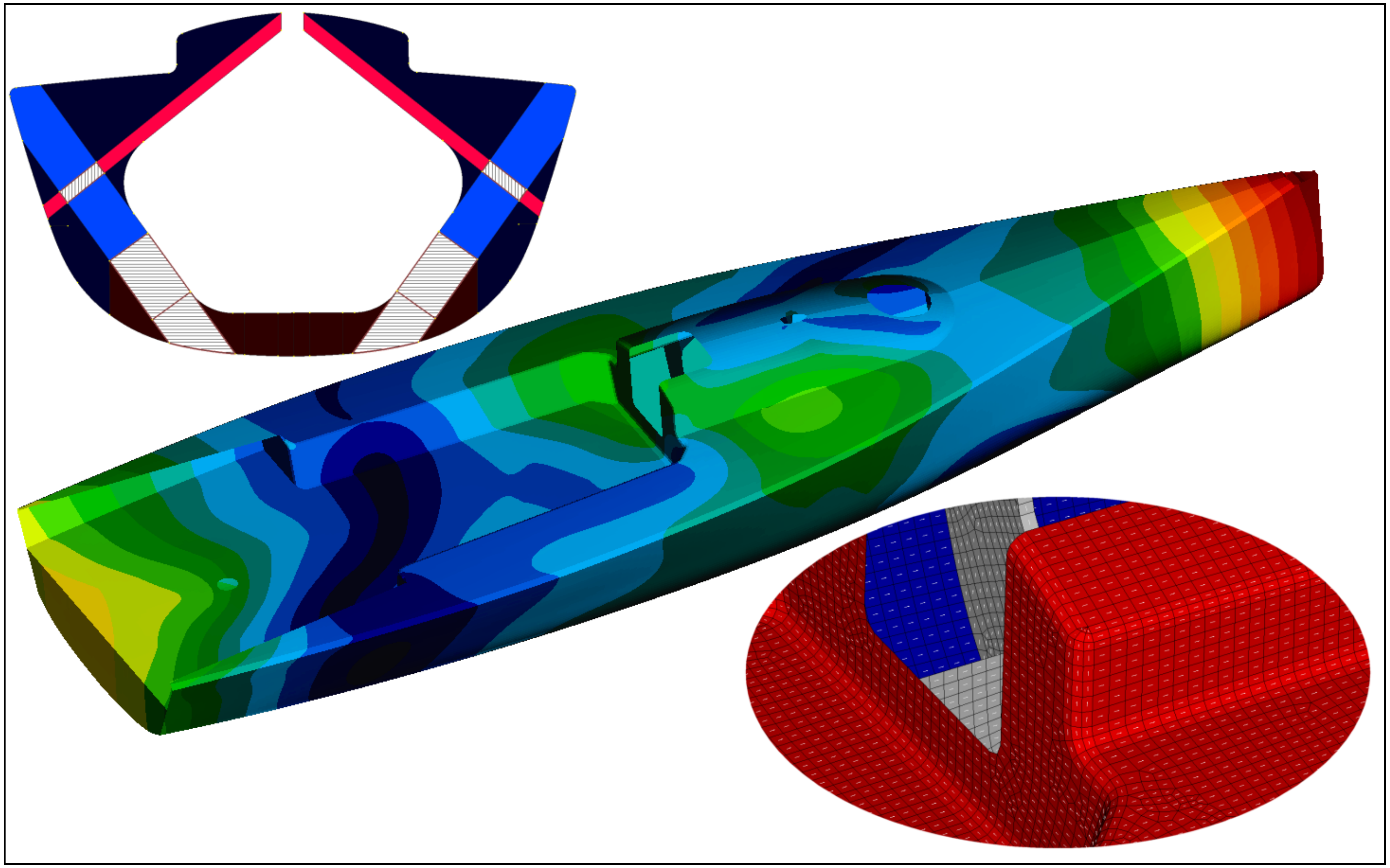
ARISTON TECHNOLOGIES

20th CSYS: ADVANCEMENTS IN THE APPLICATION OF FINITE ELEMENT ANALYSIS TO THE OPTIMIZATION OF COMPOSITE YACHT STRUCTURES



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OUTLINE

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   - Meshing
   - Ply Properties
   - Laminate Definitions & Element Orientations
2. LOAD CASES
   - Force And Moment Balance
3. POST-PROCESSING
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   - Advanced Composite Failure Theories
   - Failure Theory Results Comparison
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4. TIPS & RECOMMENDATIONS
5. ACKNOWLEDGEMENTS

PRE-PROCESSING - MESHING

- Model quality (and hence results accuracy) dependent upon:
  - Mesh density
  - Mesh quality
- Mesh density related to overall vessel size as well as size of individual structural elements
- Processor speeds and memory capacities have effectively removed limitations on mesh density
- Mesh density can be chosen based upon smallest structural elements (e.g. ring frames, deck beams, uni taping) which are typically ~100mm
- Global element edge length of ~40mm reducing to ~20mm in areas requiring detailed study works well as a general guideline
- 42 footer shown here ~85,000 shell elements; Element count scales with ~$LOA^{1.6}$
  Volvo 70 ~190,000 elements; 100ft Maxi ~340,000 elements

PRE-PROCESSING - MESHING, ctd...

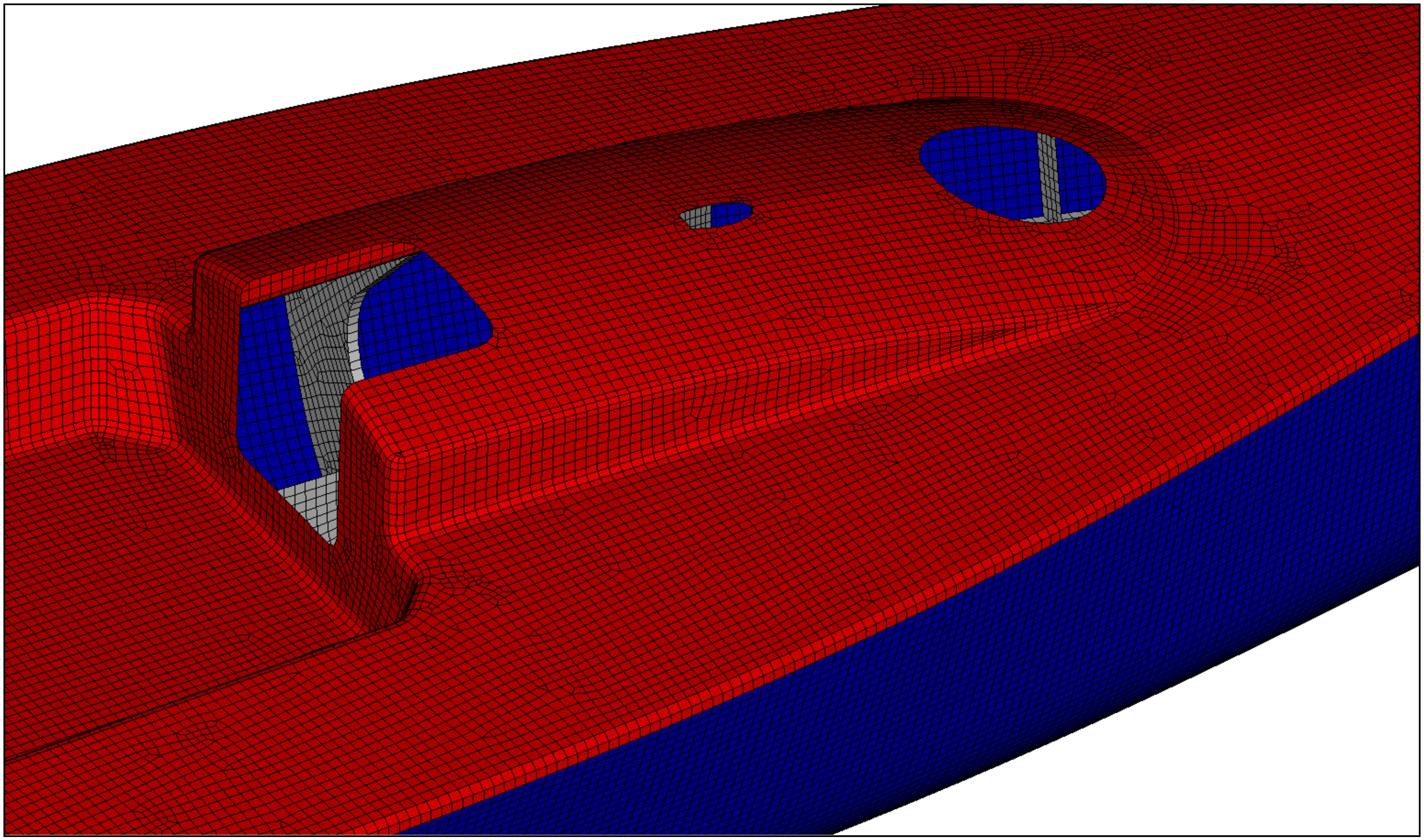

Fig. 1 – Typical Hull/Deck Mid-Body Global Mesh

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PRE-PROCESSING - MESHING, ctd…

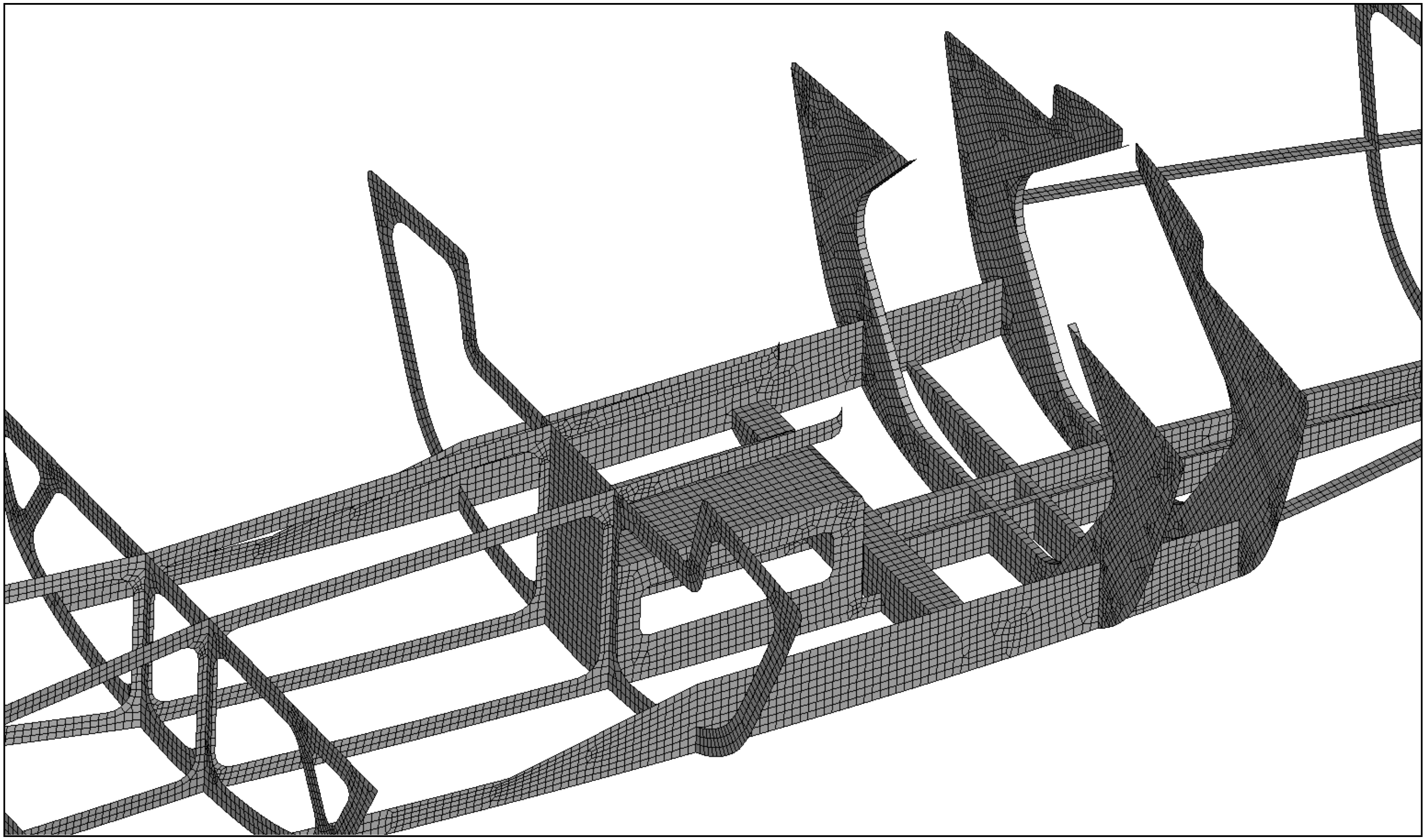

Fig. 2 – Typical Internal Mid-Body Global Mesh

PRE-PROCESSING - MESHING, ctd…

- 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
- Auto-meshers can yield good quality results, but still typically require seeding of curves and surfaces to achieve target mesh density and quality metrics
- Mesh should be ordered and structured (look pretty)
- Pre-processor quality controls should be utilized to evaluate quality metrics including connectivity, aspect ratio, taper, warp, skew, degeneracy
- Underlying surface geometry can affect mesh quality, especially for highly curved surfaces with complex u/v structure
- In some cases splitting and/or re-creation of complex surfaces may be required

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PRE-PROCESSING - MESHING, ctd...

