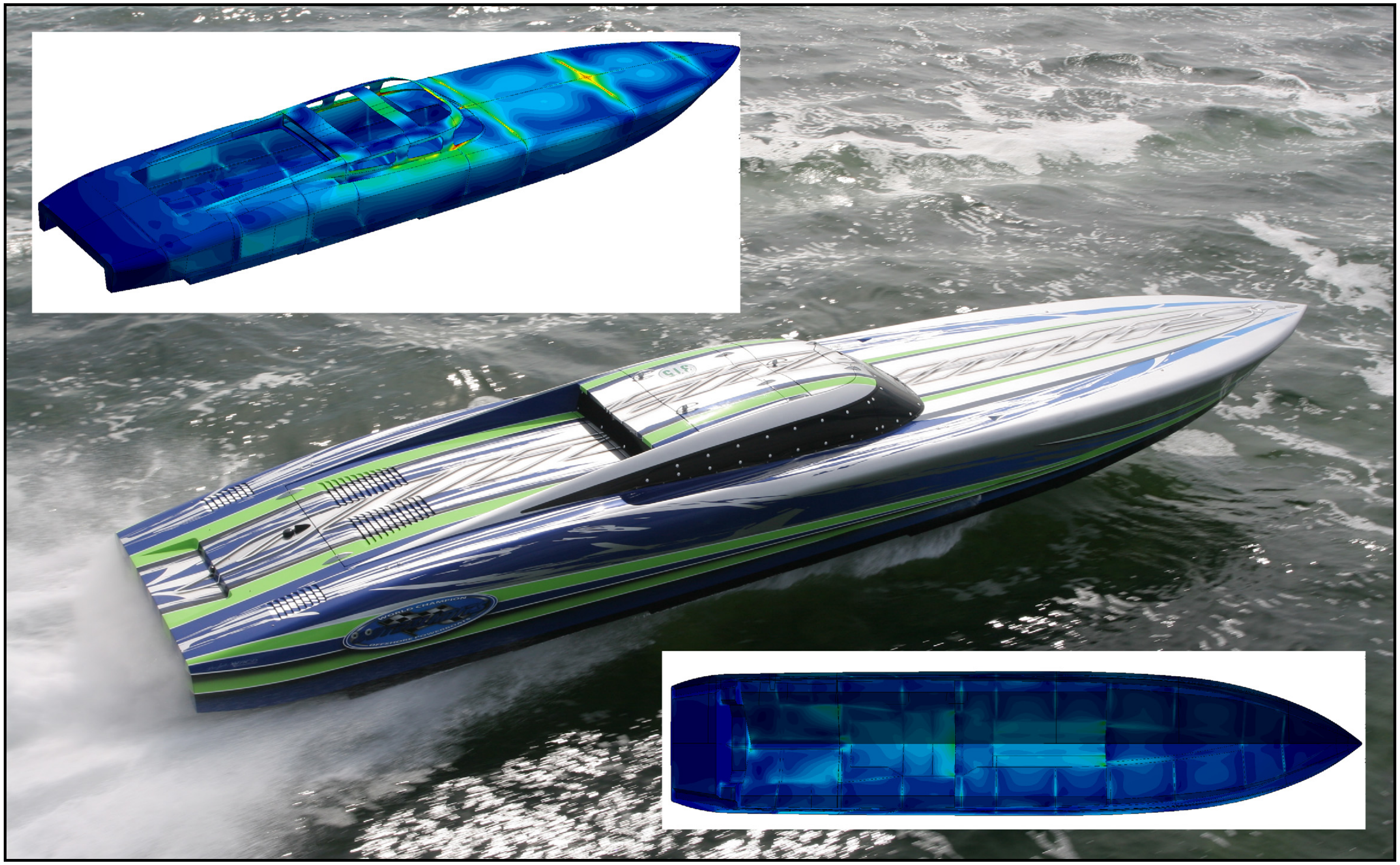
IBEX 2011 – SESSION 1201
APPLICATIONS OF FEA FOR STRUCTURAL OPTIMIZATION



PRESENTED BY:

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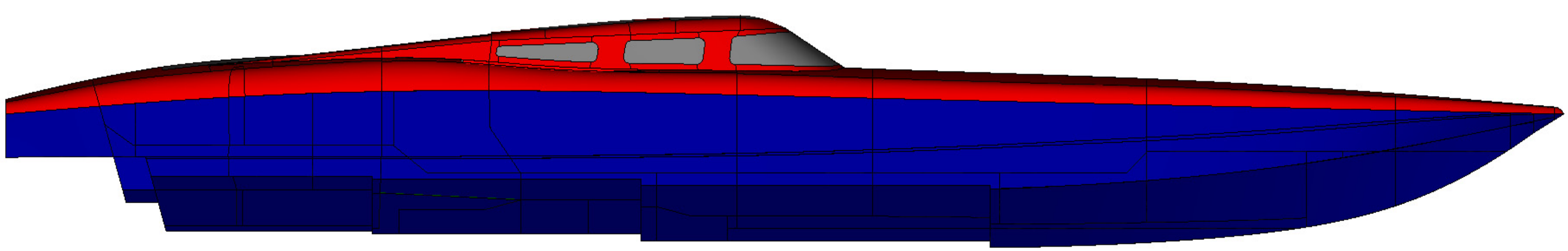
REFERENCES / BACKGROUND

1. "FEA FOR STRUCTURAL COMPOSITES OPTIMIZATION" (IBEX 2010)
2. "ADVANCEMENTS IN THE APPLICATION OF FINITE ELEMENT ANALYSIS TO THE OPTIMIZATION OF COMPOSITE YACHT STRUCTURES" (CSYS 2011)
3. "FINE-TUNING WITH FEA" (PROFESSIONAL BOATBUILDER #133, OCT/NOV 2011)
   - Comprehensive overview of composites FEA process
   - Comparisons to first principles and scantlings
   - Presentation of advanced ply/laminate pre-processing methods
   - Discussion of advanced composite failure theories
   - Case studies
   - See www.aristontech.com/publications

OUTLINE

1. BASICS OF FINITE ELEMENT ANALYSIS
2. FEA COMPARED TO FIRST PRINCIPLES & SCANTLINGS
3. ANATOMY OF A FINITE ELEMENT ANALYSIS
4. LIVE DEMONSTRATION
5. TIPS & RECOMMENDATIONS



BASICS OF FINITE ELEMENT ANALYSIS (FEA)

- Approximate mathematical method for analyzing complex systems
- How "approximate" depends on model quality
- Most useful for systems that are geometrically too complicated for closed-form (textbook) solutions
- Should be used in conjunction with sound engineering fundamentals including first principles and scantlings to establish baseline structural layouts & laminates
- Can be used to solve displacement, strain, stress, buckling, vibration, etc…
- Excellent for studying global strength/stiffness as well as local concentrations
- Solutions can be linear, non-linear, static, dynamic, etc…
- Materials can be isotropic, orthotropic, elastic, plastic, hyperelastic, etc…

BASICS OF FINITE ELEMENT ANALYSIS (FEA), ctd…

ANALYSIS TYPES:

- Linear Analysis:
  - Materials have a linear stress-strain relationship (e.g. metals below yield)
  - Deflections are small and vary linearly with applied loads

- Non-Linear Analysis:
  - Materials may have a non-linear stress-strain relationship (e.g. metals beyond yield)
  - Deflections may be large and not always be proportional to the applied loads

- Static Analysis:
  - Loads and boundary conditions do not vary with time
  - Can also be a "snapshot" – i.e. quasi-static approximation of a dynamic system

- Dynamic Analysis:
  - Loads and boundary conditions may vary with time
  - FE solution is an iterative (step-by-step) approximation of a continuous event

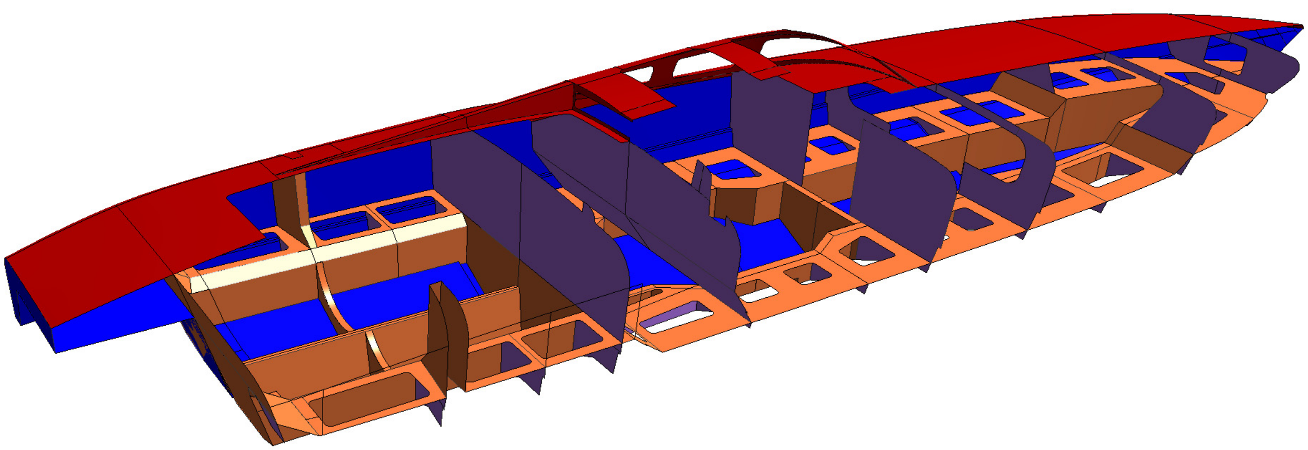
BASICS OF FINITE ELEMENT ANALYSIS (FEA), ctd…

MATERIAL TYPES:

- Isotropic Materials:
  - Properties are the same in all directions
  - Defined by two elastic constants – Young's Modulus (E) and Poisson's Ratio (ν)
  - Metals, many plastics, etc…
- 3D Orthotropic Materials:
  - Two orthogonal planes of symmetry with different properties in each
  - Defined by 9 elastic constants (E1, E2, E3, G12, G13, G23, ν12, ν13, ν23)
  - Solid composite materials (with significant through-thickness strains)
- 2D Orthotropic Materials:
  - Orthotropic in one plane only, with constant properties normal to that plane
  - Defined by 6 elastic constants (E1, E2, G12, G13, G23, ν12)
  - Applicable to planar composite materials

BASICS OF FINITE ELEMENT ANALYSIS (FEA), ctd...

