OUTERLIMITS OFFSHORE POWERBOATS

Fine-tuning with FEA

Outerlimits Offshore Powerboats turns to finite element analysis to optimize laminates for its existing model line and for new designs.

Text by Dave Fornaro

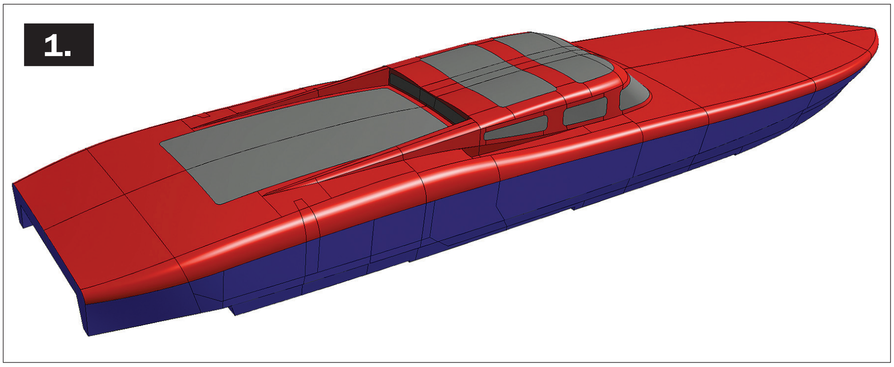
Graphics by Outerlimits and Ariston Technologies (except where noted)

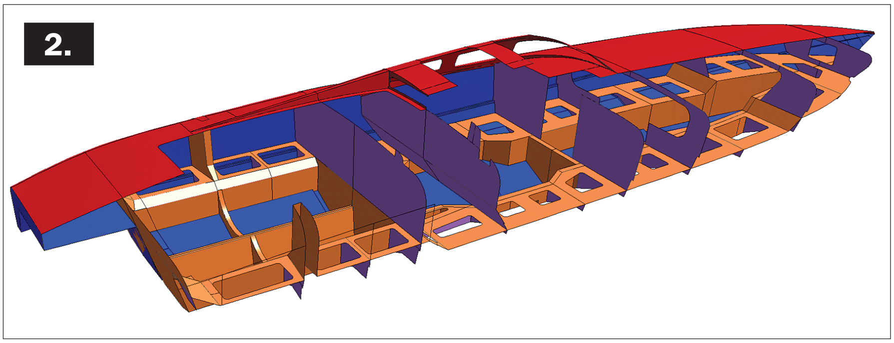
Above—Ariston Technologies optimized the 43 SV (13.2m) from Outerlimits Offshore Powerboats by employing finite element analysis (FEA). The focus in evaluating the company's laminates was to reduce materials cost for the entire model line while retaining its performance and reliability.

Outerlimits Offshore Powerboats, in Bristol, Rhode Island, has been at the forefront of high-performance powerboat design and manufacturing for nearly two decades. Under president Mike Fiore's leadership, the company has amassed impressive victories in offshore powerboat racing, as well as in innumerable recreational poker runs. With boats running at speeds exceeding 160 mph (258 kmh), developments and advancements in racing inevitably filter down, improving the company's full line of custom and semi-production boats. One area of particular benefit is its high-quality composites construction: vacuum-bagged epoxy wet-preg carbon and E-glass yield strong, lightweight, and void-free laminates. A team with more than two decades' experience produces these repeatable, cost-effective laminates for limited-production boats that have a record for structural reliability.

Over the years, Outerlimits has developed a suite of standard laminates, based on in-house experience, materials-supplier recommendations, and composites engineering support. For the past year, the company has been working with Ariston Technologies (Kingston, Rhode Island) to optimize laminates for its current production line and for new designs still in development. The emphasis is on reducing materials cost while maintaining the brand's performance and reliability.

Methodical optimization began with a basic assessment of panels and stiffeners by applying classical laminate theory, continued with a calculation of conformance to high-speed light-craft scantling rules, and ended with full optimization utilizing finite element analysis (FEA). While the first two steps are invaluable for initial design work and standards-based assessments, FEA is the only way to understand and visualize the performance of the structure as it is subjected to the full range of operating loads. The three methods together make a well-rounded tool kit for the composites engineer.





*An FEA model begins with developing a surface model of the hull, deck, and internal structure with computer-aided design. **1**—The thin black lines represent the intersections of all structural elements. **2**—The internal structure is a one-piece carbon fiber and E-glass liner with transverse bulkheads and webs.*

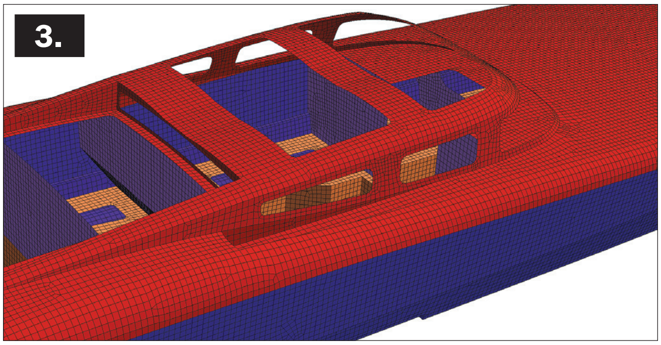
In this article, we'll outline FEA optimization for the Outerlimits 44 SL (44′4″/13.5m) and 43 SV (43′5″/13.2m) models; they share the same basic hull and internal structure but have different deck layouts. A comprehensive overview of all aspects of the optimization results is not possible here, so we'll describe the process, which can be applied to any custom or production boat to improve strength and durability, or reduce weight and cost, or both.