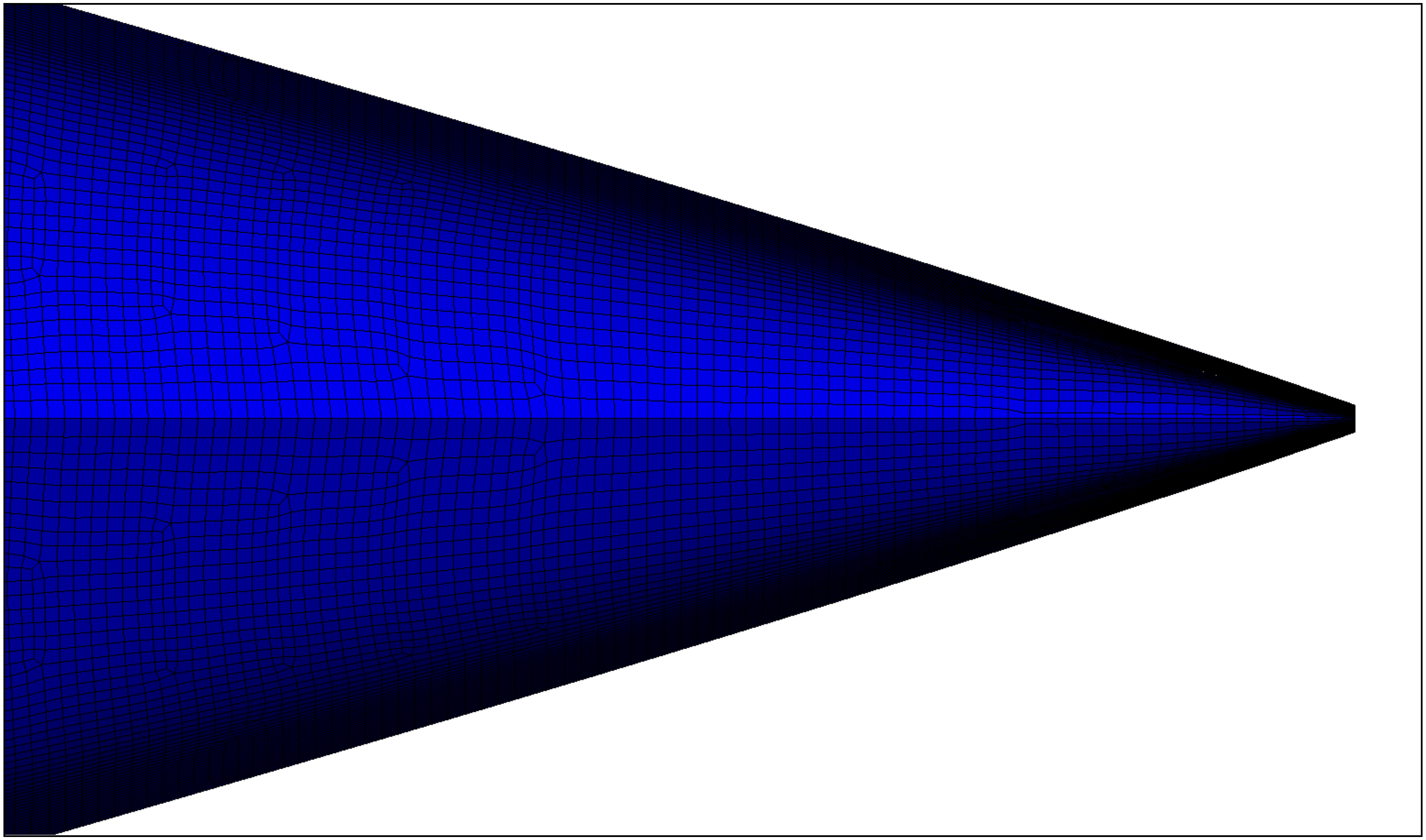

Fig. 3 – Quad mesh transition in high curvature area

PRE-PROCESSING – PLY PROPERTIES

- Most composites FEA applications use plies modeled with 2D orthotropic properties

- Individual plies 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 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

PRE-PROCESSING – PLY PROPERTIES, ctd…

- 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 modeled as solid elements)
- 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
- Test data becoming more readily available from material suppliers, standards organizations, in-house testing
- Wherever possible, test data for plies which are representative of the specific building process to be used should be used for analysis
- Lacking specific test data, generic data can be used with caution

PRE-PROCESSING – PLY PROPERTIES, ctd...

HEXCEL TYPICAL MECHANICAL VALUES ON EPOXY PREPREG LAMINATES

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
	E t	≡	GPa	8	19	8	30	9	65	9	90
	Poisson's ratio υ			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
	E t	≡	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		MPa	60	55	45	40	95	80	95	80
	G		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

Fig. 4 – Typical pre-preg ply properties (Hexcel)

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS

- Laminates combine individual plies into complete through-thickness material definition and applied to elements as properties
- Beyond laminate ply stack, two important element attributes are material orientation vector and normal direction vector
- Material orientation vectors are in-plane vectors for each element that define the direction relative to which the orthotropic ply properties for the laminate assigned to the element are applied.
- 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)
- Material orientation vectors, normal direction vectors and the laminate ply stack must be coordinated such that the resulting element properties are correct
- Pre-processor quality control tools such as vector displays and backface shading should be used to confirm that all material angles and normal vectors are correct; If these are wrong, the analysis will be meaningless

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

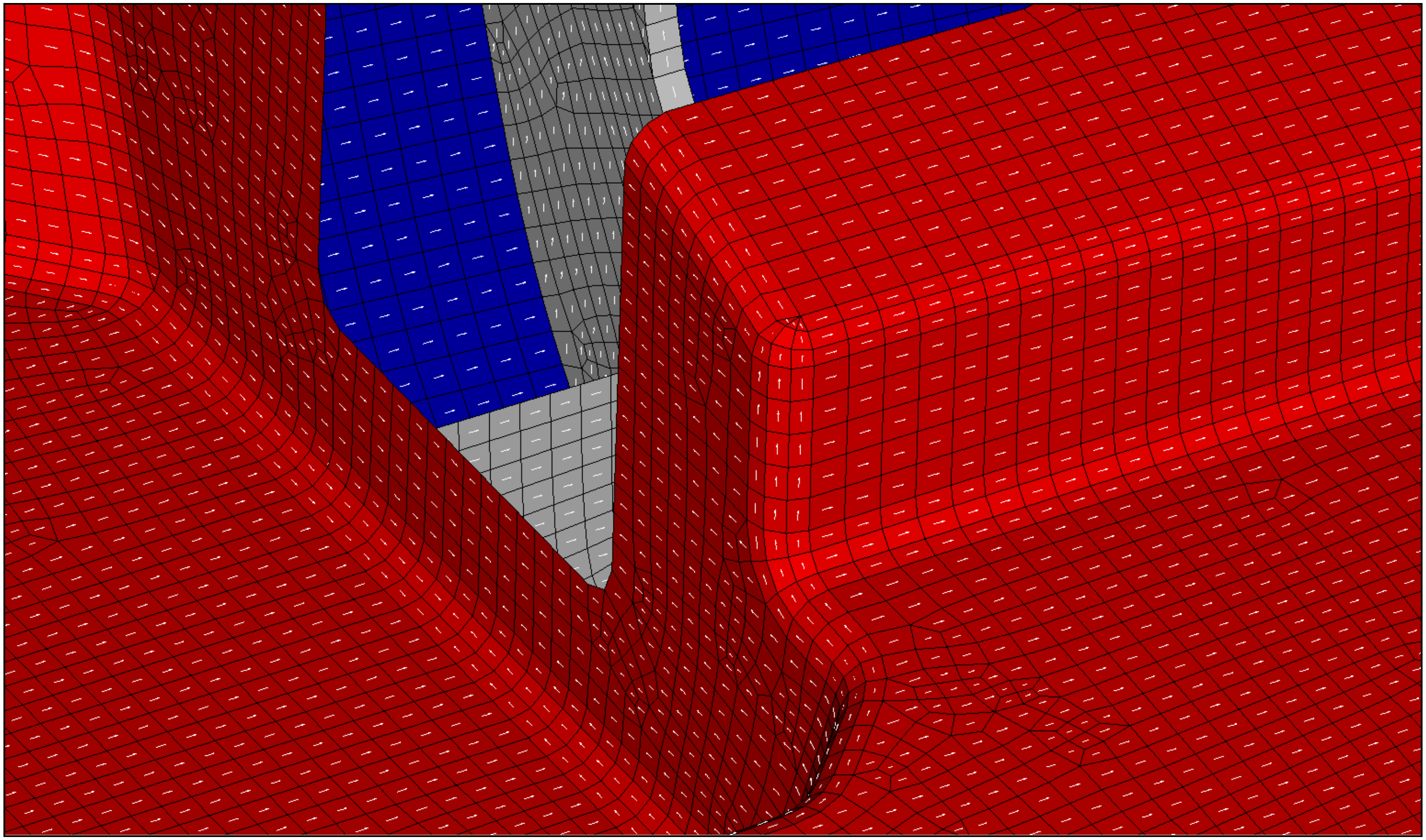

Fig. 5 – Element material orientation vectors

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PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

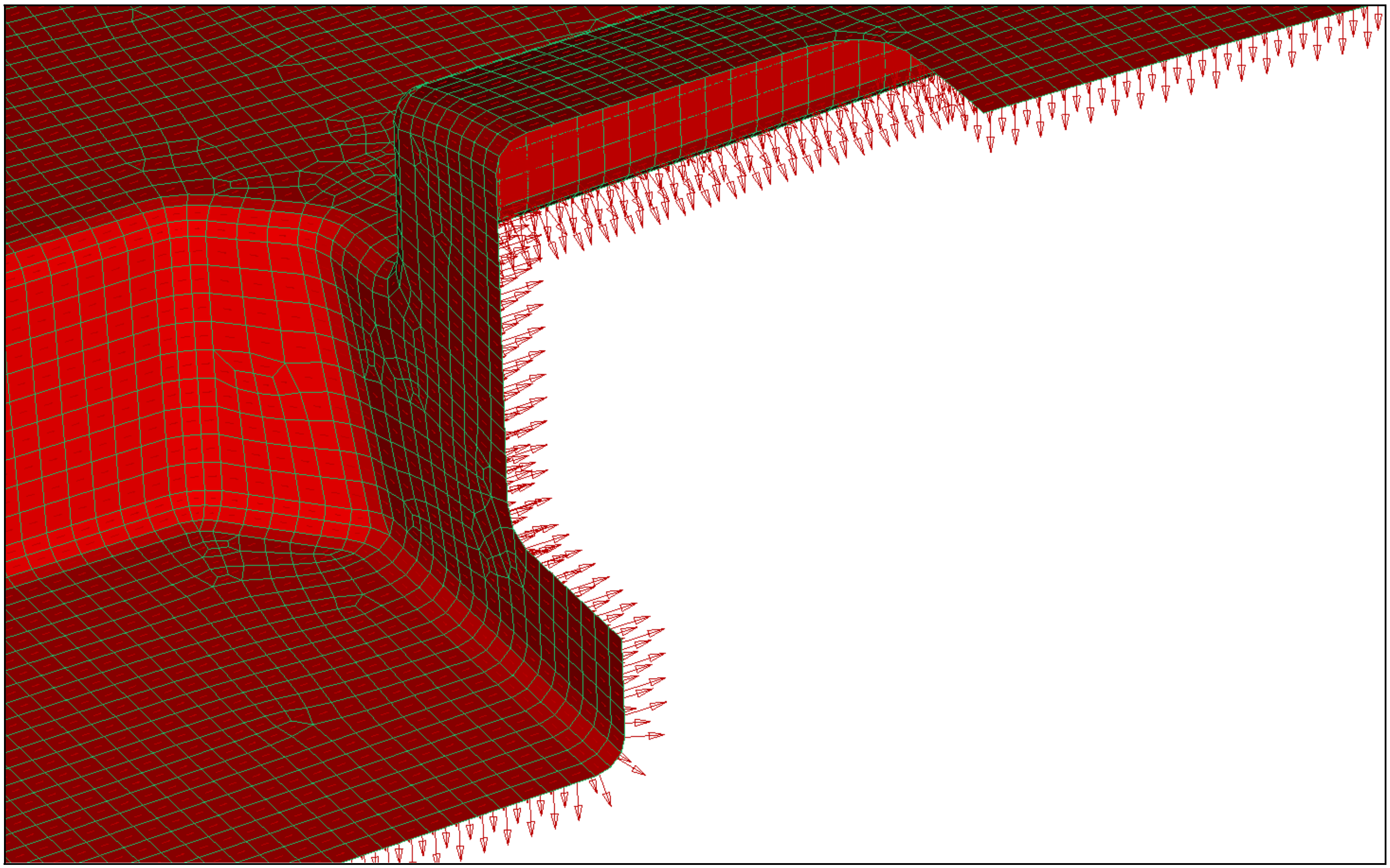

Fig. 6 – Element normal direction vectors

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

- Material orientation vectors defined on flat or gently curved surfaces using vector projection method
- For more highly curved surfaces, vector projection does not adequately account for the way a roll of material will drape over the surface, nor the possibility for in-plane shearing of the fibers to conform to the surface
- These characteristics will vary depending on the ply type (e.g. uni-directional, bi-axial, double-bias), starting point and initial direction for laying down each ply
- Advanced ply management and draping add-ons for pre-processors offer improved accuracy in determining material orientation vectors that are representative of the way in which the material will actually conform to the mold surface
- Following images display difference between vector projection and draping in the forefoot area of the hull; 11 degree shearing angle can vary biaxial carbon ply stiffness by up to 34% and strength by up to 44% relative to x-direction