- Majority of yacht design-related composites FEA applications will be linear static analyses using 2D orthotropic properties for laminates (shell elements)
- Non-linear and dynamic analyses are useful for specialized studies (e.g. slamming), although linear "quasi-static" simplifications are often made
- Isotropic properties are generally used for foam core (shell or solid elements)
- 3D orthotropic properties can be used when through-thickness stresses of orthotropic materials are required (e.g. honeycomb core)



FEA COMPARED TO FIRST PRINCIPLES

- First principles (textbook) analysis methods for simple systems can often be used to estimate the response of more complicated systems broken down into smaller parts for simplified analysis
- Can be used to assess global structures or local details
- Very useful for global stiffness estimates; for initial sizing of panels and stiffeners for strength and deflection; and for engineering of many detail components with straightforward geometry
- Usually requires some simplification of boundary conditions
- Limited accuracy as geometry becomes more complicated

FEA COMPARED TO FIRST PRINCIPLES, ctd…

GLOBAL FIRST PRINCIPLES:

- Global: Hull/deck shell in bending modeled as a beam with variable cross-section and inertia properties (common for ship structures)
- Applied loads include self-weight, cargo weight, buoyancy forces, longitudinal rigging loads; Calculations for shear forces and bending moments, which are used as inputs to scantling rules
- Buoyancy force per unit length, $F_B = \rho g a$
- Weight force per unit length, $F_W = mg$
- Net vertical applied force, $F = F_B - F_W = \rho g a - mg$
- Shear Force, $Q = \int F dx = \int (\rho g a - mg) dx$
- Bending Moment, $M = \int Q = \iint F dx = \iint (\rho g a - mg) dx dx$

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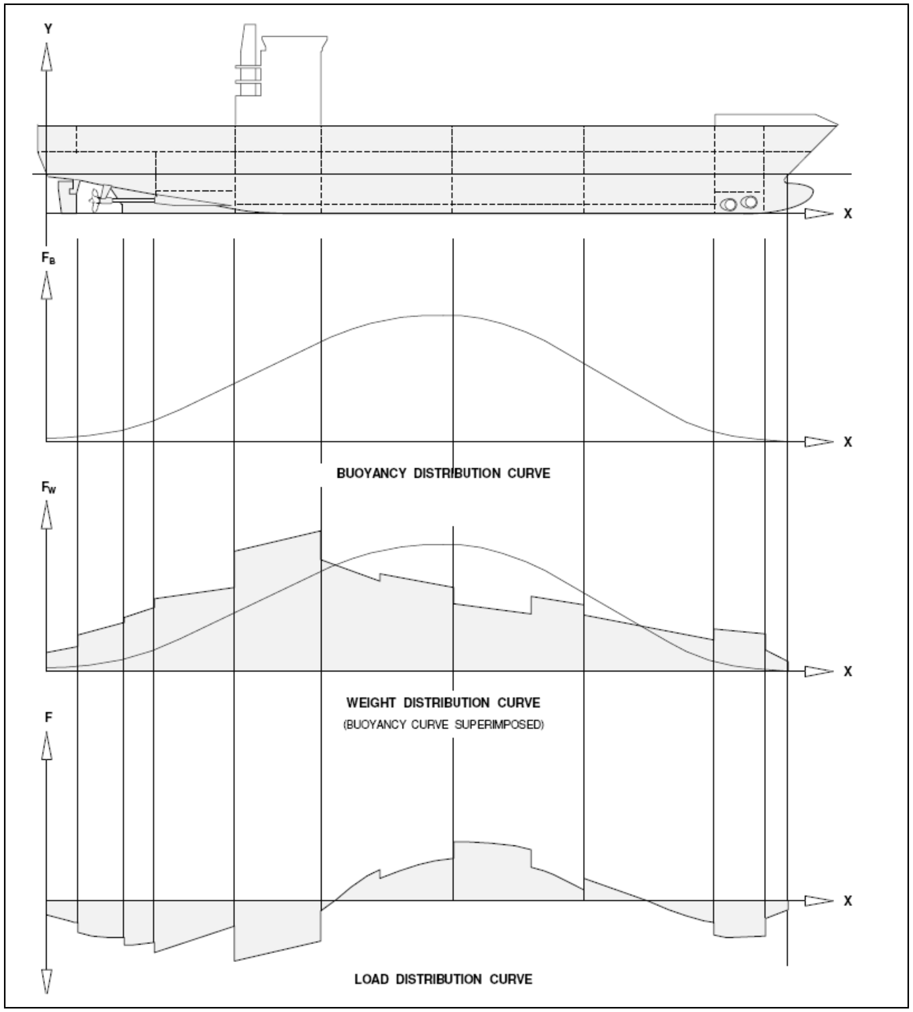
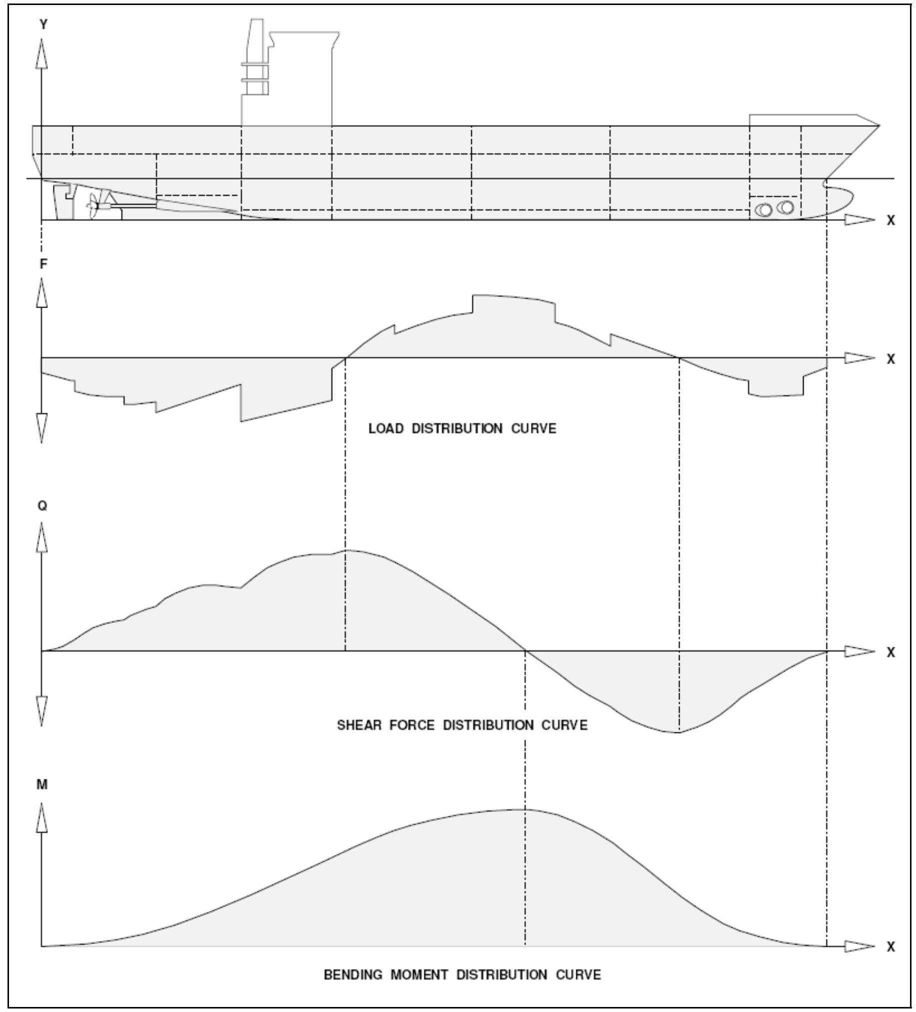
FEA COMPARED TO FIRST PRINCIPLES, ctd…





FEA COMPARED TO FIRST PRINCIPLES, ctd...

- Note that while this approach is first principles-based, it is not a simple hand calc! While it could be programmed in Excel, this type of analysis is usually carried out using dedicated software such as GHS, DELFTship or HST
- Given the bending moment and shear force, a nominal bending stress at the extreme fiber distance can be calculated according to $\sigma = Mc/I$ and a nominal shear stress calculated according to $\tau = Q/A$
- This would at best be a very rudimentary estimate of global bending stress, but will not address local loads, sectional shape changes, stress concentrations, etc...
- This can be useful for simple cases, but what if you had this...

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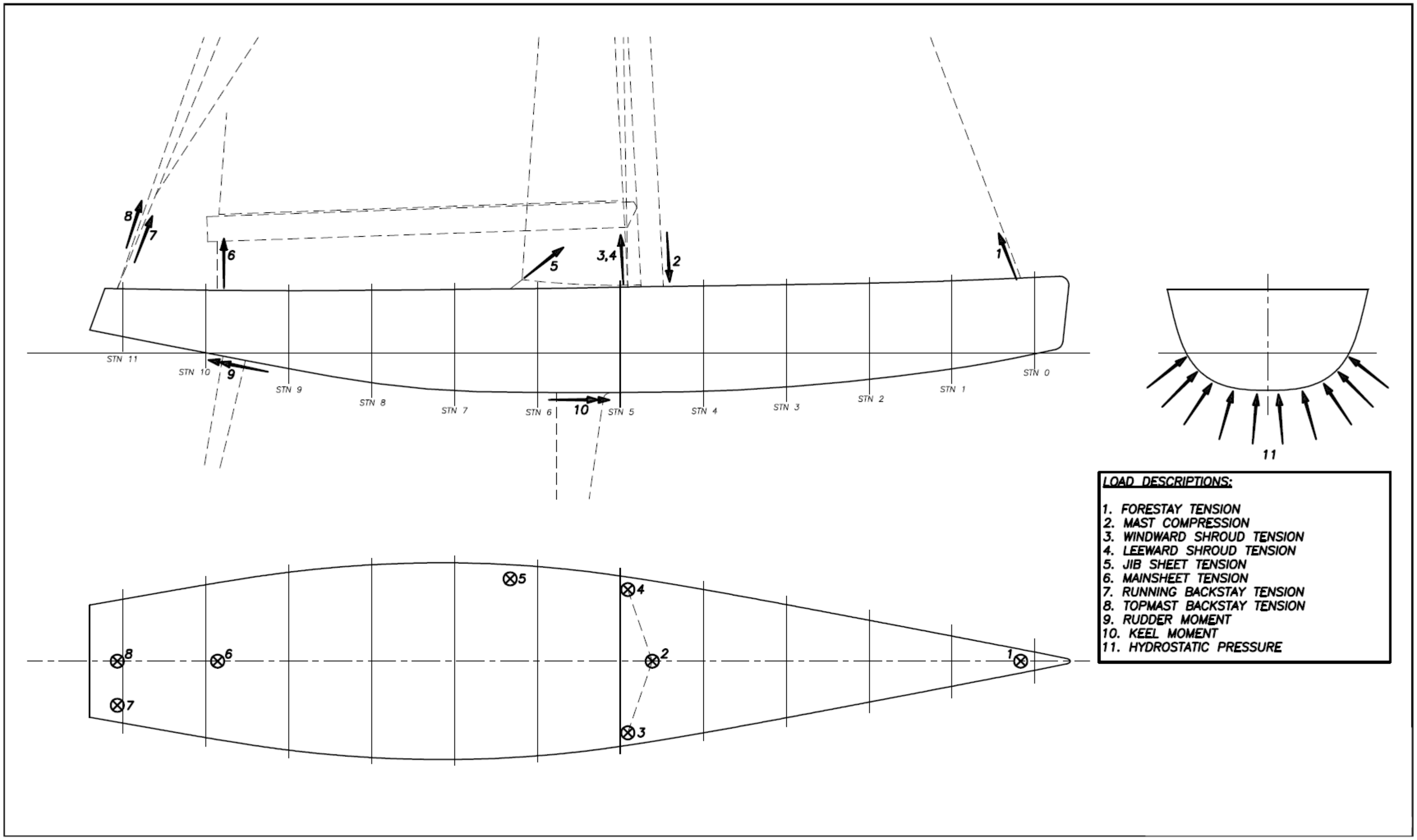
FEA COMPARED TO FIRST PRINCIPLES, ctd...