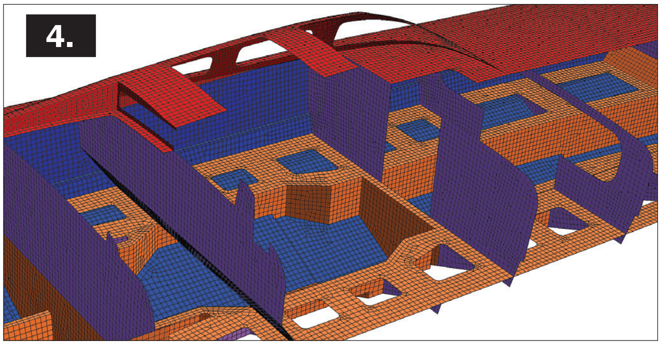
Building a Model

Building a finite element model begins with a computer-aided-design surface model. Surface models are preferable to solid models, although the former can be extracted from a solid model with some additional effort. (For more on the basics of FEA, see *Professional BoatBuilder* No. 78, page 26.) **Figures 1** and **2** show the surface geometry for the 43 SV, including a full representation of the hull, deck, and internal structure. The internal structure consists largely of a one-piece carbon/E-glass liner that provides the longitudinal structure, including the engine mounts. The liner is bonded to the hull in one step with Plexus adhesive. Transverse bulkheads and webs are subsequently laminated in situ to complete the full internal arrangement. Note that for the purposes of creating a contiguous finite element mesh throughout, coincident surface boundaries are required at all intersecting structural elements and at the intra-panel extents of any reinforcement plies. These boundaries can be seen in the figures as thin black lines on the various surfaces.

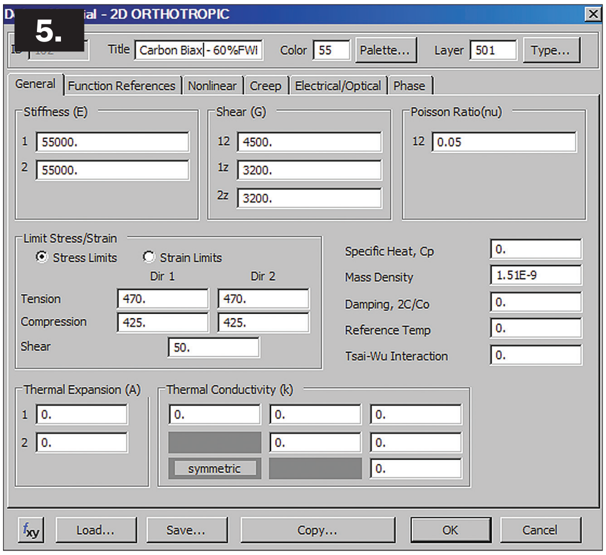
With the surface geometry prepared, the finite element mesh is then created with specialized pre-processing software (Femap) that works with a finite element solver (NEi/Nastran). Producing a quality mesh is essential for accurate results (see the sidebar on page 50). The mesh in the midbody area of the boat is shown in **Figures 3** and **4**. Most notable is the consistent arrangement of largely quadrilateral elements with a 1:1 aspect ratio and little warp or skew, as evidenced by the consistently equal length of orthogonal element edges throughout the model.

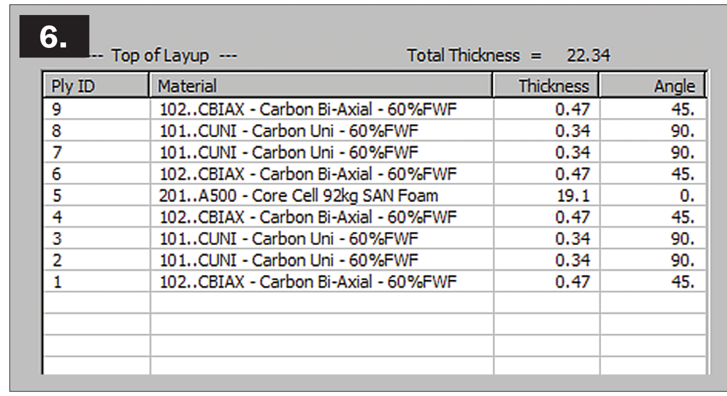
Once the mesh is complete, material properties are assigned to each region of the model, representing the combination of all base laminates plus any reinforcements. Composites are orthotropic materials (meaning their properties are *not* the same in all directions) that require significantly more information to characterize as compared to isotropic materials, whose properties *are* the same in all directions. Material properties start with definitions of the





The next step is creating the finite element mesh prepared with pre-processing software. Shown here is the mesh in the midbody area of the exterior and interior hull, deck, and canopy.




6.

--- Top of Layup --- Total Thickness = 22.34

Ply ID	Material	Thickness	Angle
9	102..CBIAX - Carbon Bi-Axial - 60%FWF	0.47	45.
8	101..CUNI - Carbon Uni - 60%FWF	0.34	90.
7	101..CUNI - Carbon Uni - 60%FWF	0.34	90.
6	102..CBIAX - Carbon Bi-Axial - 60%FWF	0.47	45.
5	201..A500 - Core Cell 92kg SAN Foam	19.1	0.
4	102..CBIAX - Carbon Bi-Axial - 60%FWF	0.47	45.
3	101..CUNI - Carbon Uni - 60%FWF	0.34	90.
2	101..CUNI - Carbon Uni - 60%FWF	0.34	90.
1	102..CBIAX - Carbon Bi-Axial - 60%FWF	0.47	45.