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

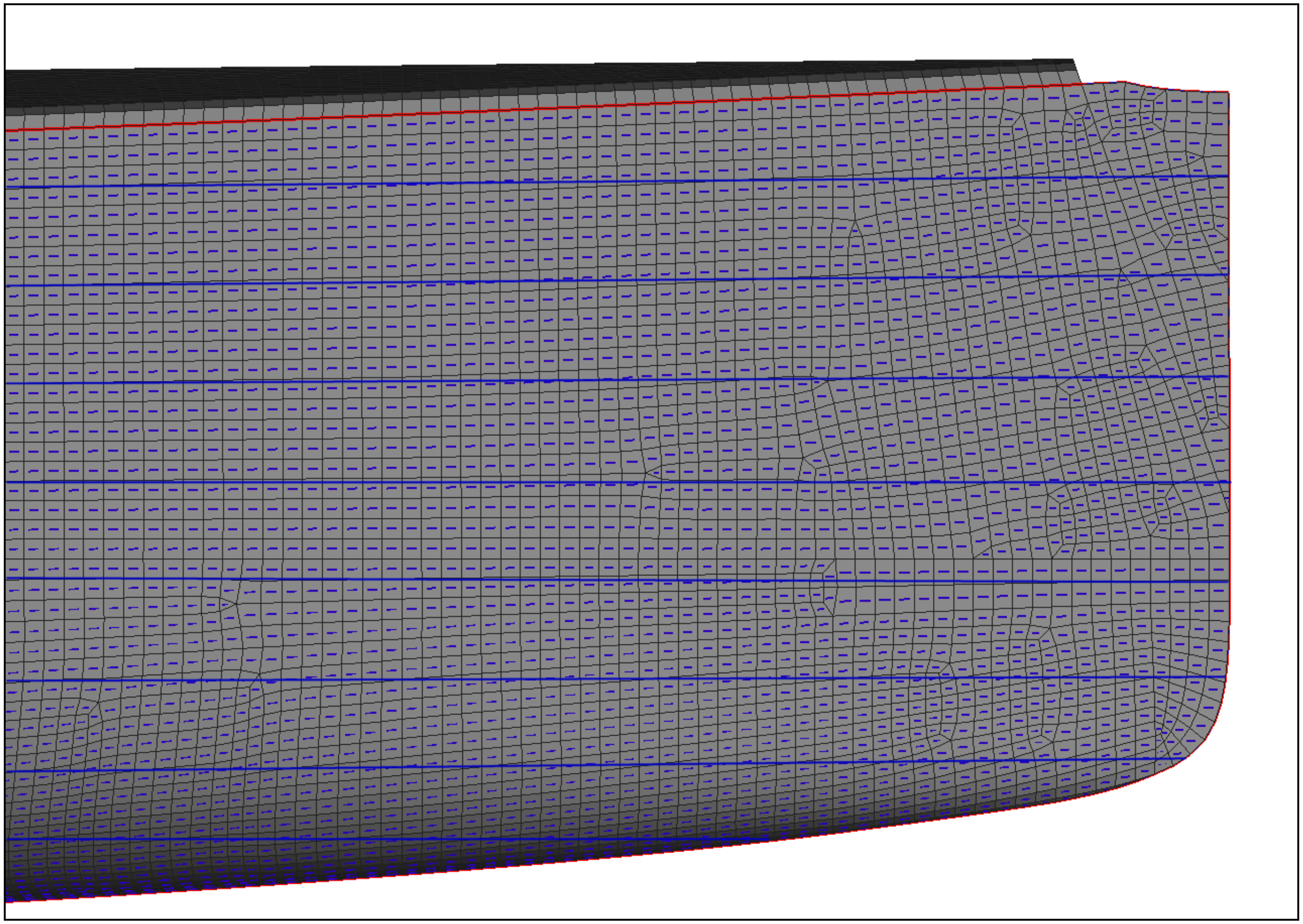

Figure 7 – Material orientation vectors via projection

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

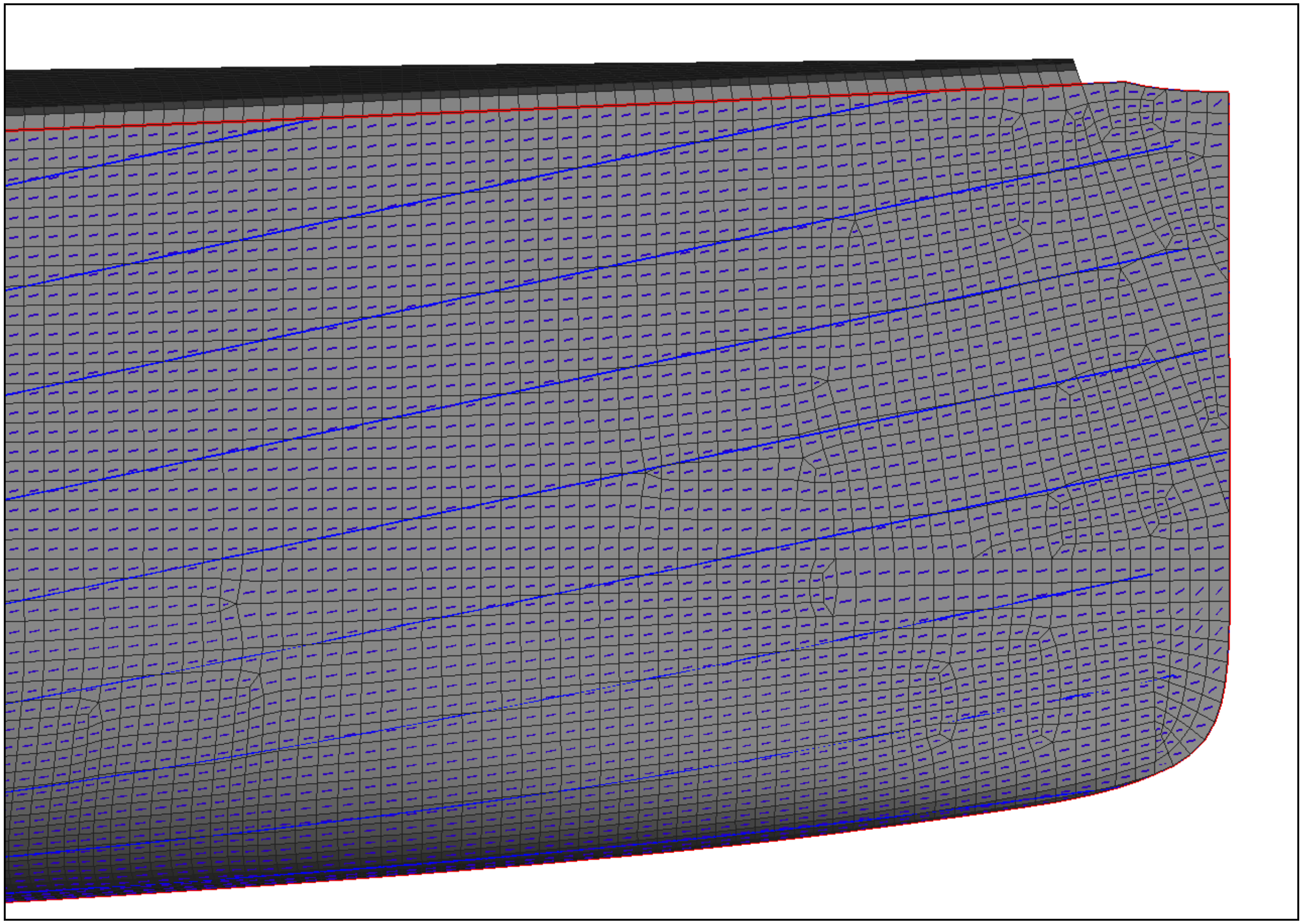

Figure 8 – Material orientation vectors via draping

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PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

- Advanced ply management software simplifies the definition of layup sequences and the generation of element properties in areas of overlapping reinforcements
- Rather than a zone-by-zone definition of laminate properties, plies are defined as they are laid down in the build process
- Ply management software then calculates revised properties in overlap zones based on the input properties of the constituent plies
- Removes much of the tedium and potential for error from manually calculating and applying properties in the overlap zones
- Improves visualization of laminate construction sequence, making it easier to validate against design drawings
- Following images show sequence of bulkhead lamination resulting in six distinct property zones from three ply sets (base laminate, double-bias reinforcement and unidirectional reinforcement)

