of the ballasting and discharge procedures in the same location and before voyage is submitted for approval (Section 4.5.7).

- *DNVGL-RU-SHIP; Part 7, Chapter 1 – Survey Requirements for Fleet in Service*

Part 7, Chapter 1 of DNVGL-RU-SHIP presents the requirements for the surveys necessary to receive and obtain DNV classification. Surveyors from the certification entity are responsible for conducting these surveys on behalf of DNV following classification request/approval from the client. The portions of the survey requirements that apply to the hybrid heave plate/barge/shipping bed in its function as a barge, are listed below.

Section 2 of DNVGL-RU-SHIP; Part 7, Chapter 1 pertains to Annual Surveys

The annual survey will verify the following requirements:

☐ Approved loading and stability information is available onboard (Section 1.2.2).

☐ An operation/maintenance manual is readily available (Section 1.2.3).

☐ Signage and notice plates meet requirements (Section 1.2.4).

☐ Inspection/maintenance records are readily available (Section 1.2.5).

☐ For any change made, there is documentation to prove the change was approved and surveyed by DNV (Section 1.2.12).

☐ An asbestos-free declaration is readily available for any installations of new materials (Section 1.3.1).

☐ Decks, plating, openings/closings, inlets/outlets, ballast spaces, (securing) fittings, piping, cable transits, electrical installations towing and mooring systems, and other equipment are adequate (Section 2.1.1, 2.1.5, 2.1.6, 2.1.8, 2.1.14, 2.1.15, 3.1.1, 3.1.5).

☐ Hatch covers function properly when randomly tested (Section 1.2.3).

☐ Structural arrangement, shell structure, and operation of doors meet requirements (Section 2.1.4).

☐ Leakage detection and drainage systems function properly (Section 2.1.4).

☐ Results of external examinations of the bilge system, spaces, and pressure vessels are adequate (Section 3.1.1).

☐ Fire protection and general alarm systems are adequate (Section 3.1.1, 3.1.4).

Section 3 of DNVGL-RU-SHIP; Part 7, Chapter 1 pertains to Intermediate Surveys

The intermediate survey will verify the following requirements:

☐ Ballast tanks are adequate (Section 2.1.1, 2.1.2, 2.1.3).

☐ Material thickness is adequate when corrosion has been found (Section 2.1.1, 2.1.8).

☐ After 10 years, cargo space is adequate (Section 2.1.1).

☐ Electrical installations are adequate and functional, and no corrosion or unauthorized changes are present (Section 3.2.1).

Section 4 of DNVGL-RU-SHIP; Part 7, Chapter 1 pertains to Renewal Surveys

The renewal survey will verify the following requirements:

☐ Draught marks are adequate (Section 1.2.1).

☐ Material thickness is adequate in accordance with Table 5 and/or Table 8 of Section 4 of this specification (Section 2.1.1, 2.1.4, 2.1.10, 2,1.21).

☐ Hatches, doors, piping, ballast tanks, bulkheads, cargo space, decks and towing/mooring equipment are adequate (Section 2.1.1, 2.1.8, 2.1.9, 2.1.11-14, 2.1.23, 2.1.25).

☐ Results of a bottom survey, including the examination of plating, frame, openings, rudder/fins, and appendages, are adequate (Section 2.1.2 of **Section 5** DNVGL-RU-SHIP; Part 7, Chapter 7).

☐ Results of a visual examination of all components of the rudder are adequate (Section 1.2.1-5 of **Section 5** DNVGL-RU-SHIP; Part 7, Chapter 7).

☐ Watertight integrity (bulkheads, decks, and cable transits) is adequate (Section 2.1.17, 2.1.18).

☐ Results of structure boundary testing in accordance with Table 2 of Section 4 of this specification are adequate (Section 2.1.19).

☐ Auxiliary systems are function properly (Section 3.1.3).

☐ Electrical installations function properly (Section 3.1.1, 3.1.5).

Section 6 of DNVGL-RU-SHIP; Part 7, Chapter 1 pertains to Additional Class Notation Surveys

☐ Ballast Water Management documentation is readily available for the initial, annual, intermediate, complete, and any additional surveys (Section 21.2-5).