5—These are typical ply properties for biaxial carbon fiber/epoxy that show stiffness, strength, and mass density. ***6—****After determining the stacking sequence and the ply orientation within each laminate zone, analysts can create a laminate definition, shown here.*

stiffness and strength characteristics for each type of ply (single layer of material) in the model. **Figure 5** shows typical ply properties for a biaxial carbon fiber/epoxy at a 60% fiber weight fraction (FWF). Note that the unit system is N-mm-s yielding stiffness and strength in MPa and mass density in tonne/mm^2. Some common materials at Outerlimits that are incorporated into this model include 400-g/m^2 (12-oz/sq-yd) biaxial carbon, 300-g/m^2 (9-oz/sq-yd) unidirectional carbon, 800-g/m^2 (24-oz/sq-yd) biaxial E-glass, and 565-g/m^2 (17-oz/sq-yd) double-bias E-glass. A limited amount of chopped strand mat is applied against the molds to reduce print-through and to provide a production-quality surface finish. Core material is typically Corecell of varying grades, ranging from approximately 90 kg/m^3 to 120 kg/m^3 (5.6 lb/cu ft to 7.4 lb/cu ft), with Nomex honeycomb in lighter weights sometimes employed for higher-performance custom boats and raceboats.

Plies are then combined into laminates; these define the stacking sequence of individual plies (typically relative to the molded surface) and their orientation (relative to a base material orientation vector). **Figure 6** shows a typical laminate definition. Definitions are created for each distinct laminate zone within the model, respecting all combinations of base laminates plus reinforcements (about 30 zones in this case). Laminate definitions are then assigned as element properties for each zone. (See sidebar for more details required to fully define orthotropic material properties.)

The final step in model building is to define the loads. While the general nature of the loads is often relatively easy to identify, magnitudes are not. Short of running a boat in a variety of conditions with full instrumentation to record accelerations and strains, you must make estimates. Beyond good judgment, scantling rules can provide guidance as they dictate accelerations and panel pressures based on a combination of first principles and empirical data. While there are no directly applicable scantling rules for boats capable of exceeding 160 mph (258 kmh) in flat water and maintaining 100–110 mph (161–177 kmh) in rough offshore conditions, it's advisable to ground FEA optimization in a scantling-based assessment to provide guidance on loads and an indication of where the current laminates fall in relation to a known and accepted standard. We chose the Det Norske Veritas (DNV) High Speed Light Craft rule.

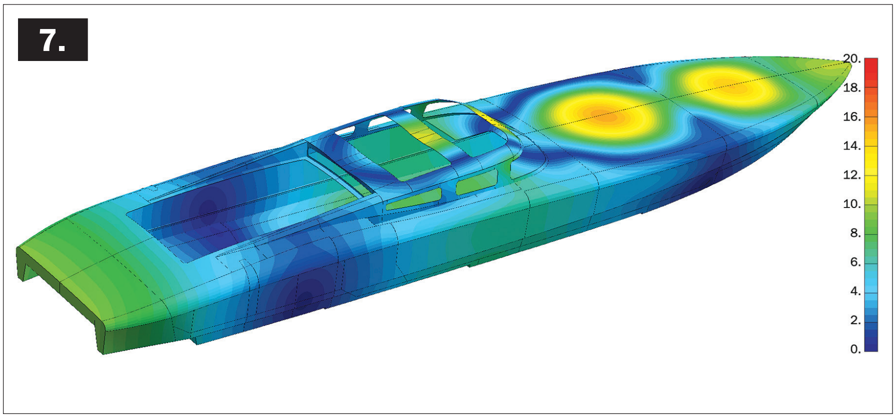
Scantling-Based Assessment

While the DNV rule has no specific category for assessing raceboats or very high-speed recreational boats, it does have a category for somewhat slower but often brutally punished patrol craft that can see extremely high slamming loads. For design purposes the rule provides a means for determining vertical and horizontal accelerations and maximum slamming pressures across a range of vessel types and service areas (corresponding to distance offshore). For our analysis we applied the essentially unrestricted service area designated for Patrol Craft, which yielded a design vertical acceleration of 7.7 g and a maximum bottom-slamming pressure of 119 kN/m^2 (12.1 tonne/m^2). Following the scantling calculations through to completion for the bottom, topsides, deck, transverse frames, bulkheads, longitudinal stringers, and girders showed that the current structure generally meets the DNV requirements for these conditions, and in most cases there is additional margin ranging from 1.5X to 3.0X beyond the DNV requirements.

We then carried over this acceleration and maximum bottom-slamming pressure into the FEA model as a baseline for optimization. We applied the 7.7-g acceleration for global analysis of deflection and stress, reacted with a uniformly distributed bottom pressure providing an equal- and opposite-force balance. We ran variations of the global acceleration for full-bottom impact (belly flop) as well as for stern-down and bow-down impacts. We also studied additional variations that incorporate a roll component to evaluate the topsides as well as the bottom panels. The 119 kN/m^2 maximum slamming pressure was applied for local individual panel analyses. Although the loads are dynamic, we ran the analyses with a quasi-static approach, applying dynamic load magnitudes without the time-varying component. (Dynamic analyses with the time-varying component of the load application can also be run, but are more time consuming and resource intensive, and are usually reserved for special cases.)