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

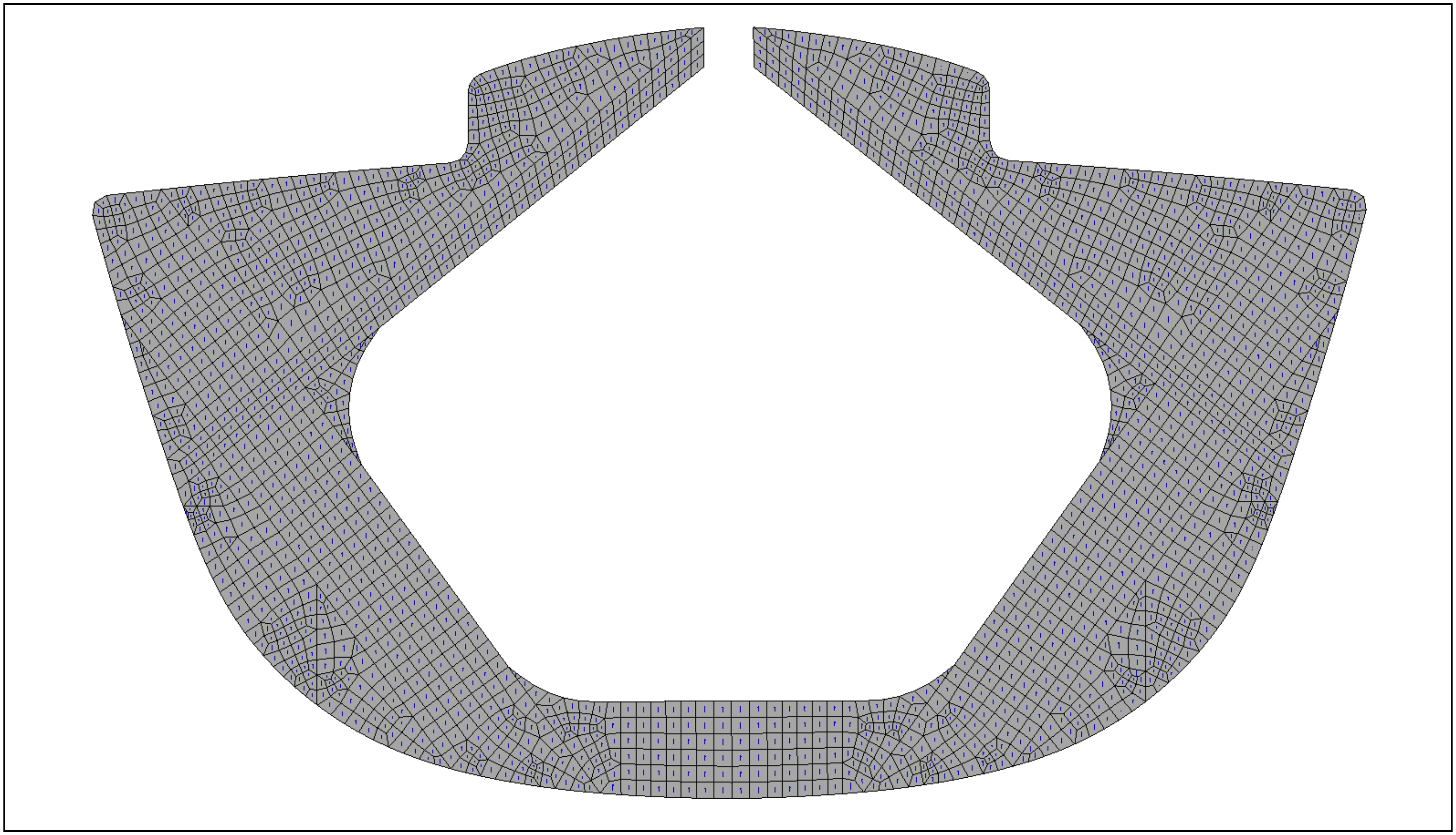

Figure 9 – Material orientation vectors via projection

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

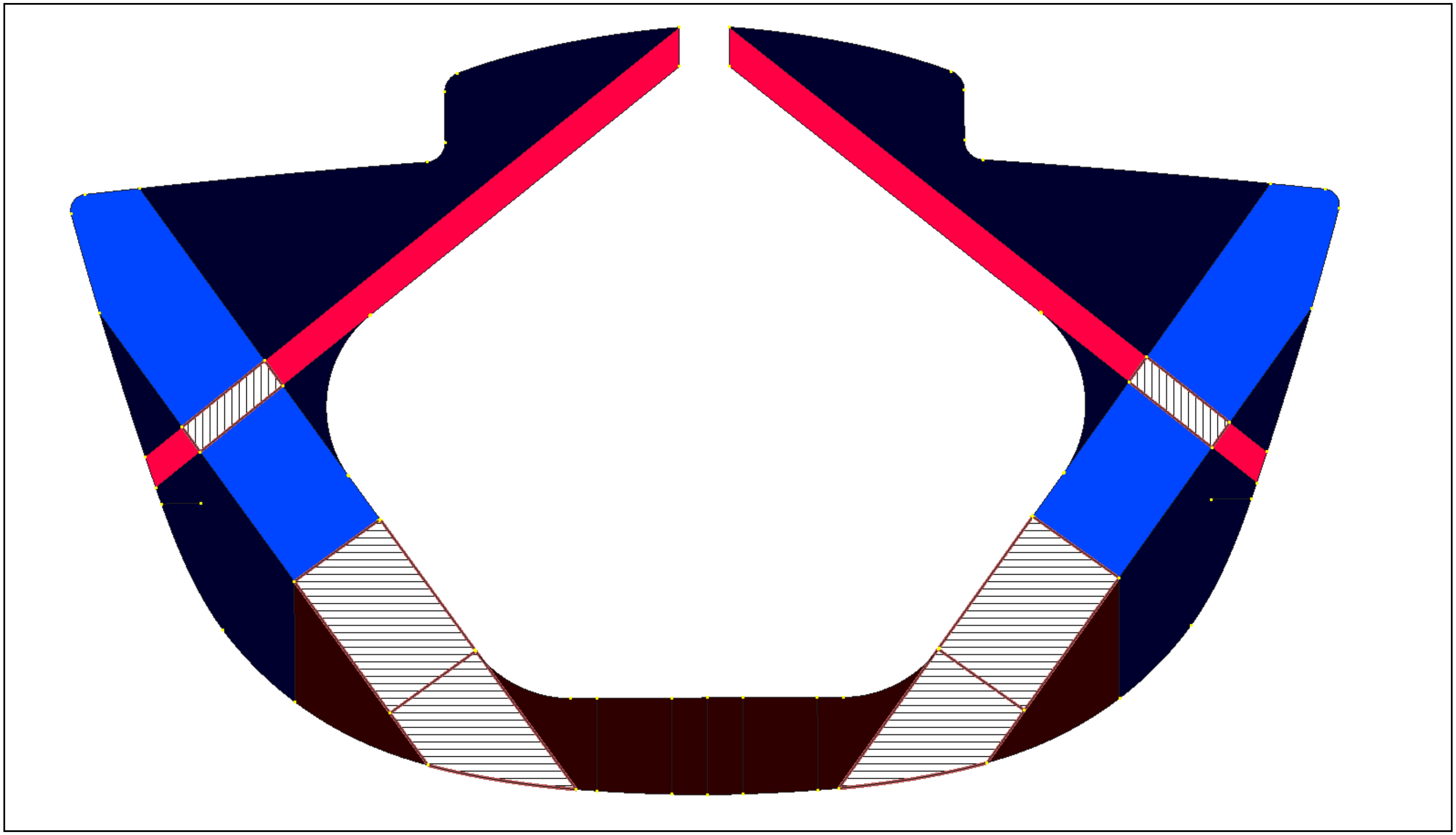

Figure 10 – Six distinct element property zones

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

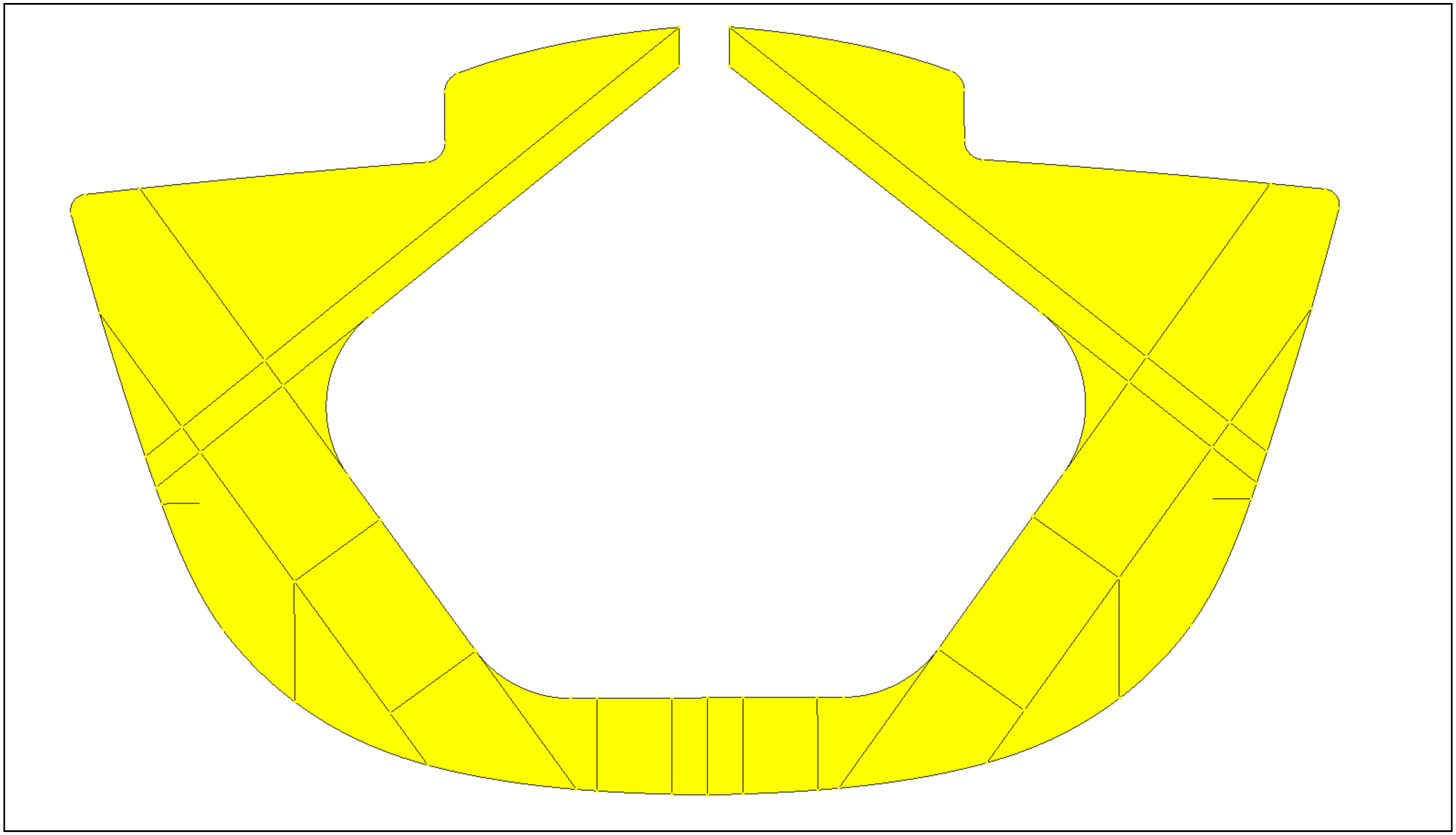

Figure 11 – Base biaxial / double bias laminate

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

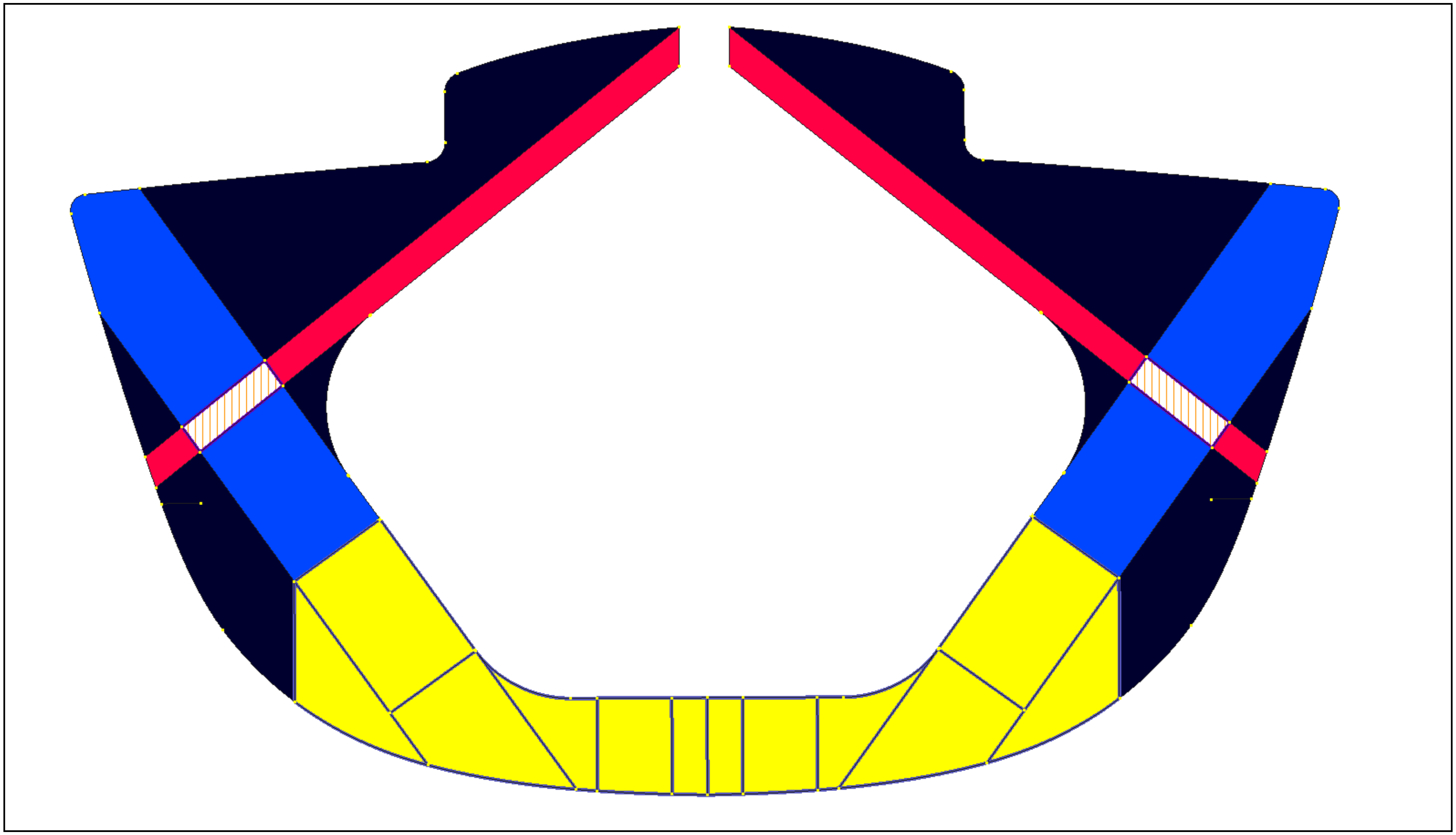

Figure 12 – Double bias laminate reinforcement extents

PRE-PROCESSING – LAMINATE DEFINITIONS & ELEMENT ORIENTATIONS, ctd…

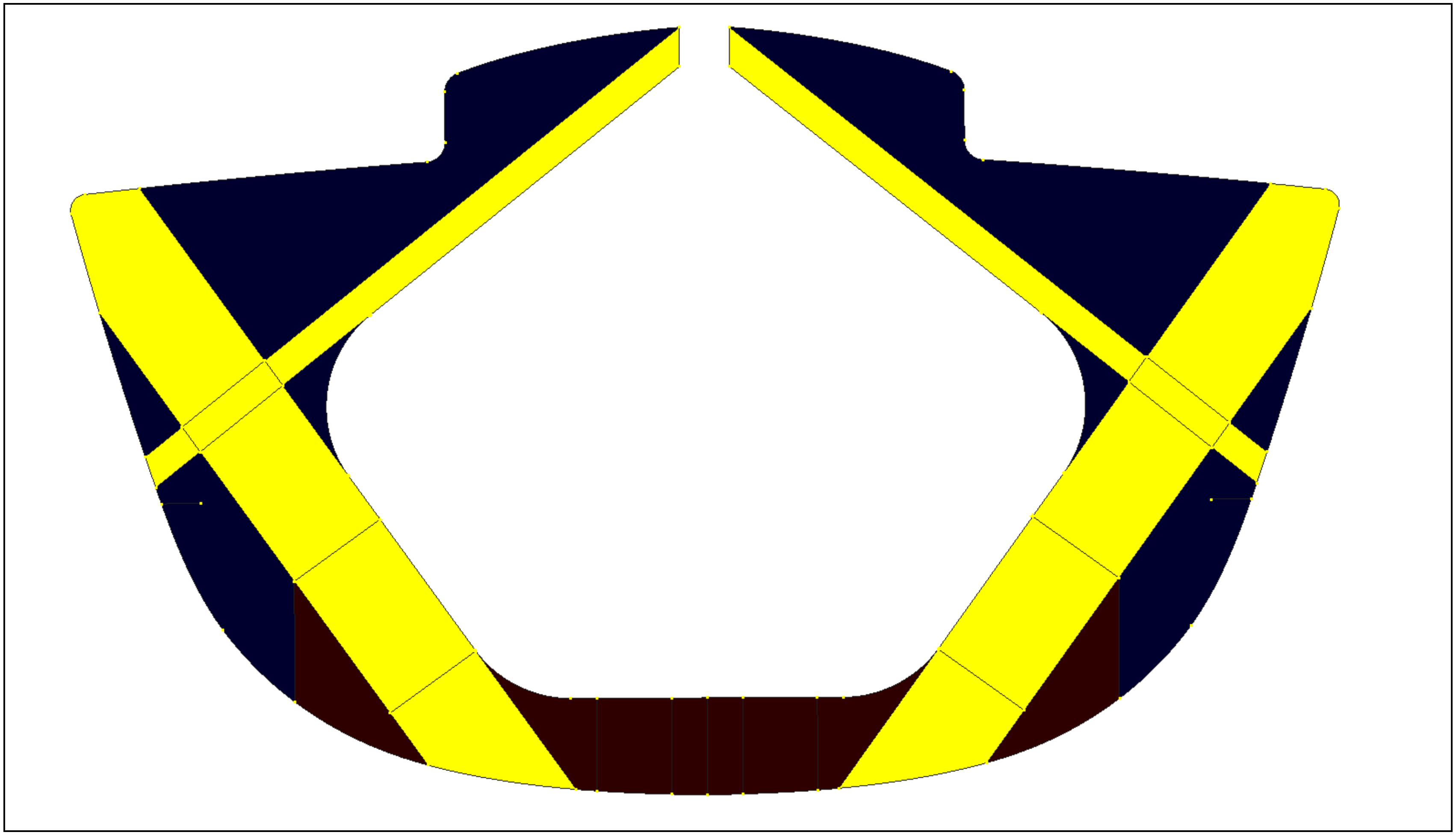

Figure 13 – Unidirectional laminate reinforcement extents

LOAD CASES – FORCE AND MOMENT BALANCE

- 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; Typical load cases include:
  - Dockside rig loads, light rig tension
  - Dockside rig loads, max rig tension
  - Steady-state upwind
  - Steady state reaching/downwind
  - Wave slamming/pitching
  - 90 degree knockdown
  - Grounding

- 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)

LOAD CASES – FORCE AND MOMENT BALANCE, ctd…

- 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

- Steady-state, upwind sailing, 20 degrees heel, typical operating condition

- Individual loads include:
  - Forestay
  - Backstay
  - Windward V1/D1 shrouds
  - Leeward V1/D1 shrouds
  - Mast compression
  - Mainsheet
  - Jib sheet
  - Keel
  - Rudder
  - Hydrostatic pressure