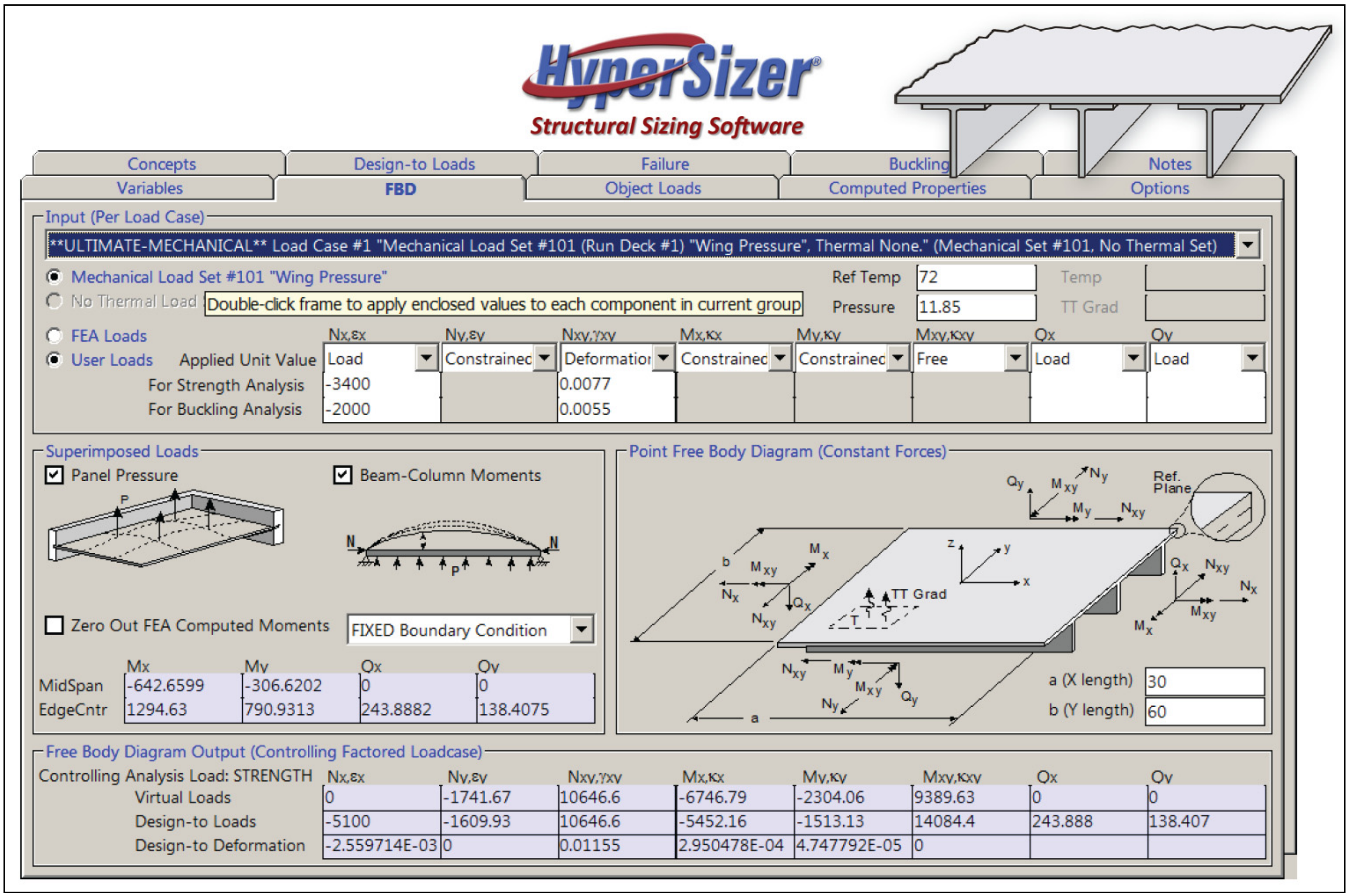


FEA COMPARED TO FIRST PRINCIPLES, ctd…

LOCAL FIRST PRINCIPLES:

- Local Panels: Hull/deck shell modeled as individual, uniformly loaded panels bounded by transverse frames and longitudinal stiffeners
- Local Stiffeners: Longitudinal girders, stringers and deck beams modeled as beams spanning between supporting frames with fixed ends
- Fairly simple formulas (see Roark) can be solved by hand or with specialized software programs
- Many useful first principles-based composites software for laminate, panel and beam analysis are available including CoDA, ESAComp, HyperSizer, CompositePro, etc…
- Capabilities include ply and laminate definitions, laminate strength & stiffness calculations, cored and monolithic panels, stiffened panels, many different beam geometries
- Indispensible tools for composites engineer!

FEA COMPARED TO FIRST PRINCIPLES, ctd...



FEA COMPARED TO FIRST PRINCIPLES, ctd…

- First principles calculations useful for providing basic information regarding global sectional shape and strength requirements for simple geometries and loading conditions

- First principles calculations can also be very useful for analyzing local strength of panels, beams, fittings, attachments, etc… although assumptions must be made regarding loading and boundary conditions that compromise accuracy

- FEA by comparison has the potential to provide close to exact solutions for global deflection and stress *given a quality model*

- FEA can also provide detailed deflection and stress results for local features such as bulkheads, frames, stringers, panels, fittings and attachments… but only if these features are modeled in sufficient detail

FEA COMPARED TO SCANTLINGS

- Scantling rules a combination of first principles calculations and databases of empirical knowledge which have been used to develop acceptable design criteria for vessels falling into various categories

- Sailing yachts, power yachts, high-speed craft, naval craft, cargo ships, barges

- First principles calculations for global shear forces and bending moments from hydrostatics programs are often used as inputs to scantling rules, particularly for cargo ships, tankers, etc…

- Typically include calculations for:
  - Hull panel pressures based on location & other factors (e.g. dynamics)
  - Bulkhead pressures based on location & other factors (e.g. collision, watertight)
  - Required skin thickness, panel & stiffener section modulus and moment of inertia based on panel pressure and stiffener spacing, material properties, core thickness, etc…
  - Required core thickness based on type and shear strength requirements
  - Required stiffener spacing, depth, section modulus & moment of inertia

FEA COMPARED TO SCANTLINGS, ctd...

- Scantling rules generally do not provide detailed global or local stresses, although the calculations for panels & stiffeners are typically based on first principles calculations for stress and stiffness

- Scantling rule calculations for panels and beams include similar simplifications and assumptions regarding loading and boundary conditions as for first principals-based software

- A good scantling rule will get you in the ballpark, and may provide the means for some degree of basic optimization (e.g. materials, stiffener spacing, core thickness, etc...) but is not an effective tool for detailed optimization of strength or stiffness

- FEA by comparison offers more detailed understanding of the response of the structure to the applied loads, and more complete capabilities for studying changes to materials and layout in order to optimize the design

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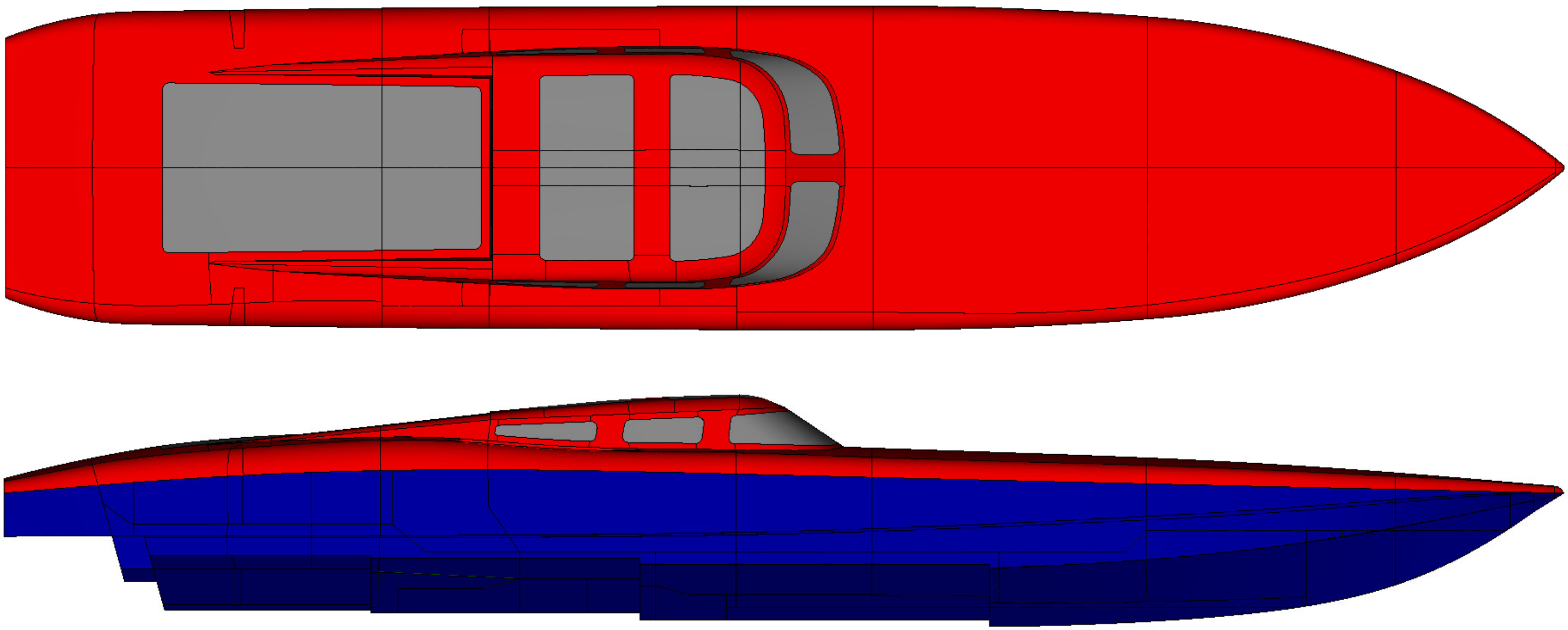
ANATOMY OF A FINITE ELEMENT ANALYSIS



- FEA process illustrated using a model of Outerlimits 43SV offshore powerboat
- Hull, deck & internal structure modeled in RHINO; FEA Pre- & Post-Processing done with FEMAP; FEA Solutions run using NEi/NASTRAN

ANATOMY OF A FINITE ELEMENT ANALYSIS

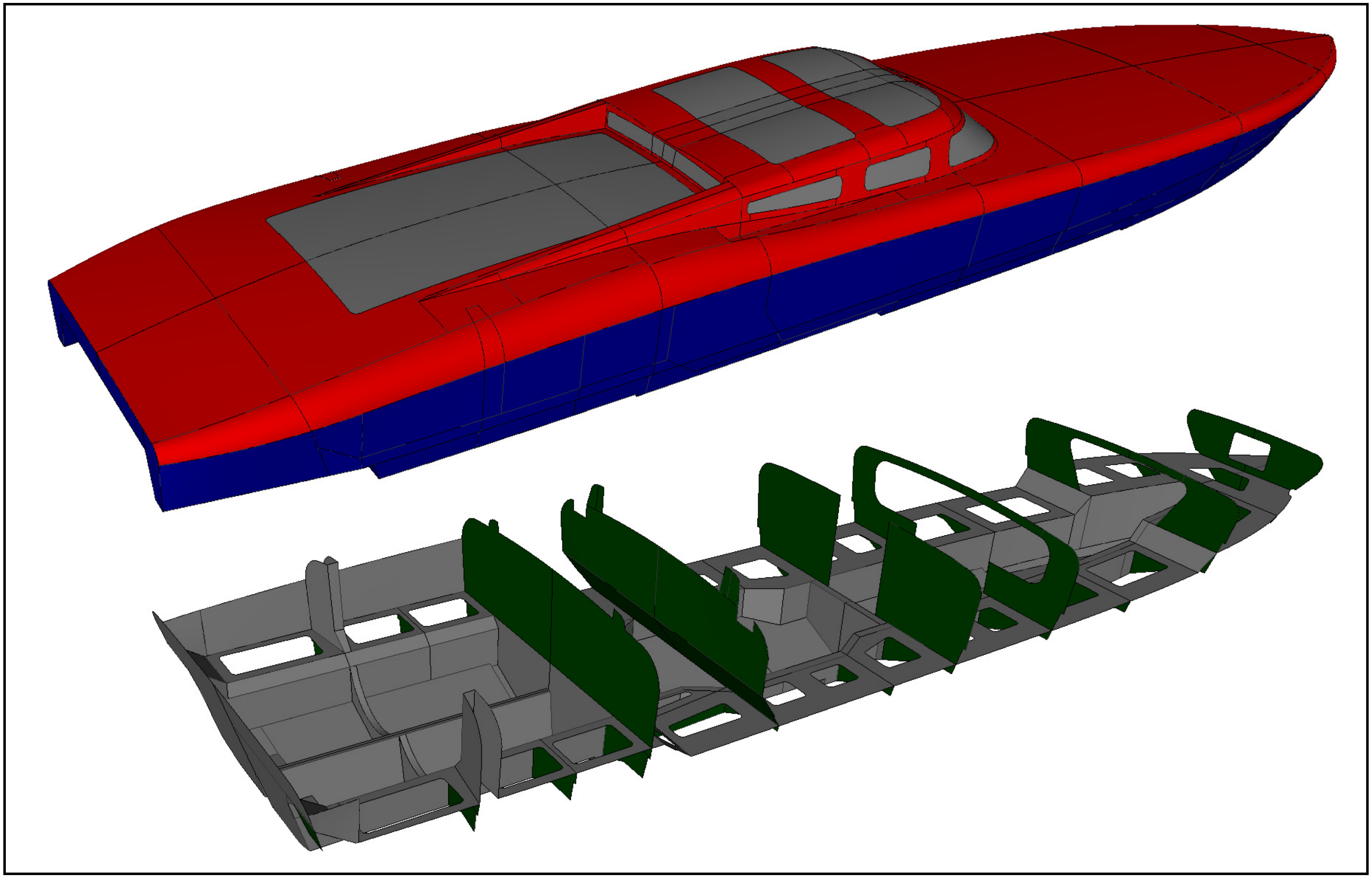
STEPS IN THE FEA PROCESS:

- GEOMETRY
- MESH
- MATERIAL PROPERTIES
- LOADS & CONSTRAINTS
- SOLUTION & RESULTS
- OPTIMIZATION

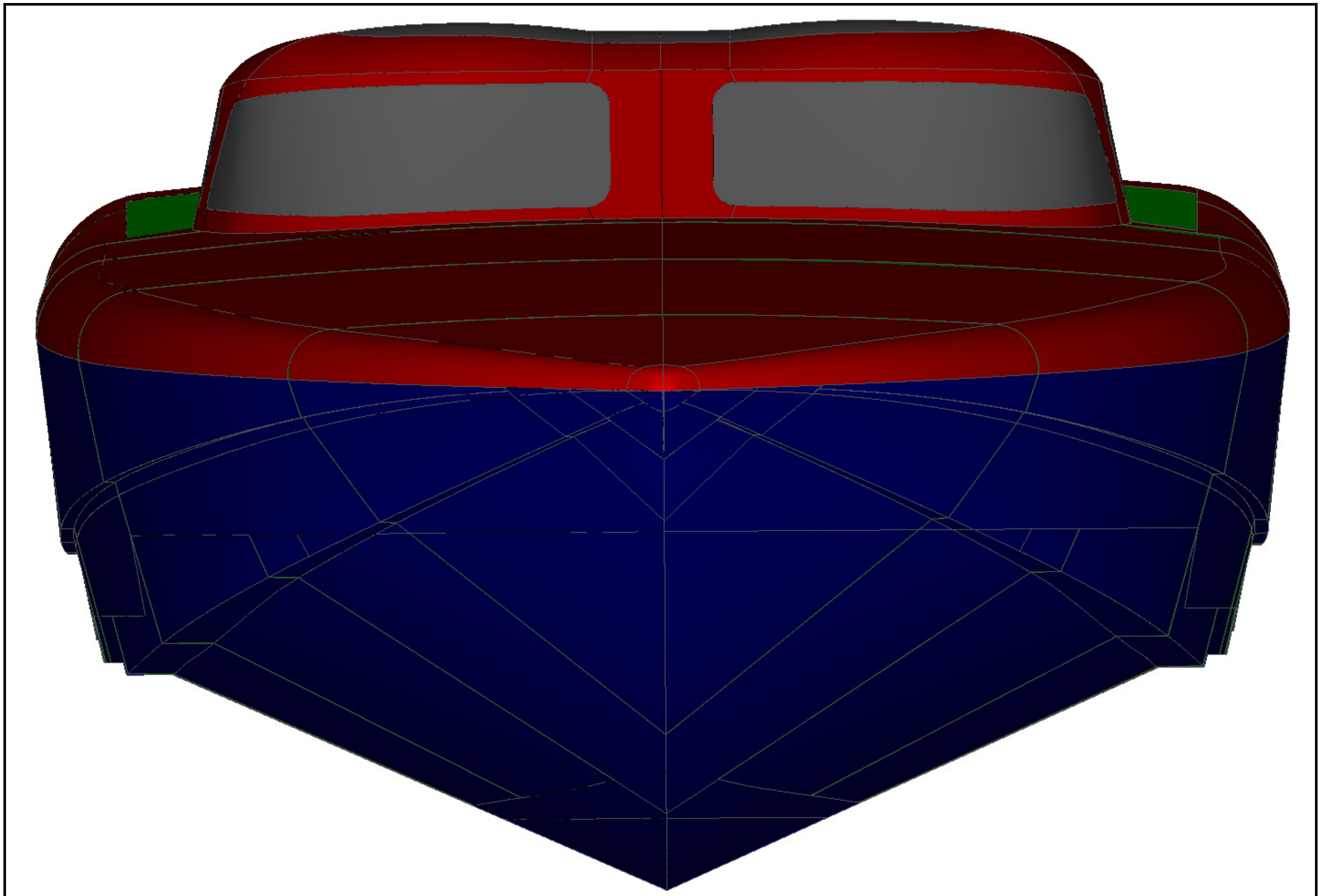
ANATOMY OF A FINITE ELEMENT ANALYSIS – GEOMETRY

- 3D model of geometry to be analyzed is required
- Surface models preferred over solid models
- Quality surface models avoid lengthy editing or re-work prior to meshing
- Hull & deck modeled at molded (usually outer) surfaces
- Internal frames and stringers modeled at centerline surfaces
- All surfaces must have consistent normal vectors for defining laminate thickness direction (normal vectors ideally defined on surfaces prior to meshing and inherited by elements during the meshing process)

ANATOMY OF A FINITE ELEMENT ANALYSIS – GEOMETRY



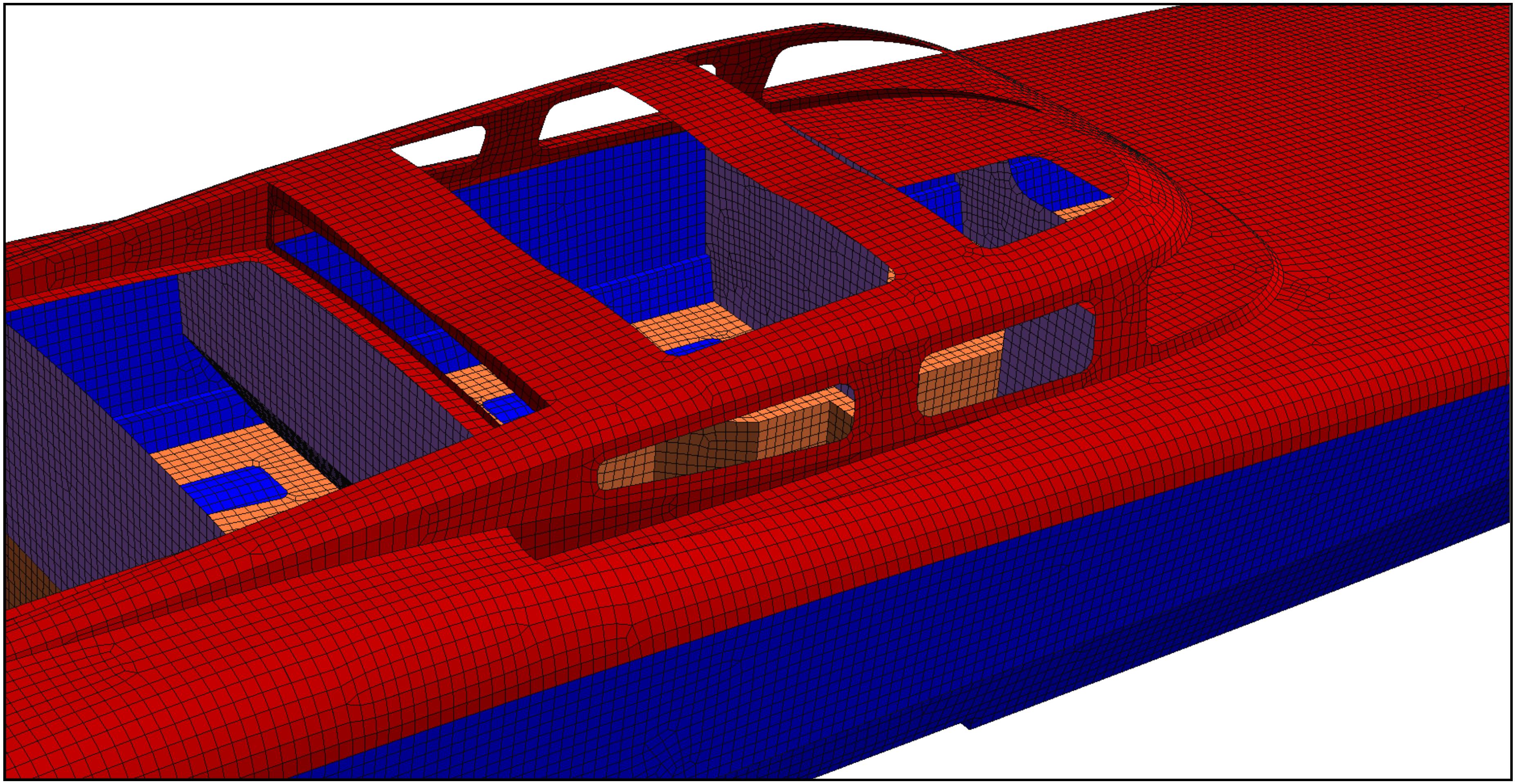
ANATOMY OF A FINITE ELEMENT ANALYSIS – GEOMETRY



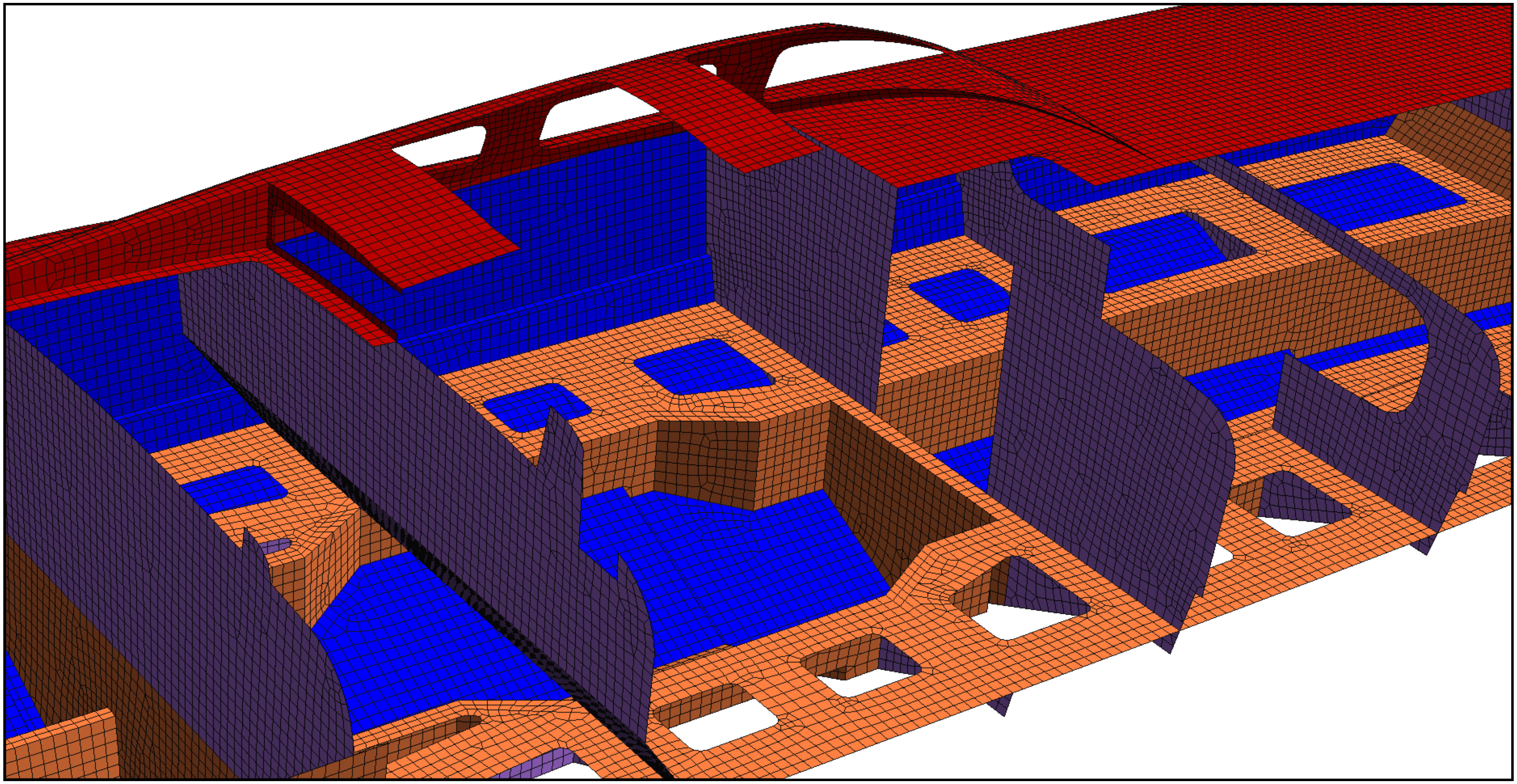
ANATOMY OF A FINITE ELEMENT ANALYSIS – MESH