Typical results are presented for the upright, full-bottom impact, 7.7-g vertical-acceleration load case. Note that the interrogation of composites FEA results is a complex and time-consuming process. With multiple load cases, tens of laminates, hundreds of individual plies, several different stress/strain components for each ply, and specialized composite failure indices, the volume of data produced is enormous. The images here provide an overview of the type of information that can be gleaned, but are by no means exhaustive.

Deflection for the global analysis is shown in **Figure 7**. Two points are worth noting. First, looking along the



According to the color scale, dark blue areas on the hull and deck indicate zero deflection, while the two large yellow circles show relatively high downward deflection in the foredeck panels where there are rather large longitudinal spans between the bulkheads.

Strength in Numbers

The main text provides an overview of building a finite element model. Below are several areas that require finer detail to fully characterize laminated composite materials and to evaluate the results of the finite element analysis.

Ply Properties

Accurate characterization of ply properties is crucial to analysis results and must include correct data for each of the following six stiffness values:

- E1 = Elastic modulus in one-fiber (parallel) direction
- E2 = Elastic modulus in two-fiber (transverse) direction
- G12 = Shear modulus in 12-plane
- G13 = Shear modulus in 13-plane
- G23 = Shear modulus in 23-plane
- υ12 = Poisson's ratio in 12-plane

To evaluate the results with a composite failure criterion, the following five strength values are required:

- σ1t = Tensile strength in one-fiber (parallel) direction
- σ1c = Compressive strength in one-fiber (parallel) direction
- σ2t = Tensile strength in two-fiber (transverse) direction
- σ2c = Compressive strength in two-fiber (transverse) direction
- τ12 = Shear strength in 12-plane

Figure S1. Typical Mechanical Values of Epoxy Prepreg Laminates

t 90° / 0°; Volume content of fibers: ≈ 60% (carbon) ≈ 50% (E-glass - aramid))		Units	E-Glass UD	E-Glass Fabric	Aramid UD	Aramid Fabric	High-Strength Carbon UD	High-Strength Carbon Fabric	Intermediate-Modulus Carbon UD	Intermediate-Modulus Carbon Fabric
Tensile	σ/ ǀǀǀ	MPa	1,100	600	1,100	500	2,000	800	2,400	900
	σt ≡	MPa	35	550	35	450	80	750	80	850
	E/ ǀǀǀ	GPa	43	20	60	30	130	70	170	90
	Et ≡	GPa	8	19	8	30	9	65	9	90
	Poisson's ratio υ/t		0.28	0.13	0.34	0.2	0.25	0.05	0.27	0.05
Compression	σ ǀǀǀ	MPa	900	550	250	150	1,300	700	1,600	800
	σt ≡	MPa	150	500	150	150	250	650	250	750
	E/ ǀǀǀ	GPa	42	17	75	31	115	60	150	80
	Et ≡	GPa	10	16	5.5	30	10	55	11	75
Flexure	σ/ ǀǀǀ	MPa	1,200	700	550	400	1,800	1,000	1,400	1,200
	E/ ǀǀǀ	GPa	42	20	40	25	120	65	140	75
In-plane shear	σ/t	MPa	60	55	45	40	95	80	95	80
	G/t	GPa	4	4.2	2.1	4	4.4	5.5	4.4	5
Interlaminar shear	σ ǀǀǀ	MPa	75	50	60	50	80	70	80	70

HEXCEL

Gathering this data is not always easy. Ply properties can come from theoretical calculations or from physical testing. Theoretical calculations of ply properties are based on micromechanics theory for combining individual matrix and fiber properties to predict cured ply properties. Alternatively, physical testing of plies can be carried out to determine strength and stiffness properties. Testing is the best way to characterize the results of a builder's processing techniques—to ensure the engineered product is representative of what the builder can deliver. If in-house test panels cannot be made, most materials suppliers offer standardized test data but don't always include all the above constants, so data from various sources will sometimes have to be judiciously combined to round out the picture. Keep in mind that ply properties depend on fiber weight fraction, which can vary with the lamination process. It is crucial that the data you employ are appropriate for your process. **Figure S1** shows some typical ply property data from Hexcel based on carbon

Continues on page 52.

topsides you can see two nodes of zero deflection at roughly 30% and 80% of LOA. The overall longitudinal bending deflection reflects a hogging condition, i.e., an arched shape with the midbody deflected upward and the ends deflected downward. With a uniform bottom-pressure load applied, this hogging shape is a reflection of the surface area distribution along the bottom, with the wider midbody having more area (and hence pressure) than the tapered ends. Second, there are two nodes of relatively high downward

Continues from page 50.

fiber at 60% fiber weight fraction, and E-glass and Kevlar at 50% FWF.

Laminate Definition Vectors

Beyond combining plies in a stacking sequence, to fully characterize its properties the definition of a laminate also importantly includes two vectors: material orientation and normal direction. These vectors must be defined for every element in the model.

Material orientation vectors are in-plane vectors for each element that define the direction relative to which orthotropic ply properties for the laminate are applied (i.e., if a ply is laid down at 0/90, which way is 0?). Material orientation vectors and the laminate stack definition *must be* developed in conjunction so the resulting properties are correct. These vector directions should be defined with an understanding of how individual plies will be laid down in the mold, so the model properties represent what will be achieved in production. An example of the definition of material orientation vectors is shown in **Figure S2**.

Normal direction vectors are out-of-plane vectors for each element that define the direction of the ply stack, typically relative to either a mold surface (hull and deck) or a center-plane (internal structure). An example of the definition of normal direction vectors is shown in **Figure S3**. Again, it is imperative to carefully set normal direction vectors to represent the correct thickness offset so that the overall stiffness of the laminate is accurately computed.