LOAD CASES – FORCE AND MOMENT BALANCE, ctd…

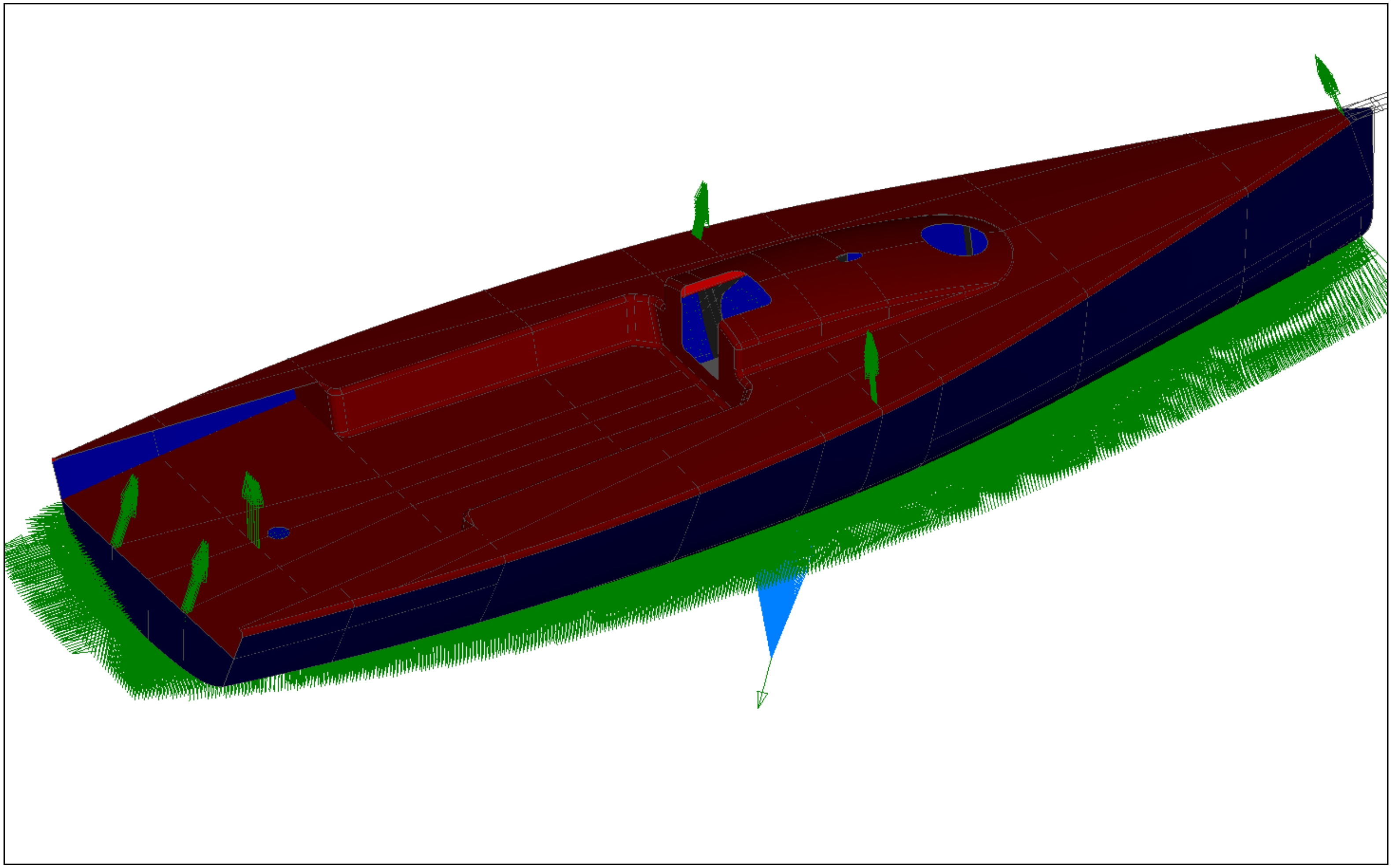

Figure 14a – Upwind load case force balance

LOAD CASES – FORCE AND MOMENT BALANCE, ctd…

	Forces		
	Fx (N)	*Fy (N)*	*Fz (N)*
Windward V1 (Stbd)	0	0	-17800
Windward D1 (Stbd)	0	-3380	-11080
Leeward V1 (Port)	0	0	-2200
Leeward D1 (Port)	0	830	-2680
Forestay	-10960	0	-30110
Backstay	4720	0	-12970
Main Traveller Car	0	0	-7920
Main Winch (Stbd)	0	-6905	720
Main Winch (Port)	0	6905	720
Jib Tack	-1535	-195	-3040
Jib Turning Block 1 (Port)	-2185	0	-4070
Jib Turning Block 2 (Port)	-25	1500	-3220
Jib Winch (Port)	4750	-670	0
Mast Base	-1200	0	**82750**
Mast Collar	4925	580	0
Rudder Upper Bearing	0	-785	285
Rudder Lower Bearing	0	1450	-530
Keel Weight	0	**-8037**	**22083**
Hydrostatic Pressure	0	9790	-26780
Self-Weight	0	-7011	14659
Total Load (N)	**-1510**	**-5929**	**-1183**
Balance Accel - Model Mass (mm/s2):	2984	11717	2338
Balance Accel - Actual Mass (mm/s2):	*337*	*1322*	*264*
Balance Accel - Actual Mass (g):	**0.03**	**0.13**	**0.03**

Figure 14b – Upwind load case force balance

POST PROCESSING – STANDARD COMPOSITE FAILURE THEORIES

- FEA results 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 individually

- In cases where certain principal stresses dominate, then direct comparison to test results for the principal 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 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; Failure index is a relative scalar value with failure = unity or higher (inverse safety factor)

- Different failure indices are appropriate for different types of laminates & loading

POST PROCESSING – STANDARD COMPOSITE FAILURE THEORIES, ctd…

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.
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

Figure 15 – Typical composite Failure Theories (NEi/NASTRAN)

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POST PROCESSING – STANDARD COMPOSITE FAILURE THEORIES, ctd…

- Maximum Strain and Maximum Stress theories are considered *non-interactive*
  - Evaluate the effects of the two orthogonal in-plane principal strains/stresses and the in-plane shear strains/stress in isolation from one another
  - Failure predicted based on any one of the three strain/stress levels exceeding the ply limit for that quantity
  - Do not accurately predict failure for multi-axial stress states
  - Still useful as a means for evaluating principal stress orientations; Principal stress vectors can be used as a guide for the application of reinforcements to best handle areas dominated by highly directional stresses

- Hill, Hoffman and Tsai-Wu theories are all considered *interactive*
  - Consider the combined effects of the principal and shear strains, with failure predicted based on some combination of their effects
  - Generally indicate first ply failure, beyond which solution is non-linear (can use progressive ply failure techniques to study if desired)
  - No distinction made between constituent fiber and matrix strains/stresses; Ply properties are "smeared"

POST PROCESSING – ADVANCED COMPOSITE FAILURE THEORIES

- Advanced failure theories go beyond "smeared" ply properties to evaluate constituent fiber and matrix strains/stresses
- Provide more detailed knowledge of failure mechanisms and better assessment of potential corrective actions
- LaRC02
  - Developed by researchers at NASA's Langley Research Center
  - Leverages Hashin, Puck, Mohr-Coulomb and Maximum Strain theories
  - Currently restricted to unidirectional plies
  - Calculates results for both fiber and matrix tension and compression
- Multi-Continuum Theory (MCT)
  - Initially developed by researchers at University of Wyoming with further development and commercial release by Firehole Composites
  - Applicable to both unidirectional and woven plies
  - Some (minimal) additional material characterization required beyond stiffness and strength values listed earlier
  - Calculates results for fiber and matrix in the two principal fiber directions

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON

- For 42ft yacht model shown here, hull and deck have base biaxial and double-bias plies plus unidirectional reinforcements in longitudinal and transverse directions
- Longitudinal reinforcements contribute to global bending stiffness which is critical to maintaining adequate forestay tension which in turn is a major determinant in maintaining accurate sail shape
- Transverse reinforcements stiffen and strengthen the mid-body section against the combined effects of shroud tension (acting upward) and mast compression (acting downward)
- Resulting stress state in the area of overlap in way of the shrouds and mast is quite complex and not easily ascertained using only a principal stress analysis
- Tsai-Wu and LaRC02 compared for unidirectional reinforcement plies
- Tsai-Wu and MCT compared for both biaxial/double bias base plies and unidirectional reinforcement plies
- Results indicate (usually) the advantages of the more advanced failure theories that can individually predict constituent fiber and matrix strains/stresses