11.1.3 Heave Plate Certification: International Electrotechnical Commission (IEC)

- *IEC TS 62600-2 – Marine Energy System Design Requirements*

IEC TS 62600-2 contains all the *design* requirements that (primarily) the WEC itself and (associatively) the hybrid heave plate/barge/shipping bed system must satisfy prior to IEC Certification. Additionally, the design of the hybrid heave plate/barge/shipping bed must comply with ISO 19900 in its function as a heave plate. This checklist is intended to present *certification* requirements for the hybrid heave plate/barge/shipping bed (in its function as a heave plate). The requirements listed below are appliable design parameters specific to the heave plate (an overall mooring system) from this standard that directly correlate to certification requirements. As described in Section 1 of this standard ("Scope"), structural considerations included in IEC TS 62600-2 pertain to the primary structure, fixed foundation, and interface to mooring. The heave plate will serve as the WEC's interface to the mooring, so the load exchange between the hybrid heave plate/barge/shipping bed and the mooring must be accounted for in structural considerations. If such a configuration exists where the WEC is not moored to the sea floor, then the requirements listed below would not be applicable to the unique certification of the heave plate/barge/shipping bed system. However, the WEC itself would still have to be certified and must meet applicable requirements from this standard to receive certification though IEC as a Marine Energy Converter.

Section 5 of IEC TS 62600-2 pertains to Principal Elements

☐ A decomposition of the WEC analyzes the specific structural and functional aspects of the hybrid heave plate/barge/shipping bed, including analyses of the smallest sub-components based on their novelty and application (Section 5.3).

☐ A risk assessment, used to define the safety level of the WEC, is completed which includes the probability and consequences of different failure modes for the heave plate (Section 5.4, 5.5).

☐ The technical framework of the hybrid heave plate/barge/shipping bed is included in the basis of design for the WEC (Section 5.6).

☐ Structural analysis demonstrates that internal section forces of the heave plate do not exceed the strength of the section (Section 5.12).

Section 6 of IEC TS 62600-2 pertains to Environmental Conditions

☐ The effects of water level variation and marine growth on the hydrodynamic characteristics of the hybrid heave plate/barge/shipping bed are accounted for (Section 6.2.4.1, 6.3.7).

☐ An analysis of seabed movement and scour demonstrates that mooring system is designed with appropriate protection in accordance with ISO 19901-4 (Section 6.3.8).

Section 7 of IEC TS 62600-2 pertains to Design Load Cases

☐ Condition after loss of station keeping is considered (Section 7.3.7.12).

Section 10 of IEC TS 62600-2 pertains to Control Systems

☐ A risk assessment of the ballast system for the hybrid heave plate/barge/shipping bed is completed (Section 10.5.3).

Section 11 of IEC TS 62600-2 pertains to Mooring and Foundation Considerations

☐ The mooring attachment point on the heave plate is designed not to fail before mooring system elements (Section 11.1).

☐ When functioning as a heave plate, the system is capable of carrying static and dynamic actions without excessive deformation or vibrations to the WEC; Analysis shows that the effects of repetitive and transient actions on the structural response of the WEC and strength of supporting soil are adequate (Section 11.4).

☐ Loads acting on the system foundation during transport and installation are considered (Section 11.4).

Section 12 of IEC TS 62600-2 pertains to Life Cycle Considerations

☐ Drawings for the hybrid heave plate/barge/shipping bed in its function as a heave plate are generated (Section 12.1).

☐ A Quality Assurance Plan and workmanship procedures are documented (Section 12.1).

☐ Procedures for the installation of mooring lines are established (Section 12.1).

☐ The stability (calculated with consideration given to mass, buoyancy, and density uncertainties) and watertight integrity of the hybrid heave plate/barge/shipping bed in its function as a heave plate is in compliance with DNV-OS-C301 (Section 12.3.1, 12.3.2).

☐ Lubrication, pre-service conditioning, and tightening of threaded fasteners is completed prior to inspections (Section 12.4.1, 12.4.2).

☐ Installation, lifting, and handling instructions are established (Section 12.4.3).

☐ Damage control contingencies and monitoring systems are established for the transportation of the WEC/heave plate when the hybrid heave plate/barge/shipping bed functions as a barge (Section 12.5).

☐ Lashing and sea fastening for inertial loads are considered for the transportation of the WEC/heave plate when the hybrid heave plate/barge/shipping bed functions as a barge (Section 12.5).

☐ A plan to alter the modularity of the hybrid heave plate/barge/shipping bed at sea (which considers dynamics, center of gravity/buoyancy transitions, and irreversible launching procedures) is established (Section 12.5, 12.10).