Composite-Failure Theories

Strength analysis of composite materials is more complex than that of isotropic materials, due to the orthotropic nature of each ply, and to the many combinations of plies and their interactions with one another across the model. Except in simple cases (say, single plies or entirely unidirectional laminates), it's easiest to evaluate the laminate strength using one or more failure theories specific to orthotropic materials.

Decades of research have yielded a multitude of composite failure theories. Some are general and apply to any orthotropic material, while others have specific limitations (such as unidirectional only or specific material types). Typical failure theories in many commercial FEA programs include Hill, Hoffman, Tsai-Wu, LaRC02, Puck, Maximun Stress, and Maximum Strain.

The Maximum Strain and Maximum Stress theories are termed *non-interactive* since they evaluate the effects of the two orthogonal in-plane principal strains/stresses and the in-plane shear strain/stress in isolation from one another, with failure predicted based on any one of the three exceeding the ply limit for that quantity. While these theories do not accurately predict failure for multi-axial stress states, they can still help in evaluating principal stress directions; and vectors associated with these constituent stresses can guide in applying reinforcements to best handle areas dominated by highly directional loads.

The Hill, Hoffman, Tsai-Wu, LaRC02, and Puck theories are all *interactive* in that they consider together the contributions of the principal and shear strains, with failure predicted based on a mathematical combination of their effects. Other advanced theories have emerged and are continuing to be developed, notably the Multi-Continuum Theory, which can separately predict failure for the constituent fiber and matrix (similar to LaRC02, but not restricted to unidirectional plies).

Correctly characterizing the composite materials in the model-building phase and then choosing the proper criteria for evaluating the results are important steps to ensure that your investment in composites FEA yields productive information.

—Dave Fornaro

Figure S2.

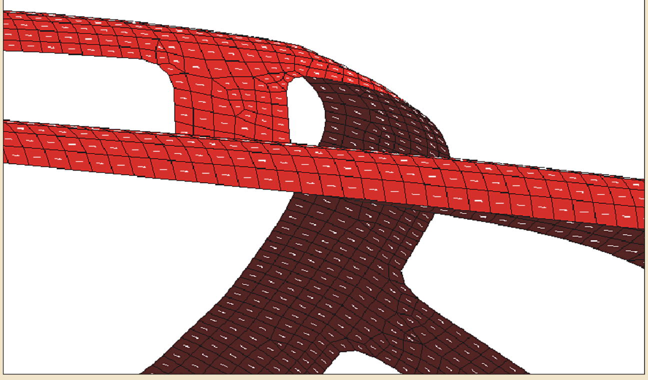
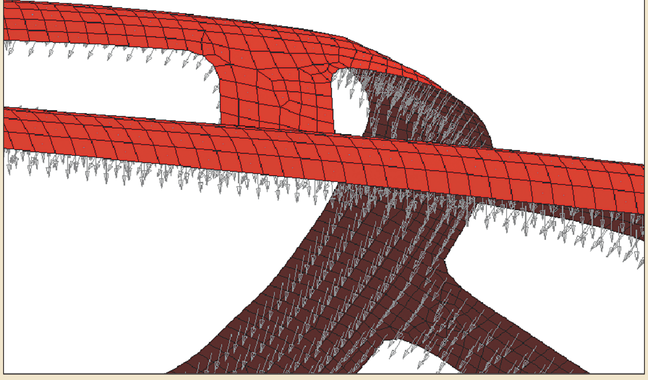
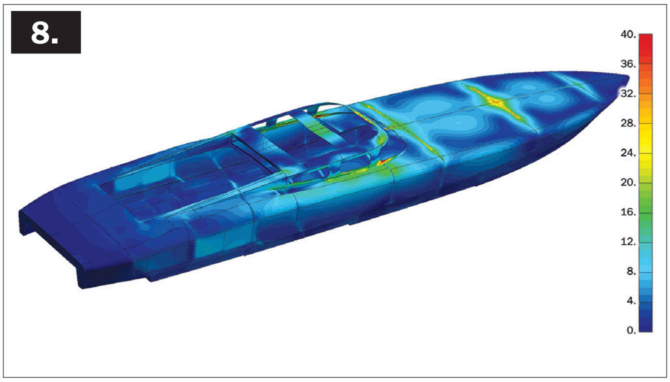
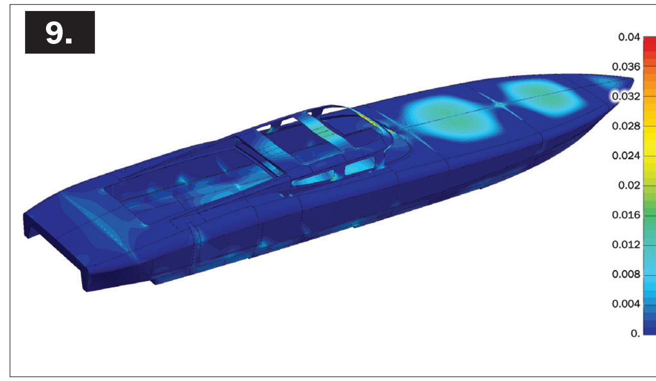


Figure S3.