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

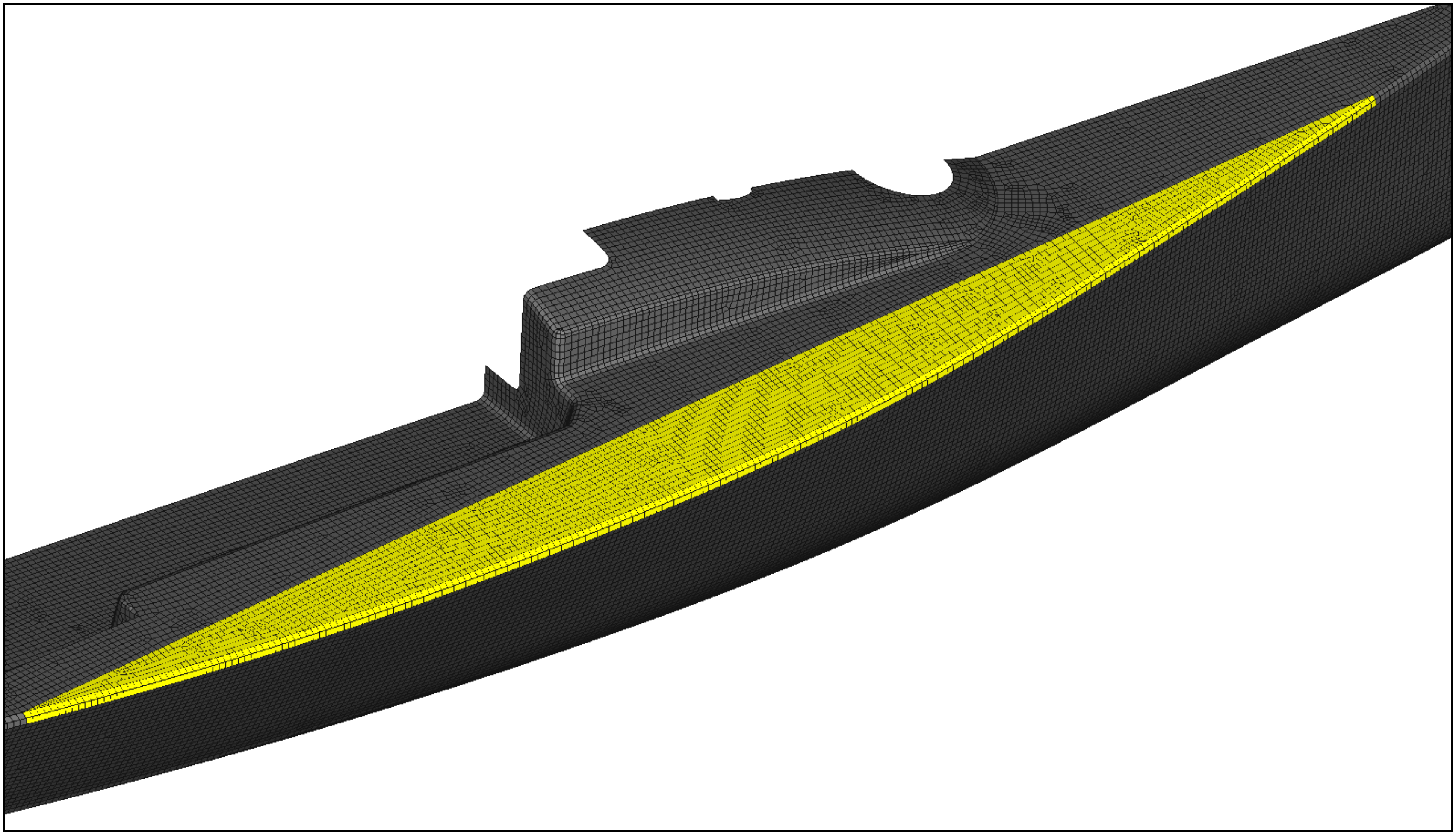

Figure 16 – Deck longitudinal unidirectional reinforcement

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

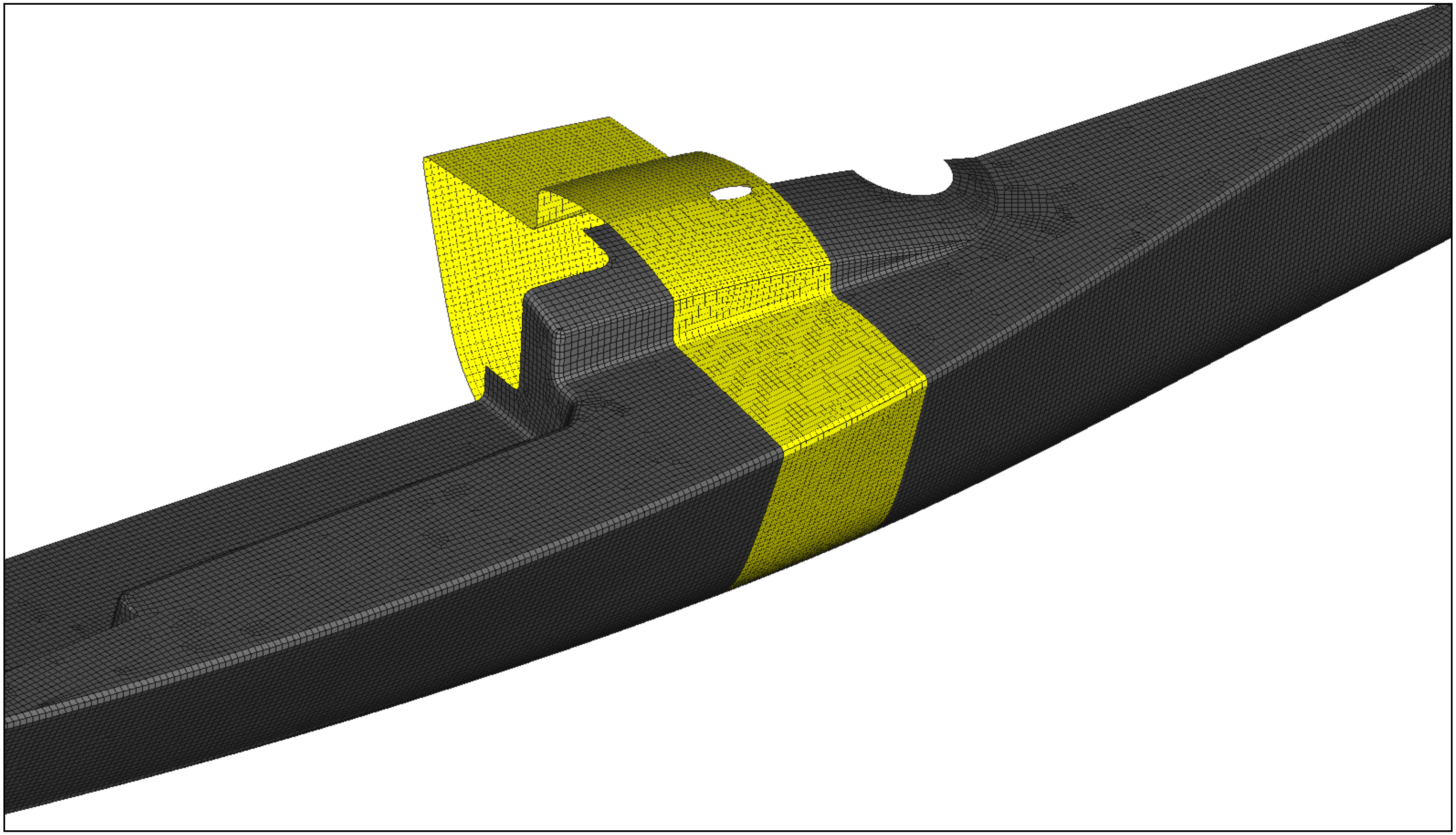

Figure 17 – Deck transverse unidirectional reinforcement

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

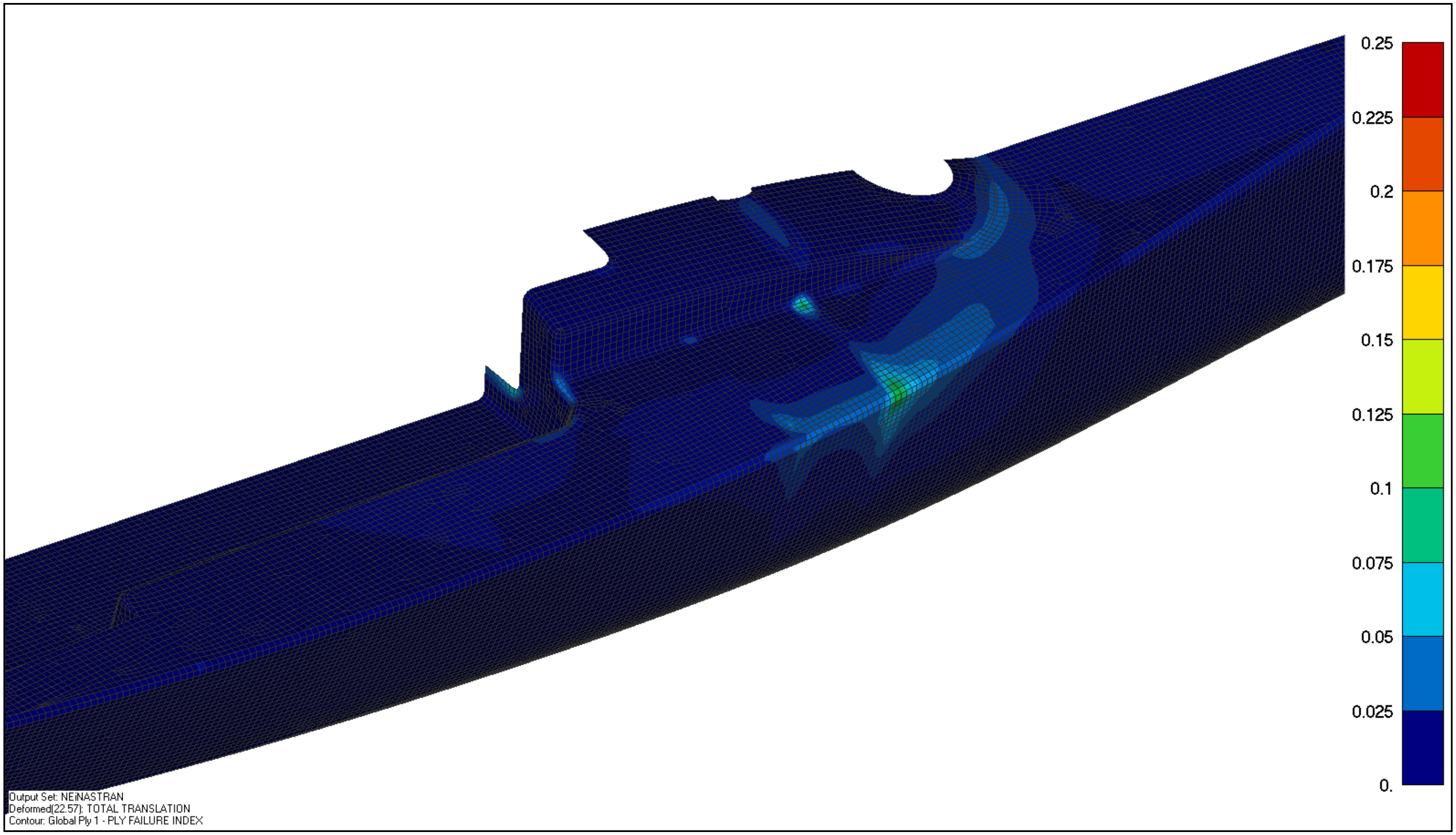

Figure 18 – Base laminate biaxial ply, Tsai-Wu FI

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POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

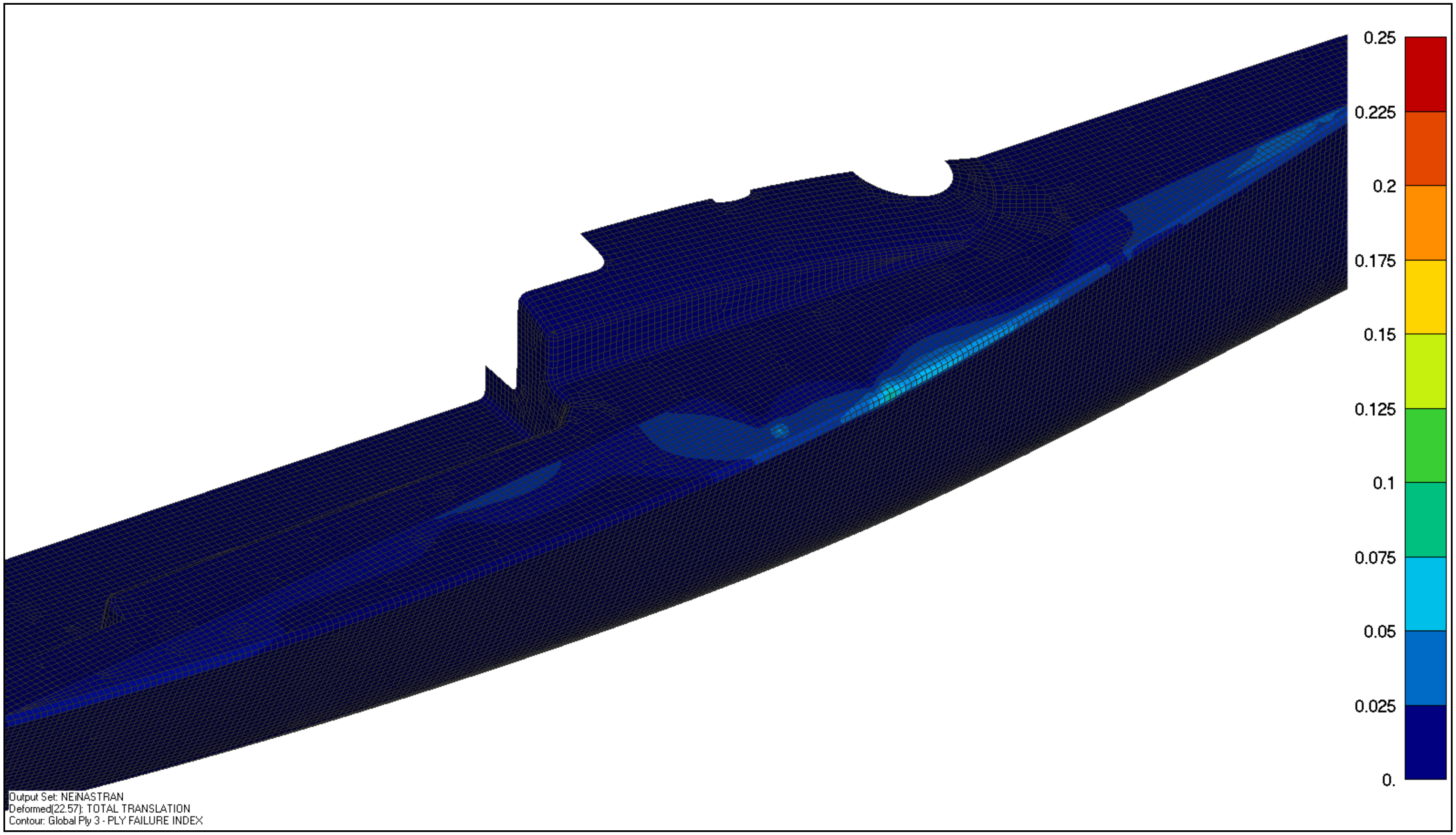

Figure 19 – Unidirectional ply, Tsai-Wu FI

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POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

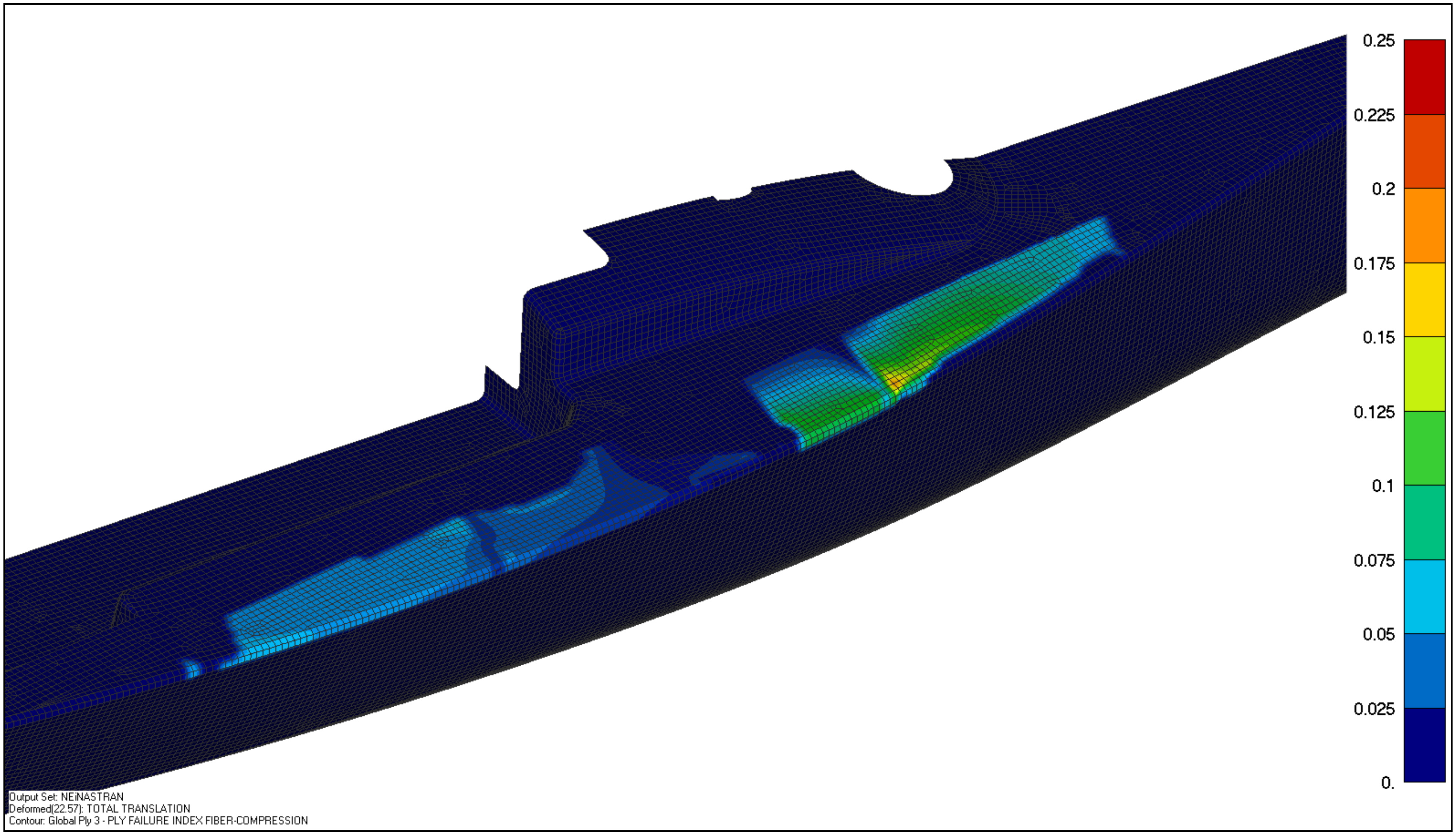

Figure 20 – Unidirectional ply, LaRC02 FI (Fiber Compression)

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

Comparing LaRC02 to Tsai-Wu for deck longitudinal unidirectional ply (Fig. 19 vs. 20):

- Contour scale for failure index (FI) ranges from 0 (blue) to 0.25 (red). FI is essentially inverse of safety factor (SF): FI = 1/SF; So, FI of 0.25 = SF 4.0
- Tsai-Wu predicts maximum FI ~ 0.1 along sheer radius in way of mast frame
- LaRC02 predicts maximum FI ~ 0.2 in same area; Dominant failure mode is fiber compression which makes intuitive sense due to global bending
- LaRC02 shows more extensive distribution of strain throughout longitudinal reinforcement; Note that LaRC02 considers fiber buckling in calculations for compressive fiber failure, while Tsai-Wu only considers “smeared” ply compression
- LaRC02 better displays boundary effects of below-deck internal framing