☐ Contingency plans for the breaking loose (and subsequent retrieval) of the hybrid heave plate/barge/shipping bed in its function as a heave plate are established (Section 12.6).

☐ Contingency plans for the structural failure of the hybrid heave plate/barge/shipping bed in its function as a heave plate established (Section 12.6).

☐ Contingency plans for mooring line failure are established (Section 12.6).

☐ Installation and heave plate deployment procedures incorporate strategies to quickly secured all components without causing unacceptable loads on the WEC (Section 12.6).

☐ Weather windows with specified limits on the sea state parameters during which heave plate operations can be performed are established (Section 12.7).

☐ A strategy for inspection (including inspection of the coatings) and possible removal of marine growth (which considers potential environmental impacts) for the WEC, including the hybrid heave plate/barge/shipping bed, is established (Section 12.8.3, 12.9.3).

Annex A of IEC TS 62600-2 pertains to Corrosion Protection

☐ The hybrid heave plate/barge/shipping bed is given adequate corrosion protection based on the corrosion zone it will reside in during its function as a heave plate (Section A.1).

- *IEC TS 62600-4 – Specification for Establishing Qualification of New Technology*

The WEC itself will need to be certified through the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE). As part of the WEC system when functioning as a heave plate, portions of this certification pertain to the hybrid heave plate/barge/shipping bed. "Technical Qualification" through IEC allows a system, such as the hybrid heave plate/barge/shipping bed which may not entirely conform to existing certification standards, to be certified. IEC TS 62600-4 broadly describes the requirements, regarding technology qualification methodology, to support the IECRE certification process. Portions of this standard which are applicable to the hybrid heave plate/barge/shipping bed system are listed below.

☐ Potential risks associated with the hybrid heave plate/barge/shipping bed system are mitigated though testing and design studies. A combined technology and risk analysis results in the generation of a Technology Appraisal Report (Section 5).

☐ A qualification basis, consisting of component specifications, operating conditions, system integration, and performance/reliability targets, is decomposed specifically to address the hybrid heave plate/barge/shipping bed. This information is prepared by C·Power to be used for a technology assessment and risk assessment (Section 6.3, 6.4).

☐ A technology assessment is completed per Section 6.6 and includes installation, float-out, lifting, and transportation (deployment/retrieval) considerations in the feasibility documentation (Section 6.6).

☐ A risk assessment is completed per Section 6.8 and includes a risk matrix (FMECA, HAZID, SWIFT, etc.), used for a criticality assessment, compliant with Annex A (Section 6.8, 6.10).

☐ The Technical Qualification Plan (the deliverable of the technology qualification process) incorporates the content listed in Section 7.1 and is structured in accordance with the format given in Annex E (Section 7).

☐ Development of a Technology Qualification Plan per Section 6.11, which is subject to updating, results in the generation of a Statement of Feasibility (Section 5).

- *IEC TS 62600-10 – Assessment of Mooring Systems for Marine Energy Converters*

IEC TS 62600-10 contains all the technical requirements for WEC mooring systems; the hybrid heave plate/barge/shipping bed system will be a portion of the mooring system for the C·Power SeaRAY WEC as the heave plate will serve as the WEC's interface to the mooring. Applicable portions of this standard which relate to the contributions of the interface between the heave plate and mooring system to the requirements that must be met for the certification of the WEC are listed below. If such a configuration exists where the WEC is not moored to the sea floor, then the requirements listed below would not be applicable to the unique certification of the hybrid heave plate/barge/shipping bed system.

☐ The hybrid heave plate/barge/shipping bed meets Technical Qualification requirements (see *IEC TS 62600-4* checklist) (Section 5.2).

☐ Risks associated with the design, installation, operation, and maintenance of the mooring system, and their potential effects on the heave plate, are assessed in accordance with Annex B (Section 5.3, 5.4).

☐ Specific load cases and limiting state analysis at the interface of the mooring line and heave plate are considered during the design of the mooring system (Section 5.5).

☐ The effect of marine growth on the hydrodynamic properties and dynamic response of the hybrid heave plate/barge/shipping bed is accounted for (Section 6.3.2).

☐ The potential effects of noise generated by rattling of heave plate components on sensitive marine animals is accounted for (Section 6.4.2).

☐ Accessibility of mooring components is limited as necessary to deter the misuse as a tie-off and entanglement of the hybrid heave plate/barge/shipping bed with sport and commercial/fishing vessels (Section 6.4.4, 6.4.5).