*In addition to the laminate's stacking sequence, you must define its material orientation vector and normal direction vector. **S2—**Material orientation vectors define the direction a layer will be laid and must be developed in conjunction with the laminate stack definition. **S3—**An example of normal direction vectors.*



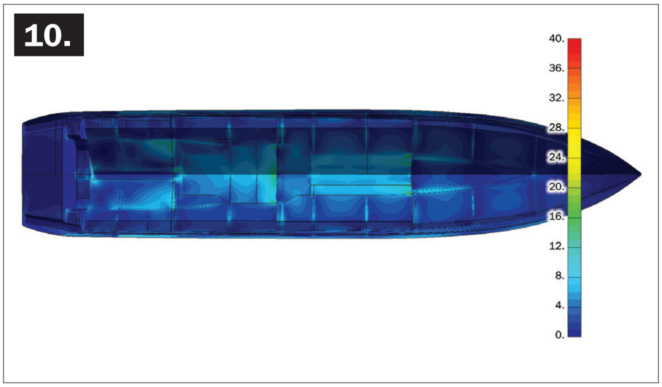


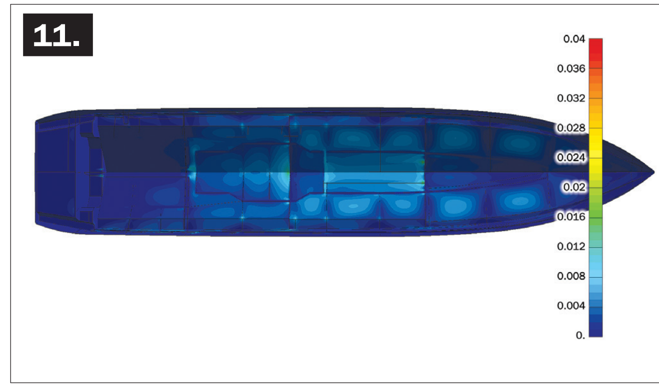
8—Composite equivalent stress combines the effects of tension, compression, and maximum shear stresses to represent an overall stress value for the laminates as a whole. The panel stresses are low, but hot spots appear in the deck at the forward transverse bulkheads. 9—A plot of the Tsai-Wu composite failure index, a common predictor of ply failure. This image shows the effects of deflection and stress results from Figures 7 and 8. The overall panel safety margin is high, but slightly altering the longitudinal deck stringer could improve it.

deflection in the foredeck panels. These panels have relatively large longitudinal spans between the supporting transverse bulkheads and athwartship spans between the sheer and the centerline deck stiffener.

Figure 8 shows composite equivalent stress, combining the effects of maximum principal (tension), minimum principal (compression), and maximum shear stresses. This is an overall stress value for the laminates as a whole, lacking any specific information on individual ply stresses. Generally the panel stresses are fairly low, but there are local hot spots in the deck in way of panel supports at the forward transverse bulkheads.

Because each ply has different strength properties in each direction, and because there are plies of different material and weight within each laminate zone, a simple stress-based approach generally cannot predict whether or not a panel is nearing failure. Instead, composite failure theories are employed to predict the combined



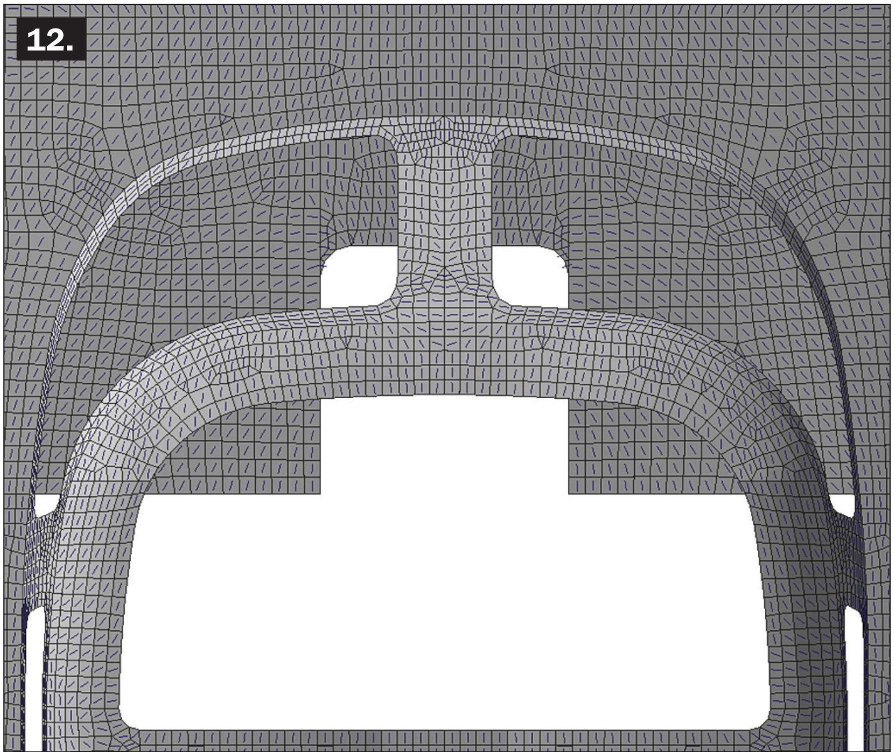


*Stress **(10)** and failure **(11)** index plots for the hull bottom's outer E-glass biaxial ply. The asymmetry of stresses around the aft steps is due to the staggered engine installation.*

damage due to the in-plane tension, compression, and shear stresses relative to the strength properties of each ply.