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

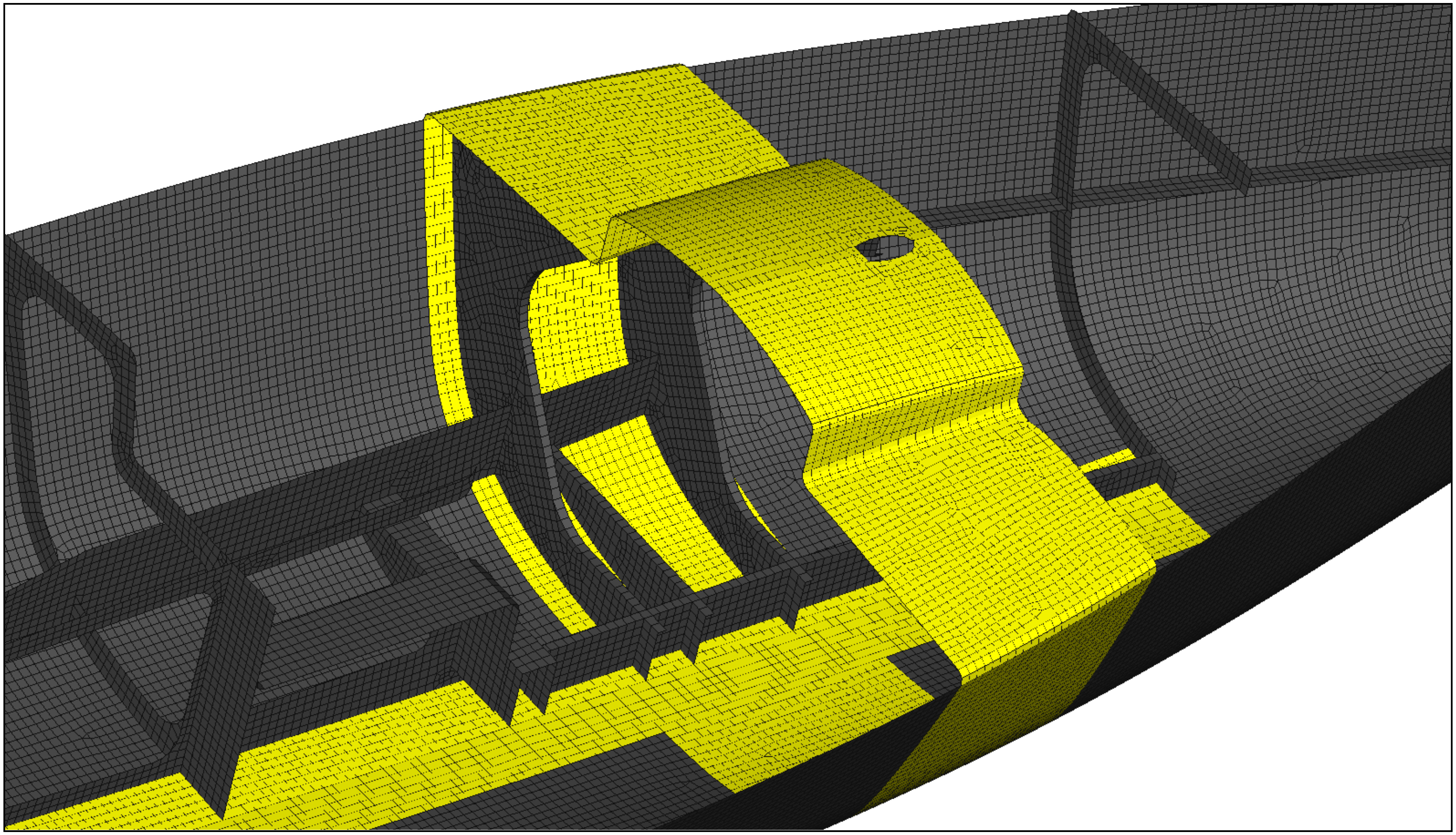

Figure 21 – Hull transverse & longitudinal unidirectional reinforcements

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

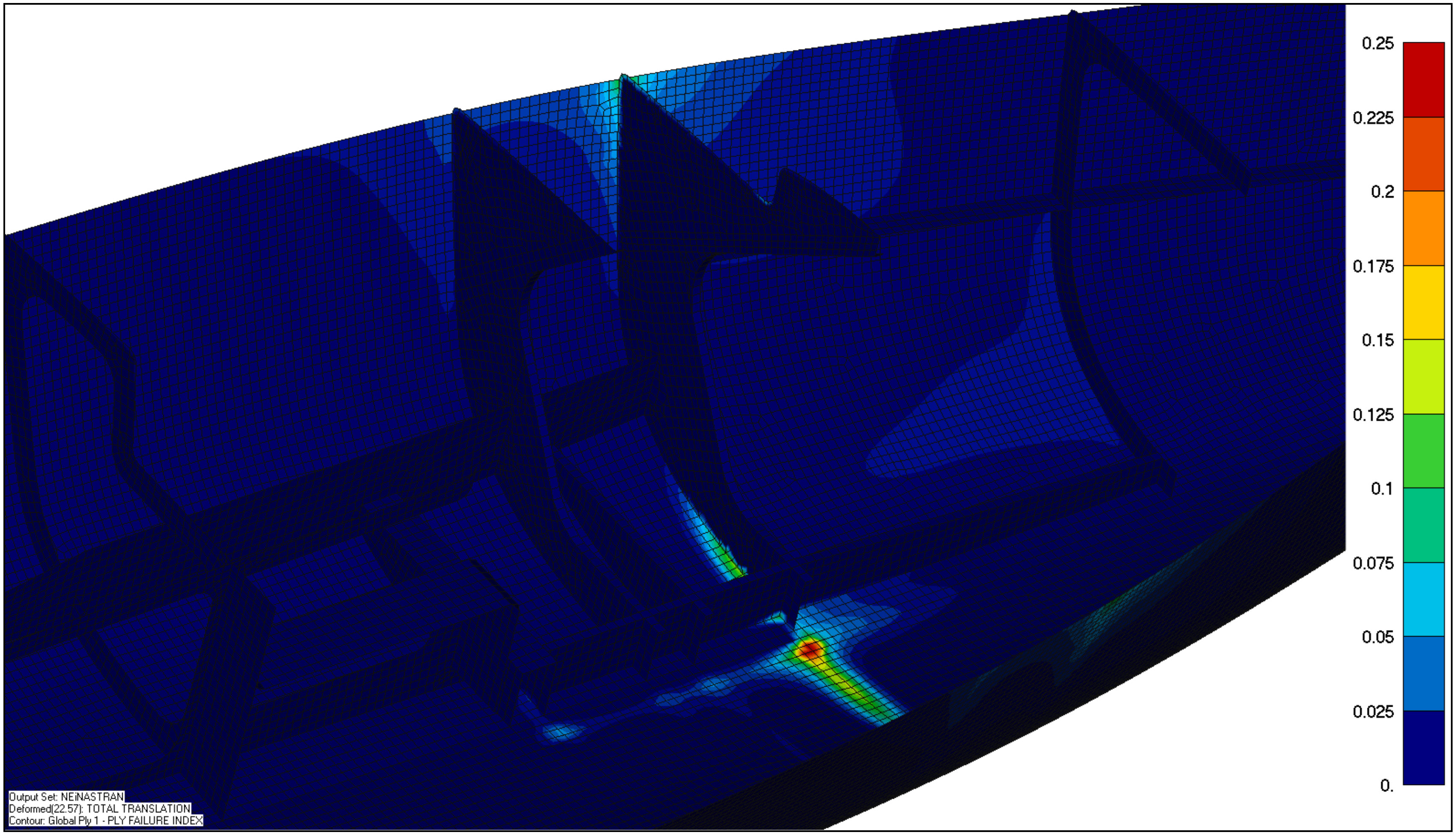

Figure 22 – Base laminate biaxial ply, Tsai-Wu FI

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

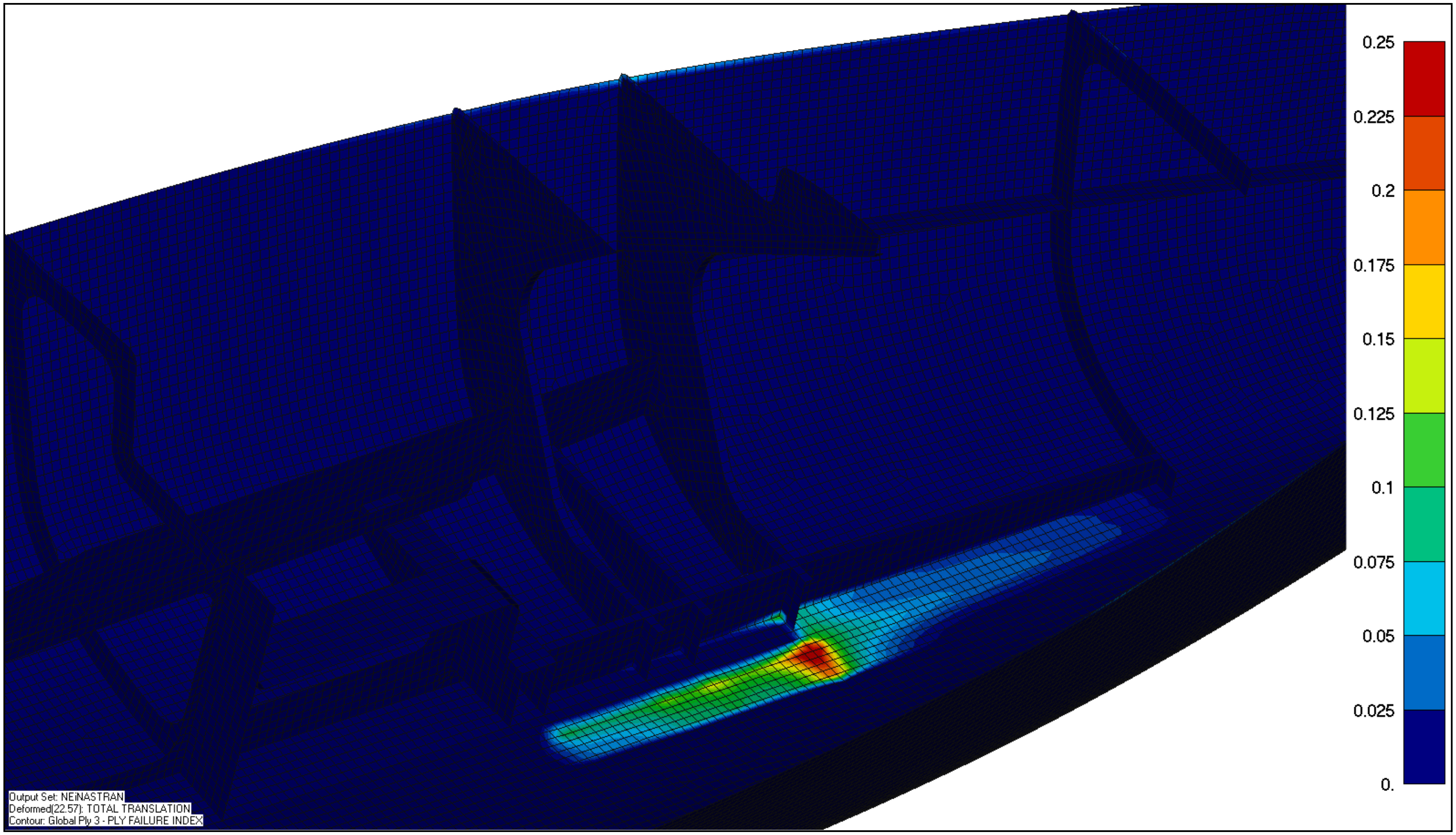

Figure 23 – Unidirectional ply, Tsai-Wu FI

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

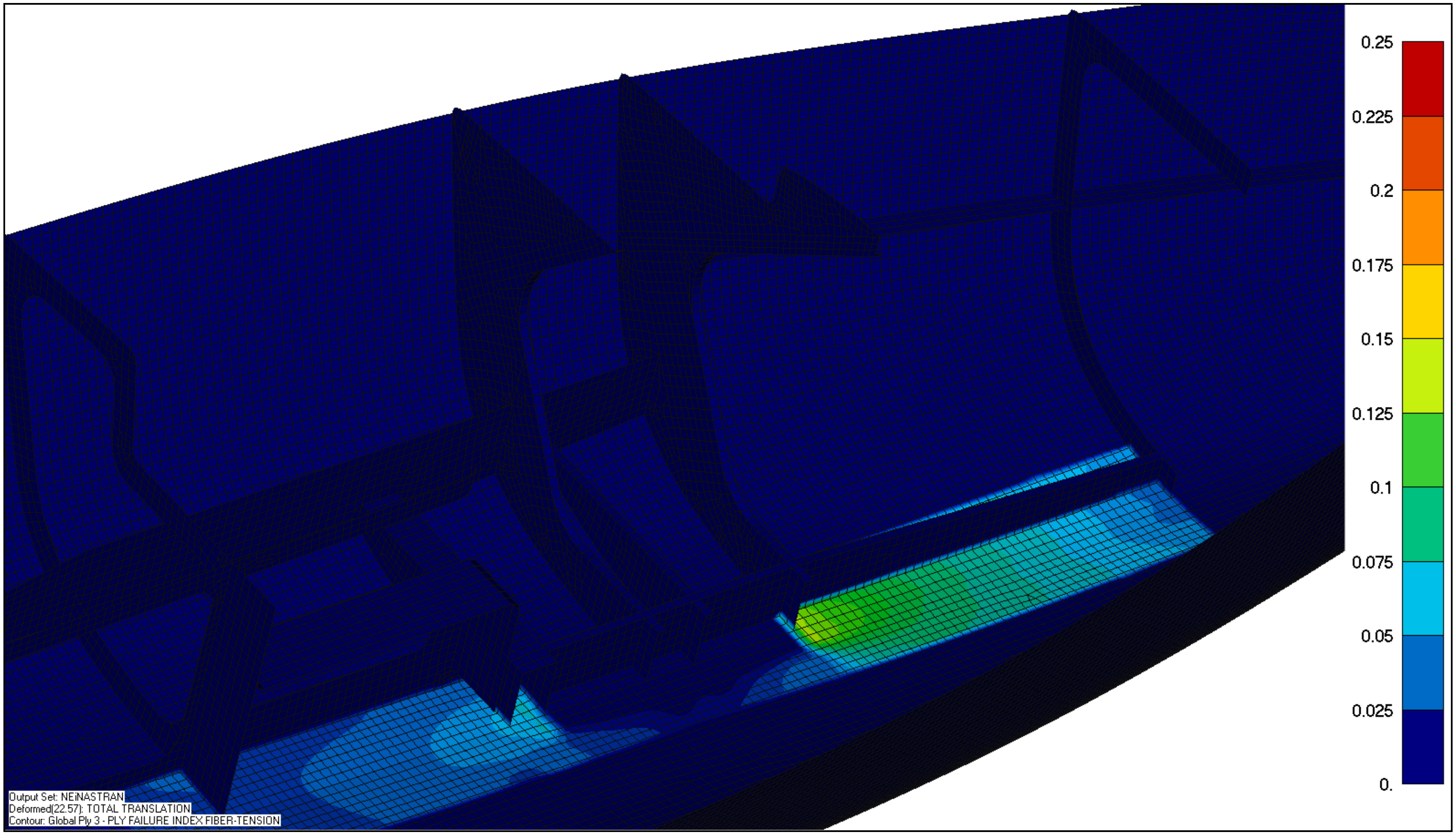

Figure 24 – Unidirectional ply, LaRC02 FI (Fiber Tension)