- Auto-meshing pre-processor typically utilized
- All curves and surfaces seeded with mesh controls to produce a quality mesh
- Quadrilateral (4-sided) shells preferred over triangular (3-sided) shells for accuracy
- Mesh should be quad-dominant, but a few tris are unavoidable in transition areas
- Mesh density should be sufficient to replicate geometric shapes with high fidelity
- Mesh should be ordered and structured (look pretty)
- Pre-processor mesh quality controls should be utilized to search for connectivity problems(free edges) as well as warped, skewed or otherwise badly formed elements and any errors should be corrected

ANATOMY OF A FINITE ELEMENT ANALYSIS – MESH



ANATOMY OF A FINITE ELEMENT ANALYSIS – MESH



ANATOMY OF A FINITE ELEMENT ANALYSIS – MATERIAL PROPERTIES

- Individual plies modeled as 2D orthotropic materials defined by 6 elastic constants required to run an analysis:
  - E1 = Elastic Modulus in 1-fiber (parallel) direction
  - E2 = Elastic Modulus in 2-fiber (transverse) direction
  - G12 = Shear modulus in 12-plane
  - G13 = Through thickness modulus in 13-plane (often taken as resin modulus)
  - G23 = Through thickness modulus in 23-plane (often taken as resin modulus)
  - ν12 = Poisson's Ratio in 12-plane

- Strength properties required only for failure index calculation:
  - σ1t = Tensile Strength in 1-fiber (parallel) direction
  - σ1c = Compressive Strength in 1-fiber (parallel) direction
  - σ2t = Tensile Strength in 2-fiber (transverse) direction
  - σ2c = Compressive Strength in 2-fiber (transverse) direction
  - τ12 = Shear strength in 12-plane

ANATOMY OF A FINITE ELEMENT ANALYSIS – MATERIAL PROPERTIES

- Ply data can be taken from vendor testing, in-house testing, standards; Can be difficult to get good data (esp. for shear) – estimates sometimes have to be made
- All elements must have normal direction defined, relative to which laminate stack thickness is developed
- All elements must have material angle defined, relative to which fiber directions are oriented (methods include vector projection, draping)
- Pre-processor quality control tools such as vector displays and backface shading should be used to confirm that all normal vectors and material angles are correct; If these are wrong, the analysis will be meaningless
- Laminates are built-up using pre-processor functionality to assemble plies at correct angles relative to material angle for each element; Large models (up to 150 laminates) require good housekeeping to create, manage and update laminates; Can integrate with Excel or other proprietary interfaces for managing plies and laminates

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ANATOMY OF A FINITE ELEMENT ANALYSIS – MATERIAL PROPERTIES

HEXCEL TYPICAL MECHANICAL VALUES ON EPOXY PREPREG LAMINATES

t 90° / 0° — Volume content of fibres : ≈ 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 /	|||	MPa	1100	600	1100	500	2000	800	2400	900
	σt	≡	MPa	35	550	35	450	80	750	80	850
	E /	|||	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 /	|||	MPa	900	550	250	150	1300	700	1600	800
	σt	≡	MPa	150	500	150	150	250	650	250	750
	E /	|||	GPa	42	17	75	31	115	60	150	80
	Et	≡	GPa	10	16	5.5	30	10	55	11	75
Flexure	σ /	|||	MPa	1200	700	550	400	1800	1000	1400	1200
	E /	|||	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	|||	MPa	75	50	60	50	80	70	80	70

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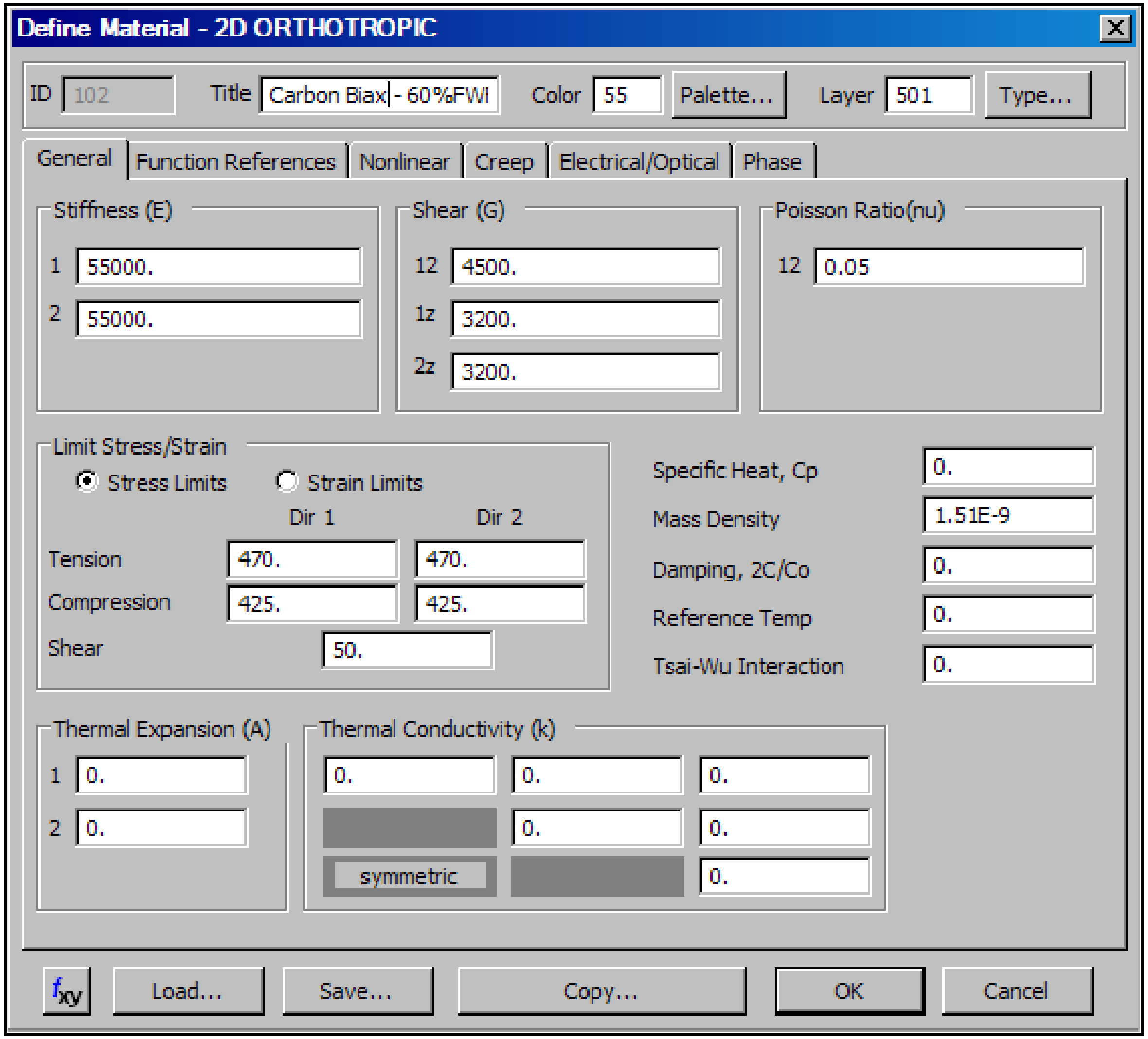
ANATOMY OF A FINITE ELEMENT ANALYSIS – MATERIAL PROPERTIES



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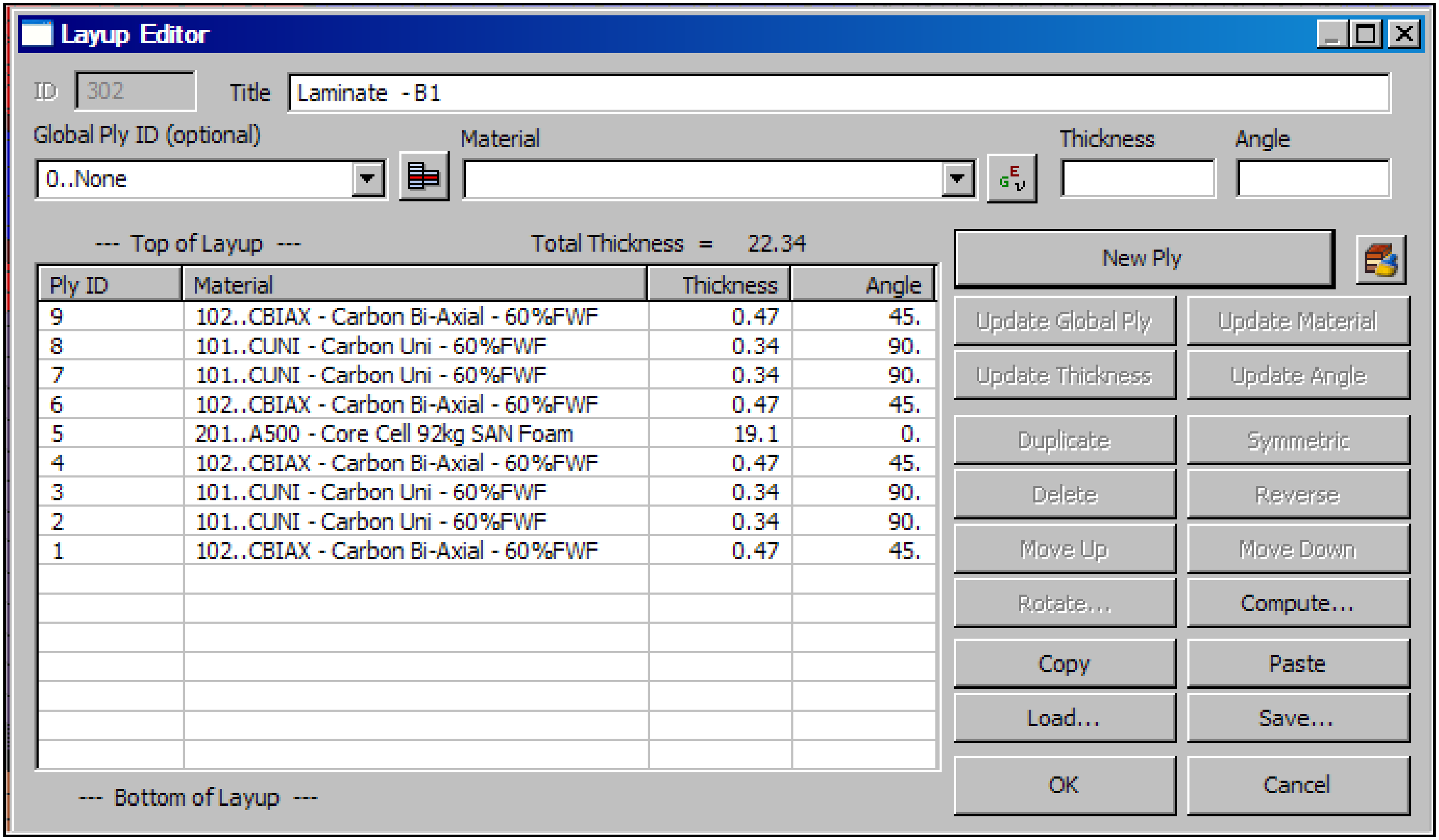