☐ The effects of wind and wave drift on the heave plate are included in the analysis of loads on the mooring system (Section 7.3.1).

☐ Dynamic modeling simulations (or alternative conservative analyses), in accordance with Annex C, demonstrating consistent peak responses generated for each sea state incorporate inertia, damping, and stiffness of the hybrid heave plate/barge/shipping bed and WEC (Section 7.3.2, 7.3.6.4, 7.7.9).

☐ The fatigue life of socket connections (and other discontinuities) between mooring lines and the heave plate is assessed for vortex induced vibrations (Section 7.3.6.2).

☐ Fatigue life of mooring system components is determined in accordance with Clause A.9 of ISO 19901-7:2013 (Section 7.5.3).

☐ The consequences of mooring line impact with the hybrid heave plate/barge/shipping bed and WEC, with consideration to potential marine growth, is investigated (Section 7.5.5).

☐ The performance of the WEC and mooring system is described with reference to the ultimate limit state, accidental limit state, serviceability limit state, and fatigue limit state (Section 7.7).

☐ Mooring system component strength is calculated as a factor of minimum breaking load and design tension (Section 7.7.7).

☐ The potential effects on mooring system component fatigue life from the transition of the function of the hybrid heave plate/barge/shipping bed as a barge to its function as a heave plate (and its subsequent installation mooring) must be investigated (Section 7.7.10.10).

☐ In-service inspection of mooring system components is in accordance with American Petroleum Institute RP 2I guidance (Section 8.1).

☐ Safe operating limits (environmental conditions, etc.) of mooring system components and equipment are defined for installation operations (Section 8.6).

11.1.4 Certification of Tidal and Wave Energy Converters

- *DNV-OSS-312 – Certification of Tidal and Wave Energy Converters*

As an alternative to IEC certification, it is also possible to certify a WEC to DNV standards. DNV currently provides services for certify floating wind energy mechanisms, underwater working machines, and various other marine technologies. The novel system intended to serve as a hybrid heave plate/barge/shipping bed does not entirely match the criteria of any one of these certification options. However, when functioning as a heave plate, the system may be considered part of the mooring apparatus for the WEC. All components of wave energy converters certified by DNV are ultimately certified through DNV-OS-312, which culminates with a DNV Tidal and Wave Energy Converter Certificate and an associated DNV Project Certificate if successfully validated by DNV. Applicable portions of this standard pertaining to specifically to (the hybrid heave plate portion of) the mooring apparatus are listed below.

☐ The entirety of the mooring system is analyzed in detail as part of the prototype design evaluation which is required for the Project Certificate request (Section 1.E.107/110).

☐ To qualify the hybrid heave plate as new technology, the following are submitted with the request for certification: Failure Mode Identification & Risk Ranking, Concept Improvement, Section of Qualification Methods, Probability of Success Evaluation, Analysis & Testing, and Reliability Assessment (Section 2.A.201/202/206).

☐ To qualify the hybrid heave plate as new technology, the performance limits, boundary conditions, interfacing requirements and functional, safety, and environmental targets are based on the certification basis (Section 2.B.201/301).

☐ To qualify the hybrid heave plate as new technology, the functionality and limiting operating parameters for system are analyzed using assumed loadings and the identification of failure modes and their associated risks (Section 2.B.301).

☐ To qualify the hybrid heave plate as new technology, reliability data is collected and used to evaluate the risk of not meeting the specifications through experience, numerical analysis, and testing (Section 2.B.301).

☐ To qualify the hybrid heave plate as new technology, a functionality assessment, statement of feasibility, and documentation of fitness for service are included in the Project Certificate request (Section 2.B.301/601).

☐ It is demonstrated that the transportation and float-out phases do not affect the feasibility of the hybrid heave plate concept and integrity of the WEC (Section 2.A.302).

☐ Fabrication specifications, welding procedures, and corrosion protection documentation for the hybrid heave plate are included in the Project certificate request (Section 3.B.101).

☐ Analysis and testing demonstrating that the entirety of the mooring system is capable of surviving site conditions for the lifetime of the basis of certification is included in the Project Certification request (Section 3.B.401).

☐ Documentation of mooring line tensions and fatigue calculations of mooring line segments and accessories, such as the hybrid heave plate, are included in the Project Certificate request (Section 3.C.101).