For a biaxial E-glass outer ply, **Figure 9** shows a plot of the Tsai-Wu composite failure index—a fairly common and generally conservative predictor of ply failure. A failure index is essentially the inverse of a safety factor. A value of 1.0 indicates the onset of first ply failure, with values below 1.0 having a safety margin, and values above 1.0 having failed. The results shown in this image reflect the effects of the deflection and stress results from the prior two images. Overall panel safety margin is quite high, but stress concentrations at bulkhead supports result in areas of lower (but still sufficient) safety margin. In these areas, thin reinforcement strips and/or additional taping in way of the intersections can easily improve the situation with minimal additional weight. A revised longitudinal deck stringer arrangement could also reduce the midpanel deflections *and* the boundary stresses.

Figures 10 and **11** show stress and failure index plots respectively for the hull bottom's outer E-glass biaxial ply. The overall panel stresses and failure indices are low, with a few local hot spots in way of the transitions at the transverse steps in the hull. The slight asymmetry seen in the hot spots at

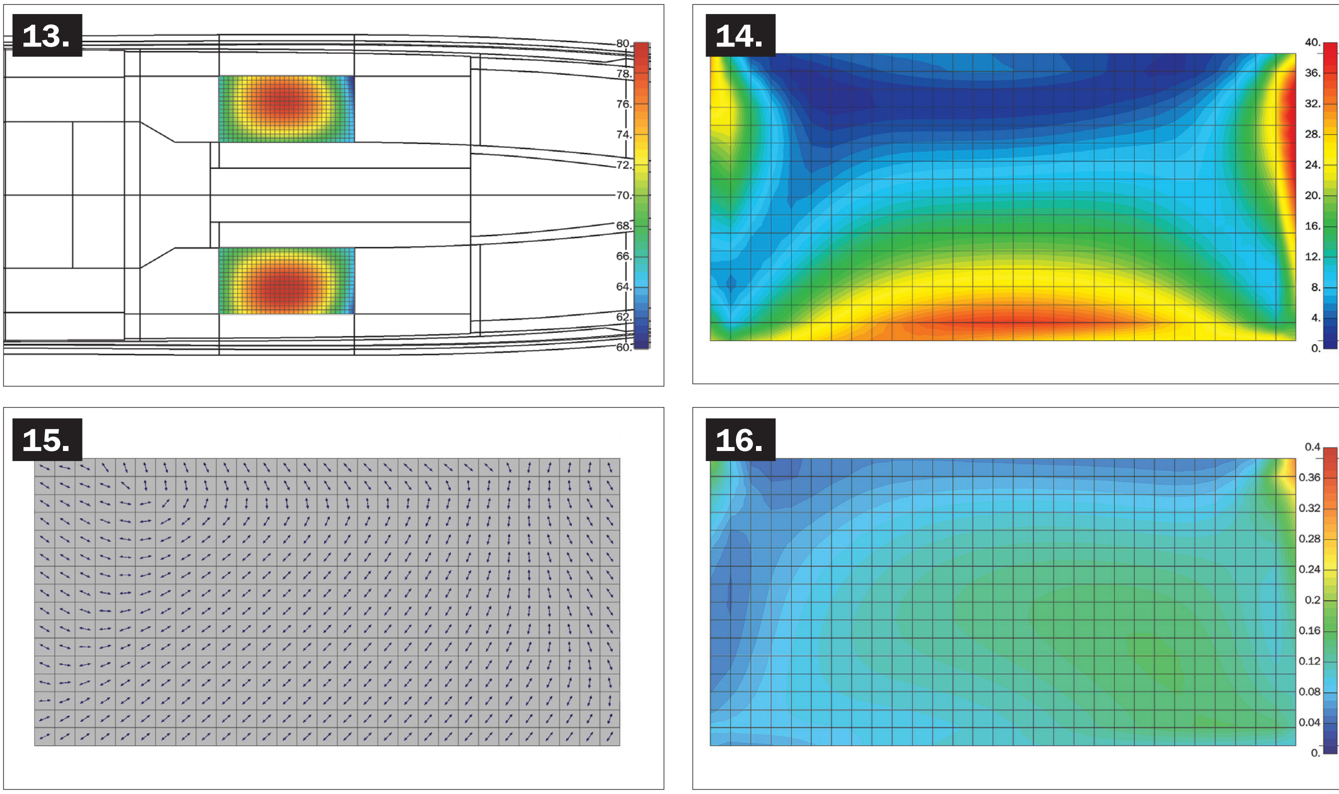


A vector plot aids in understanding the flow of tension, compression, and shear stresses in a structure. Here, the maximum principal stress directions are shown for a biaxial E-glass ply in the deck canopy.

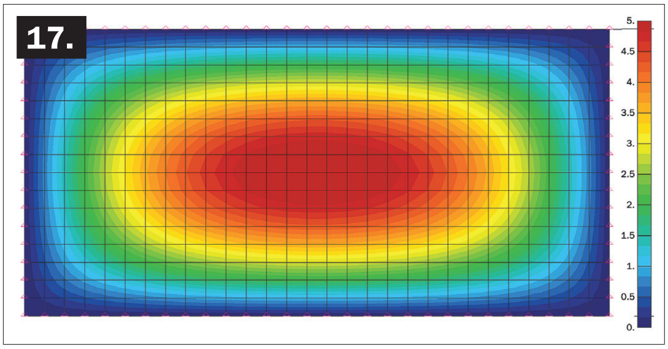
about 70% LOA is due to the longitudinally staggered engine locations, with the port engine at the forward end of the engine bay and the starboard engine at the aft end. The offset weights of the engines somewhat bias the local bottom panel stresses when subjected to the 7.7-g vertical acceleration.