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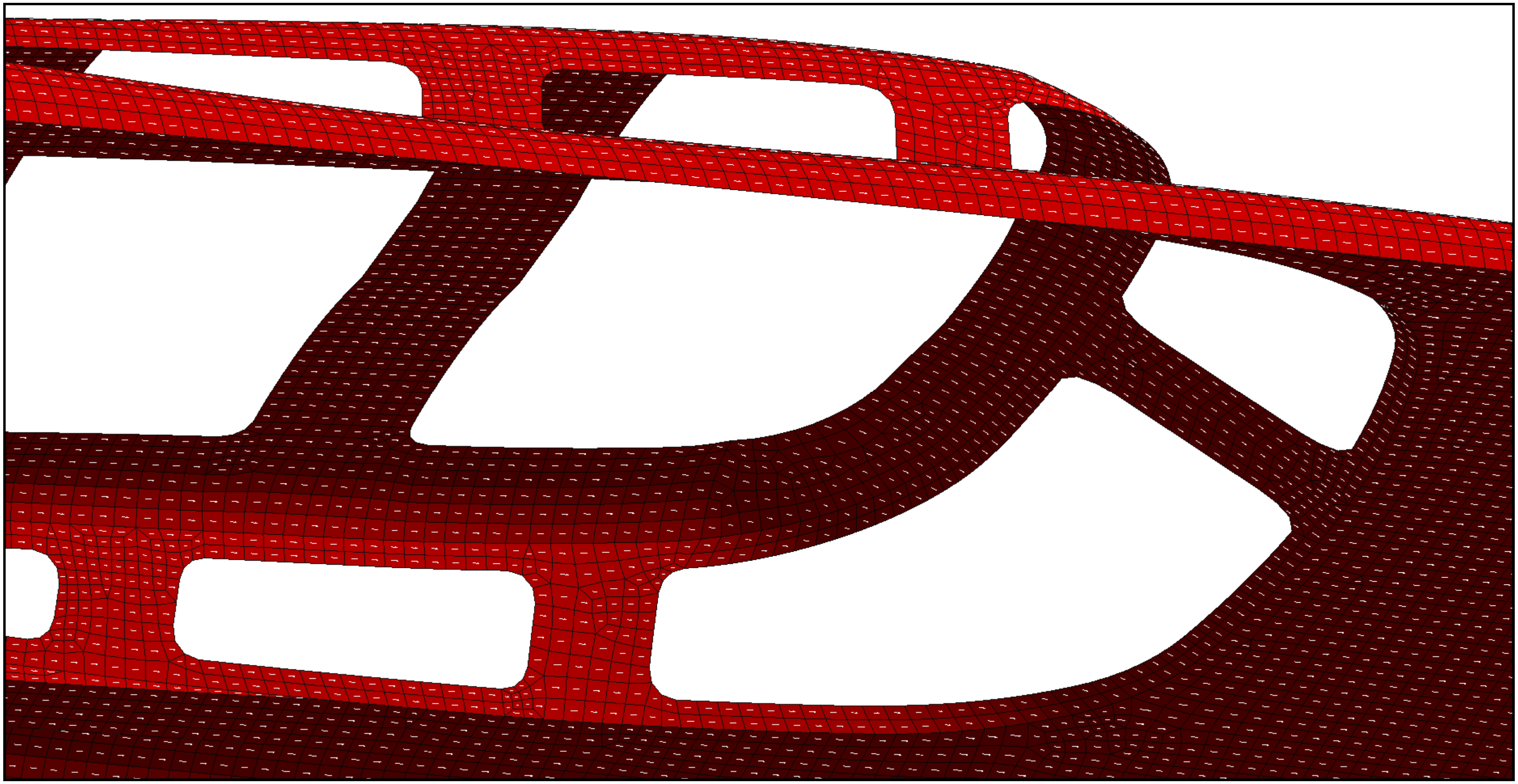

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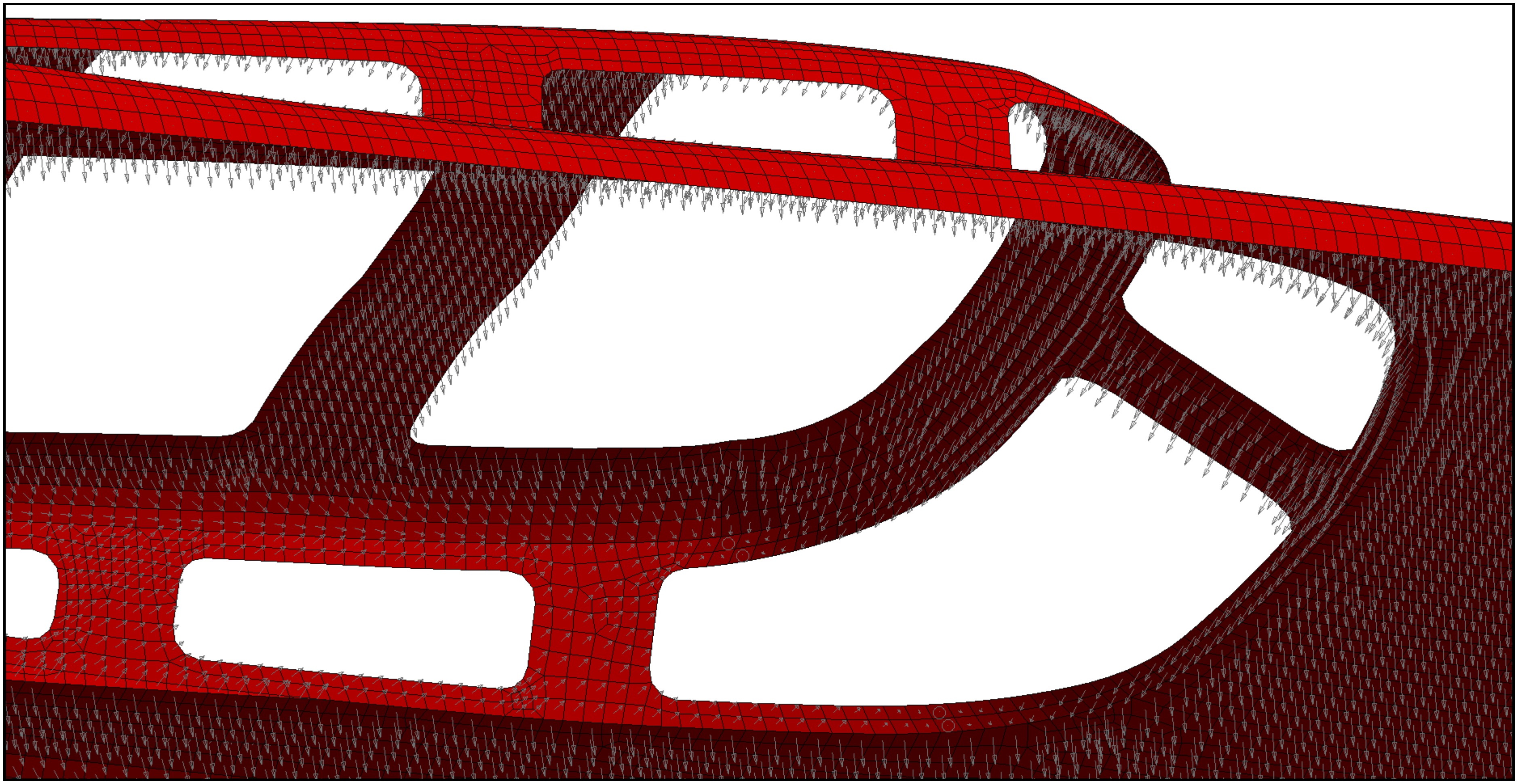
ANATOMY OF A FINITE ELEMENT ANALYSIS – MATERIAL PROPERTIES



ANATOMY OF A FINITE ELEMENT ANALYSIS – LOADS & CONSTRAINTS

- Accurately modeling realistic load cases is critical to successfully utilizing FEA for structural composites optimization

- Typical load cases can be operating loads or limit loads; Required safety factors and other acceptance criteria should be developed prior to beginning the analysis

- Global load cases representing steady-state operation should be as close to fully force and moment balanced as possible; This can often require input from various sources (CFD, VPP, Hand-calcs, rule-of-thumb); Whatever the source(s) of the load data, the complete load picture should be balanced (or as close as possible)

- Artificial constraints should be avoided if possible; Floating structures are inherently unconstrained and should be modeled as such for best results; Inertia relief can handle small residuals but should not be a crutch for poor load case development

ANATOMY OF A FINITE ELEMENT ANALYSIS – LOADS & CONSTRAINTS

- Scantling rules can offer good empirical methods for estimating loads
- No scantling rule applicable to offshore powerboats capable of 160+mph in flat water and continuous operation in a seaway at 100+mph
- DNV High Speed Light Craft (HSLC) rule used for patrol craft in unrestricted operation as a baseline estimate
- Design vertical acceleration of 7.7g
- Maximum bottom panel slamming pressure of 119 kN/m^2 (12.1 tonne/m^2)
- Load cases studied included variations for pitch & roll

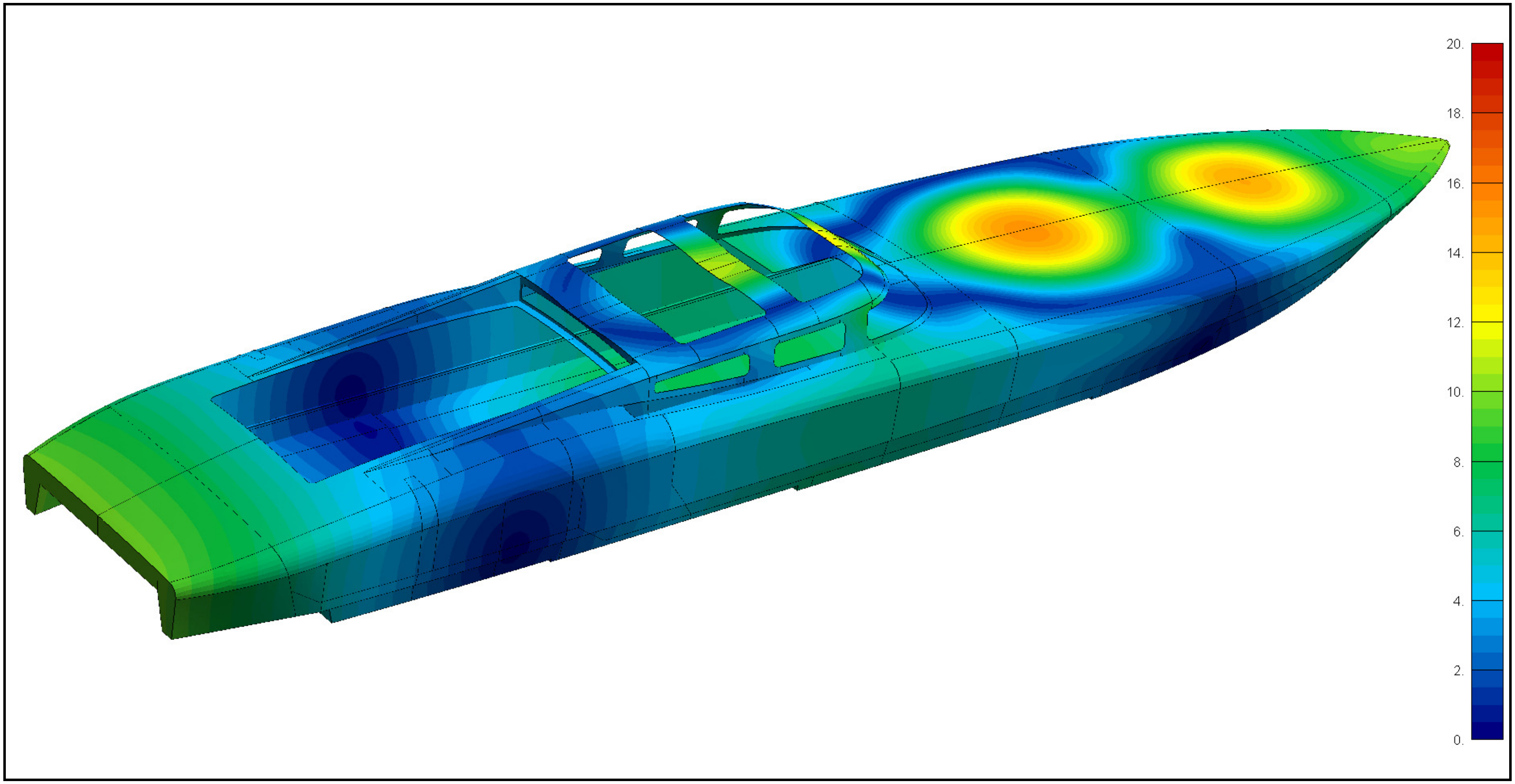
ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS

- Results parameters include various metrics for deflection, stress, strain and failure index; In particular for composites there are many components of stress/strain that can be studied for both the laminate as a whole as well as for each ply
- In cases where certain principal stresses dominate, then direct comparison to test results for the equivalent strength values can be made; Studying principal strain vectors can give good clues as to the flow of strain in the laminate which can help with determining the orientation of reinforcements
- More often, the state of stress is multi-axial and too complicated to be simply compared to one or more principal strength values; In this case it is more appropriate to utilize one of several failure indices
- Failure Indices are mathematical models that predict failure based on the combination of maximum principal, minimum principal and maximum shear stresses in each ply, relative to the respective strength values for the ply
- Different failure indices are appropriate for different types of laminates; Need to be sure to choose the appropriate failure index for the application being studied

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS

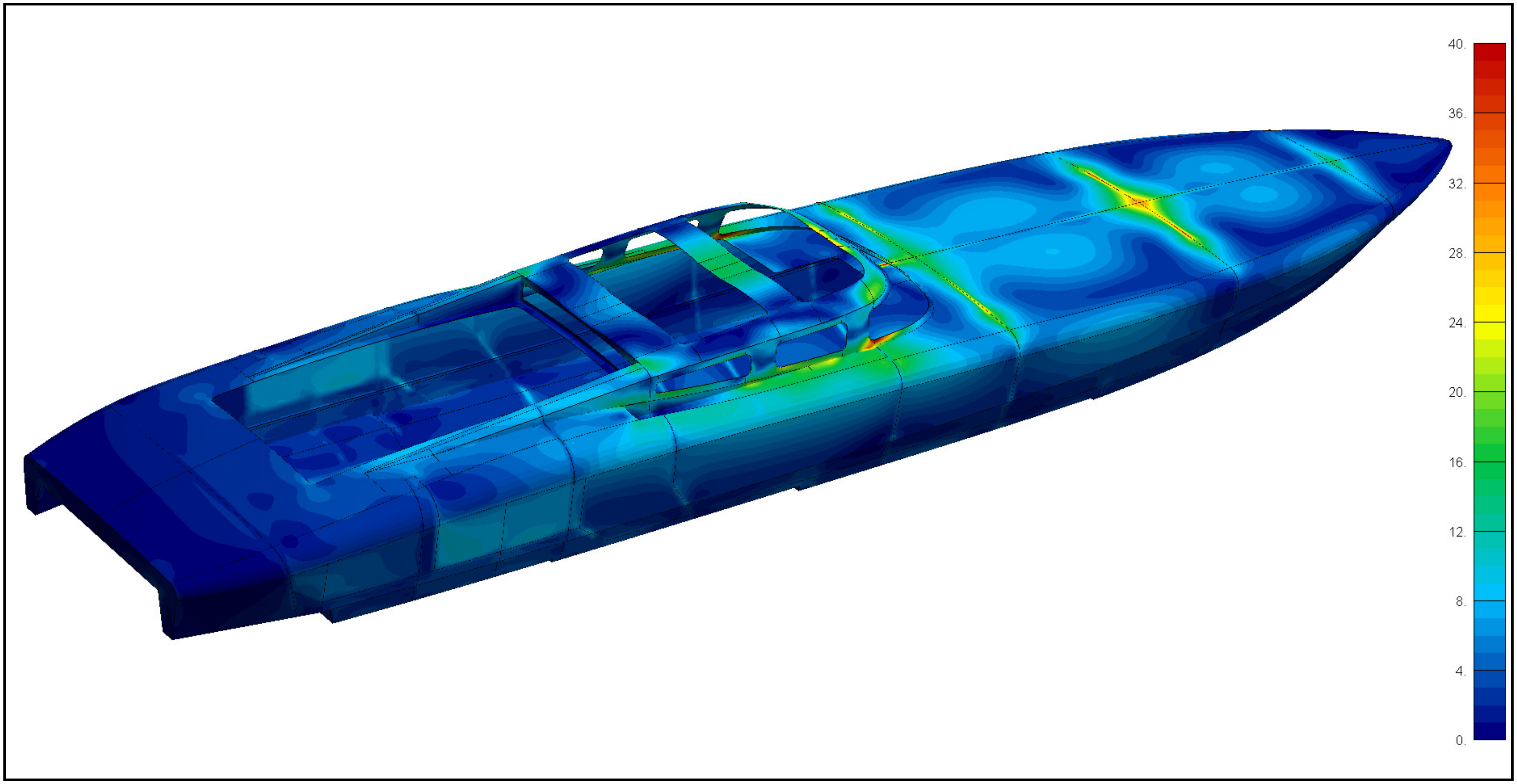
Theory	Failure Index	Remarks
Hill	$\frac{\sigma_1^2}{x^2} - \frac{\sigma_1\sigma_2}{x^2} + \frac{\sigma_2^2}{y^2} + \frac{\tau_{12}^2}{s^2} = \text{F.I.}$	Orthotropic materials with equal strengths in tension and compression.
Hoffman	$\left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} - \frac{\sigma_1\sigma_2}{x_t x_c} = \text{F.I.}$	Orthotropic materials under a general state of plane stress with unequal tensile and compressive strengths.
Tsai-Wu	$\left(\frac{1}{x_t} - \frac{1}{x_c}\right)\sigma_1 + \left(\frac{1}{y_t} - \frac{1}{y_c}\right)\sigma_2 + \frac{\sigma_1^2}{x_t x_c} + \frac{\sigma_2^2}{y_t y_c} + \frac{\tau_{12}^2}{s^2} + 2F_{12}\sigma_1\sigma_2 = \text{F.I.}$	Orthotropic materials under a general state of plane stress with unequal tensile and compressive strengths.
LaRC02	See the NEiNastran User's Manual, Reference 5.	Orthotropic materials comprised of unidirectional plies under a general state of plane stress.
Puck	See the NEiNastran User's Manual, References 12 and 13.	Orthotropic materials comprised of unidirectional plies under a general state of plane stress.
Max Stress	$\text{Max}\left[\left(\frac{\sigma_1}{X_t}\right), \left(\frac{\sigma_2}{Y_t}\right), \left(\frac{\lvert\tau_{12}\rvert}{S}\right)\right]$	None
Max Strain	$\text{Max}\left[\left(\frac{\varepsilon_1}{X_t}\right), \left(\frac{\varepsilon_2}{Y_t}\right), \left(\frac{\lvert\gamma_{12}\rvert}{S}\right)\right]$	None

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS



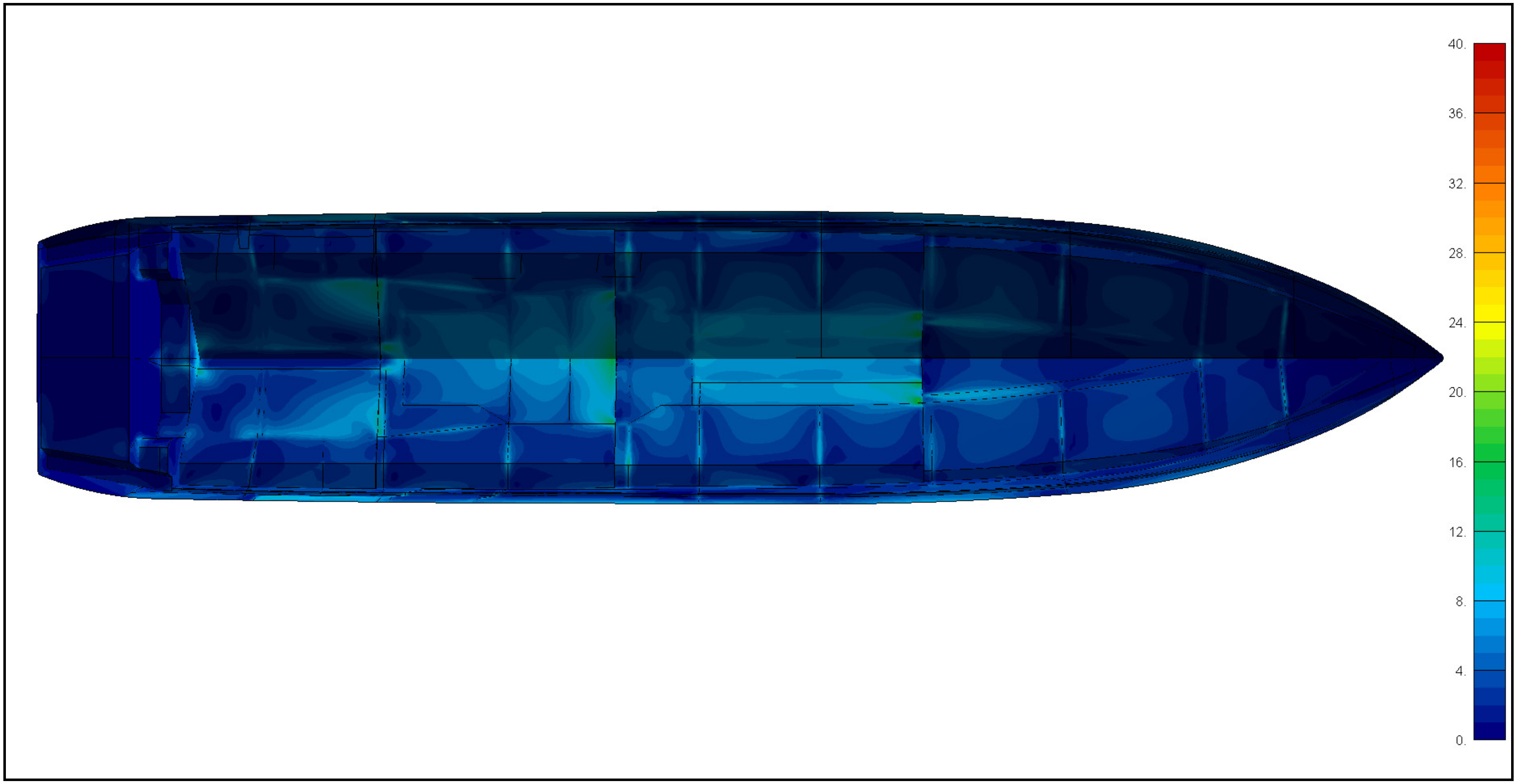
RESULTS – DEFLECTION (mm)

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS



RESULTS – COMPOSITE MAXIMUM EQUIVALENT STRESS (MPa)

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS



RESULTS – COMPOSITE MAXIMUM EQUIVALENT STRESS (MPa)