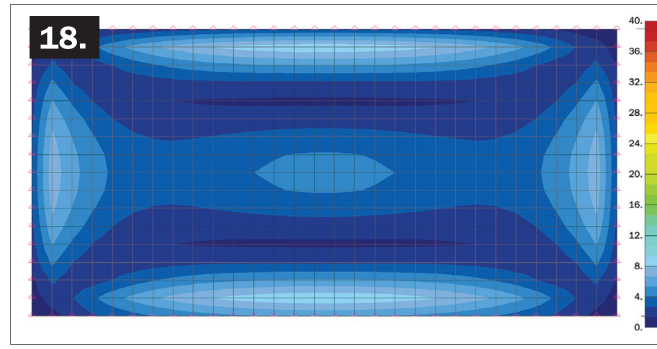
In addition to color contour plots, another useful output is vector plots for the principal stress directions. These can aid in understanding the flow of tension, compression, and shear stresses throughout the structure. In conjunction with failure index plots, vector plots help orient base laminates and reinforcements to guide laminate optimization. **Figure 12** shows a plot of maximum principal stress vectors for a biaxial E-glass ply in the deck canopy.

Beyond the global assessment with the DNV-prescribed acceleration, we carried out local panel analysis with the DNV-prescribed maximum bottom-slamming pressure. This is comparable



Four images of a single panel in the hull's midsection under maximum bottom-slamming pressure of the complete structure. ***13*** *shows deflection;* ***14*****—***maximum shear stress;* ***15*****—***maximum shear vectors; and* ***16*****—***failure index.*





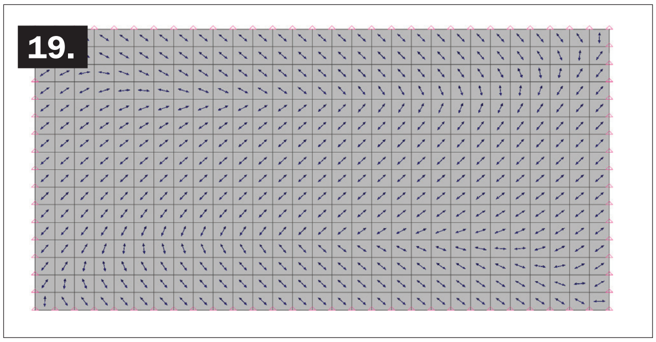
*Without the influence of the global structure, the same panel in Figures 13–16 is analyzed with rigidly fixed boundaries. **17** shows deflection in the center of the panel, while **18** indicates relatively low shear stress.*

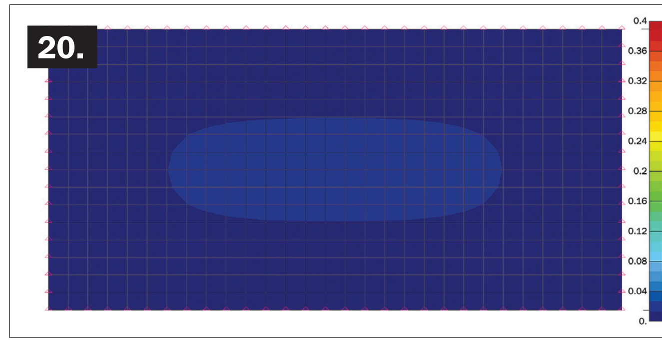
to what would typically be done with a laminate analysis program and what is usually the basis for most scantling rules.

Figures 13–16 show the results of such an analysis for a typical panel in the midbody area of the hull. These figures display deflection (13), maximum shear stress (14), maximum shear vectors (15), and failure index (16). Although just one panel is shown, it is taken from the context of a model fully loaded and reacted with the presence of the complete structure. The panel is influenced by the effects of global deflections and stresses and by the compliance of the supporting transverse bulkheads and longitudinal stiffeners.

By comparison, **Figures 17–20** show results for an analysis of the same panel with rigidly fixed boundaries, without the influence of the global structure. This is analogous to how a panel analysis would be performed using a first principles or scantling approach. You can see significant differences in the results, underscoring the benefits of the global model for local panel analysis.

The limited subset of images presented here shows the complexity of fully studying and comprehending the results of a complete finite element analysis across a range of load cases. Translating the results into optimized laminate definitions and production drawings is another step that requires specific attention. The benefit, however,





Continuing our look at the bottom panel with maximum slamming pressure with fixed boundaries, the local shear vectors are shown in ***19*** *(compare to Fig. 15), and failure index is shown in* ***20*** *(compare to Fig. 16). Figs. 17–20 (similar to analyses performed with a first-principles or scantling approach) indicate the importance of using the global model for local panel analysis, as in Figs. 13–16.*

is a level of optimization that cannot be achieved solely with first principles or scantling rule approaches. By applying all three methods in an integrated design and analysis process, you can find an ideal balance that weighs the time and cost against the results achieved.

Production laminate optimization is ongoing for the team at Outerlimits Offshore Powerboats. The company has realized meaningful cost savings for existing models while minimizing weight increase and maintaining structural durability. Results from the analyses performed to date also help guide laminate design and structural arrangements for new models in development. With a market still in retreat and increasing pressure to reduce costs while delivering a superior product, there is no margin for inefficient use of materials or labor. By employing all the technology at its disposal, Outerlimits has weathered the economic downturn and repositioned itself for a leaner, more efficient future. PBB

About the Author: *Dave Fornaro founded Ariston Technologies in 2008 to provide services in composites engineering, structural analysis, and mechanical systems to clients in the marine, wind energy, automotive, architectural, and aerospace industries.*