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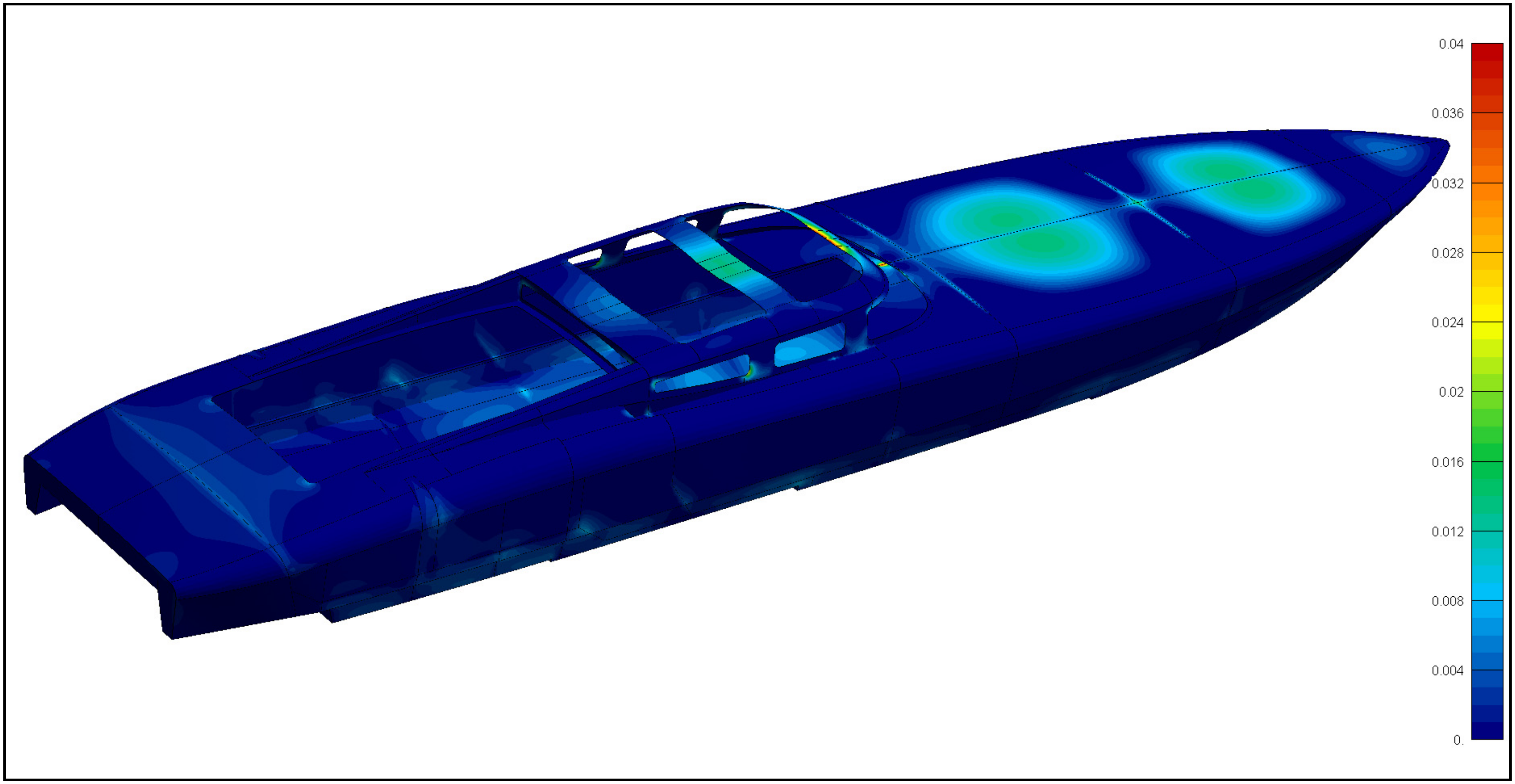
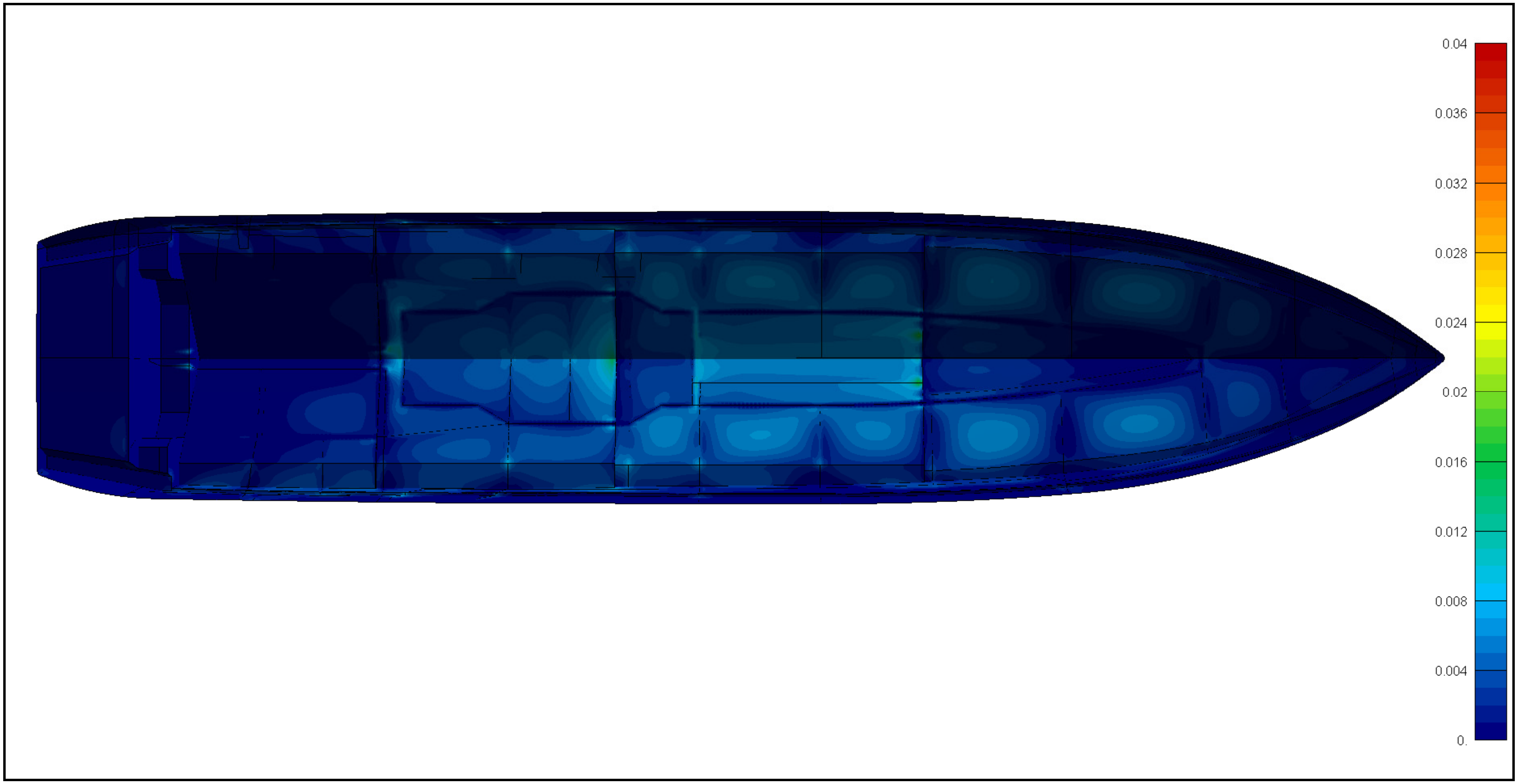
ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS



RESULTS – TSAI-WU FAILURE INDEX

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS



RESULTS – TSAI-WU FAILURE INDEX

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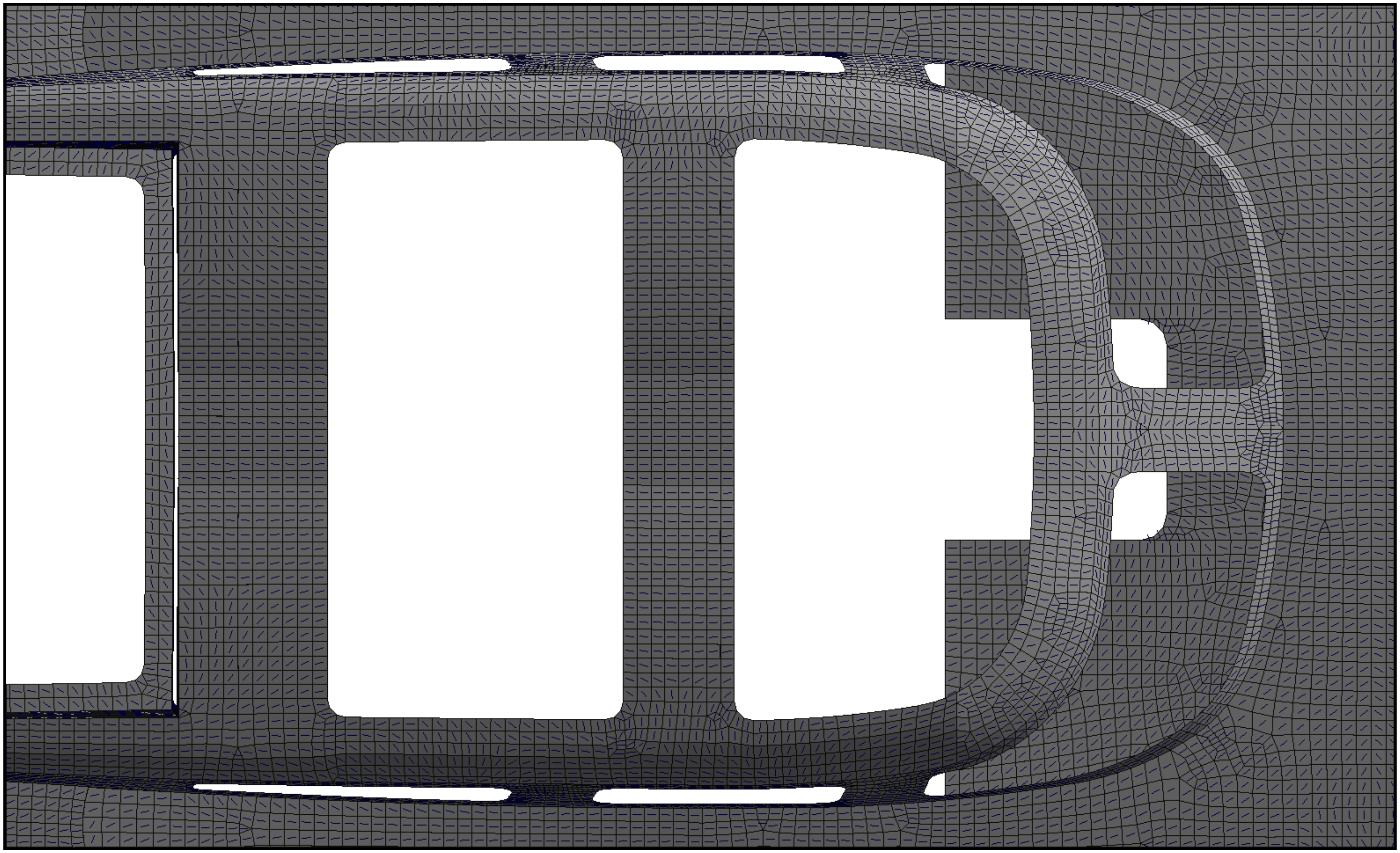

RESULTS – MAXIMUM PRINCIPAL STRESS VECTORS

ANATOMY OF A FINITE ELEMENT ANALYSIS – SOLUTION & RESULTS

- Results for deflection, stress, failure index can be studied on a ply-by-ply basis or on a maximum-of-all-plies basis
- Areas of concern can be addressed via laminate changes or geometry changes
- Model can be iterated to converge to an acceptable solution for all stiffness and strength criteria
- Live demonstration follows to further investigate and discuss results…

TIPS & RECOMMENDATIONS

- FEA is only useful if done correctly and accurately; "Quick & Dirty" FEA is an oxymoron – an accurate solution to an incorrectly or incompletely posed problem will be of no benefit but rather could be erroneous and misleading
- FEA should only be performed by a competent analyst with requisite experience to fully understand the process and recognize the potential pitfalls
- Composites FEA is an order of magnitude more complicated than isotropic materials, in terms of both material characterization and results interpretation
- Be critical! Common sense should rule the day when assessing what FEA is telling you; if it doesn't make sense, then it's probably not right; Search the model for errors in meshing, materials, loads, constraints, etc…
- Careful documentation is critical, as the database of information generated can quickly become overwhelming
- When done right, FEA is excellent as a tool for composites optimization

FURTHER INFORMATION

- Download a copy of this presentation at:

www.aristontech.com/publications

- Thank you for attending