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

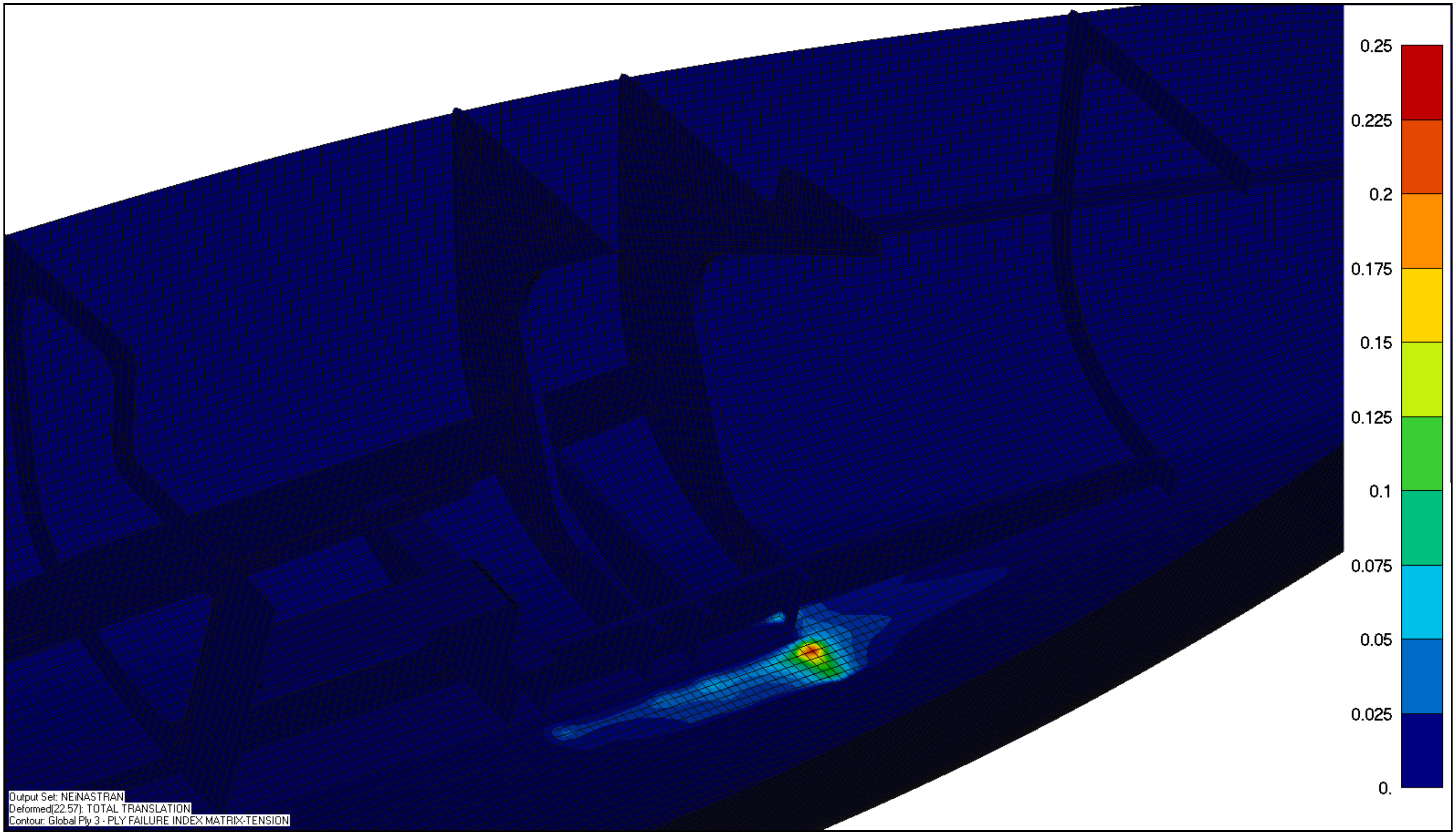

Figure 25 – Unidirectional ply, LaRC02 FI (Matrix Tension)

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

Comparing LaRC02 to Tsai-Wu for hull longitudinal unidirectional ply (Fig. 23 vs. 24/25):

- Note: Internal structure on starboard side hidden in order to better view hull skin
- Note: Stiffening of hull skin in way of keel head (solid blue contour on C/L between frames)
- Tsai-Wu failure index contour for "smeared" ply appears to be reasonably close to a combination of LaRC02 failure index contours for fiber and matrix
- LaRC02 provides additional insight into the nature of failure beneath the mast step, indicating matrix-dominated failure
- Tsai-Wu maximum FI ~0.26
- LaRC02 fiber tension maximum FI ~0.15 and matrix tension maximum FI ~0.23

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POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd...

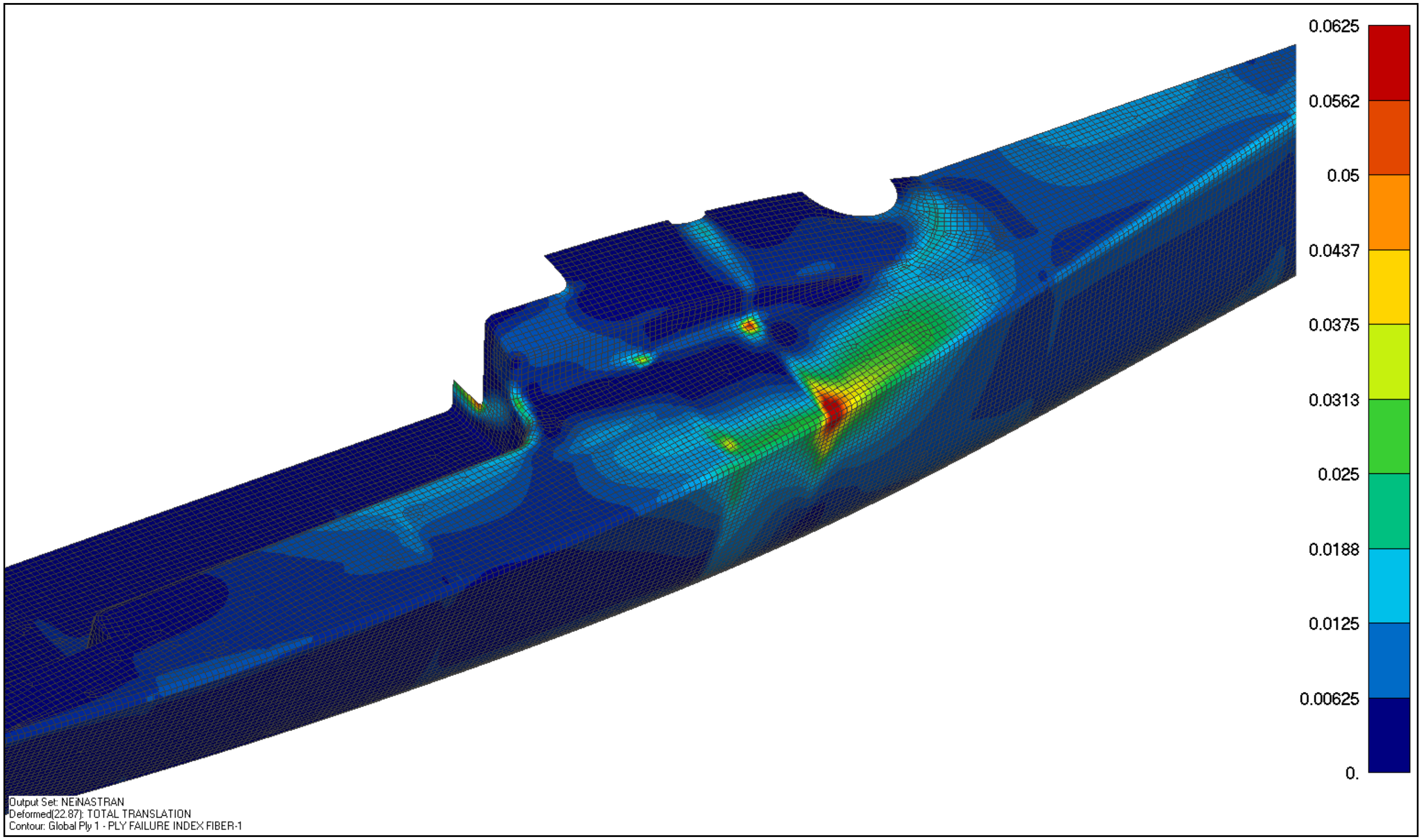

Figure 26 – Biaxial ply, MCT FI (Fiber 1)

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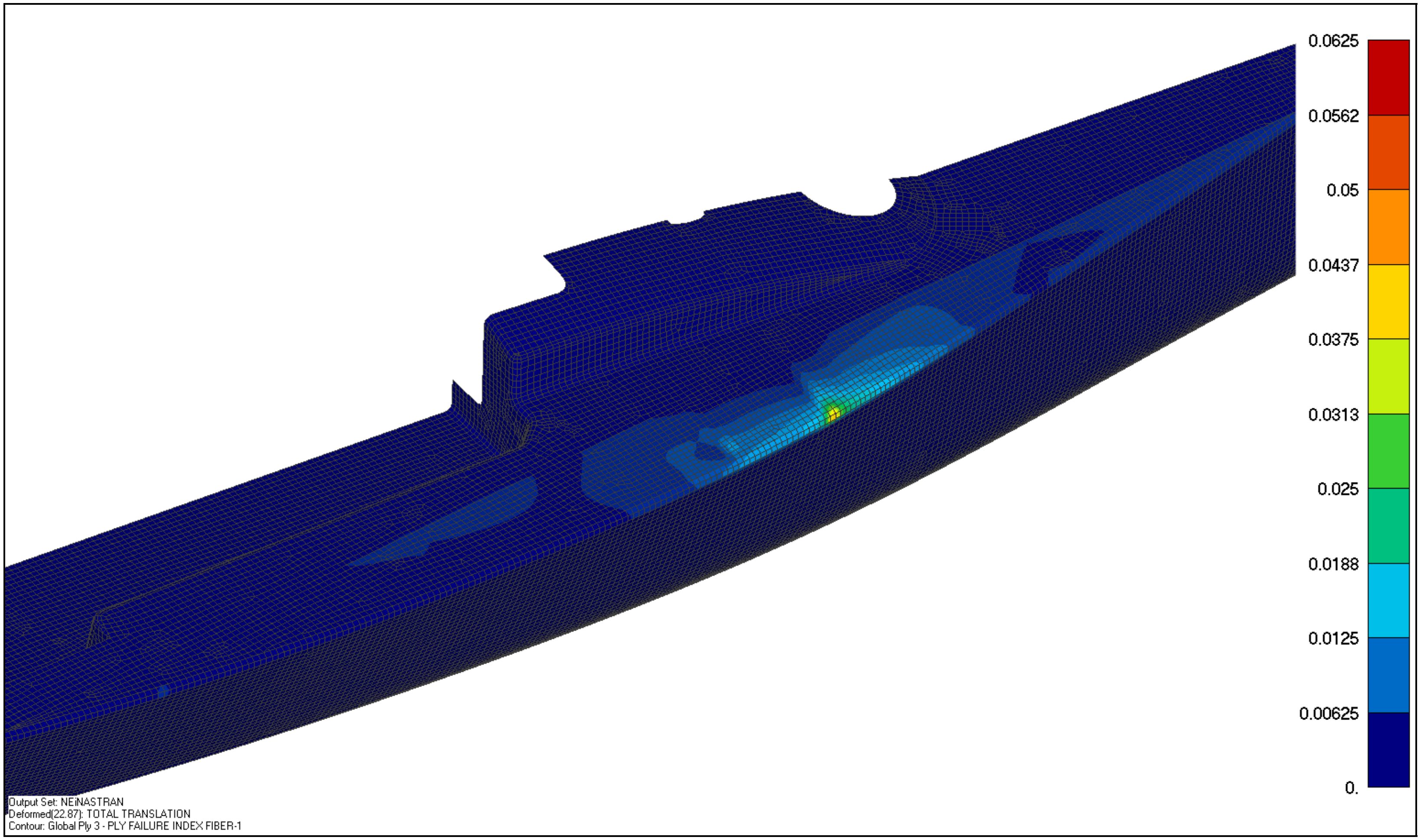

Figure 27 – Unidirectional ply, MCT FI (Fiber 1)

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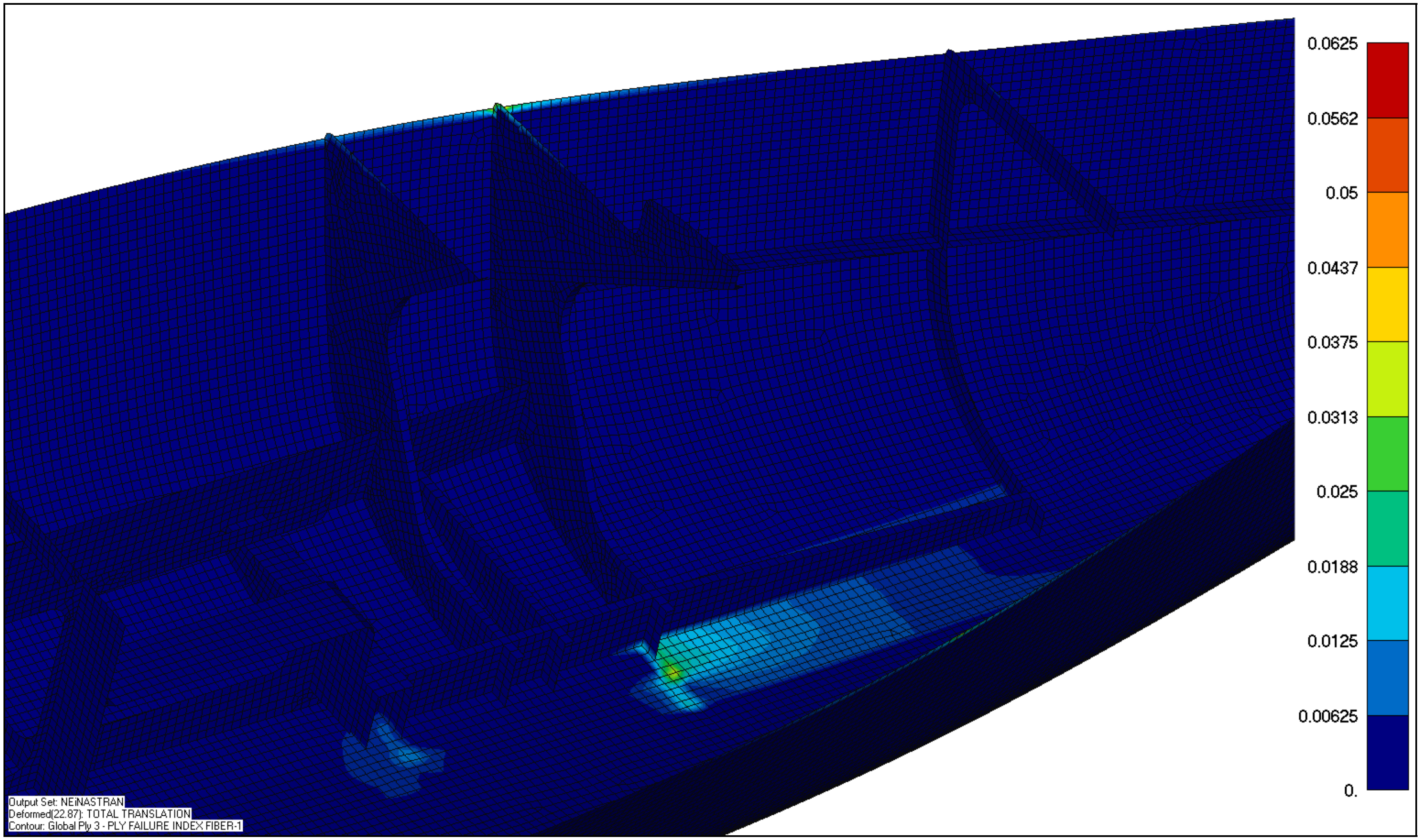

Figure 28 – Unidirectional ply, MCT FI (Fiber 1)

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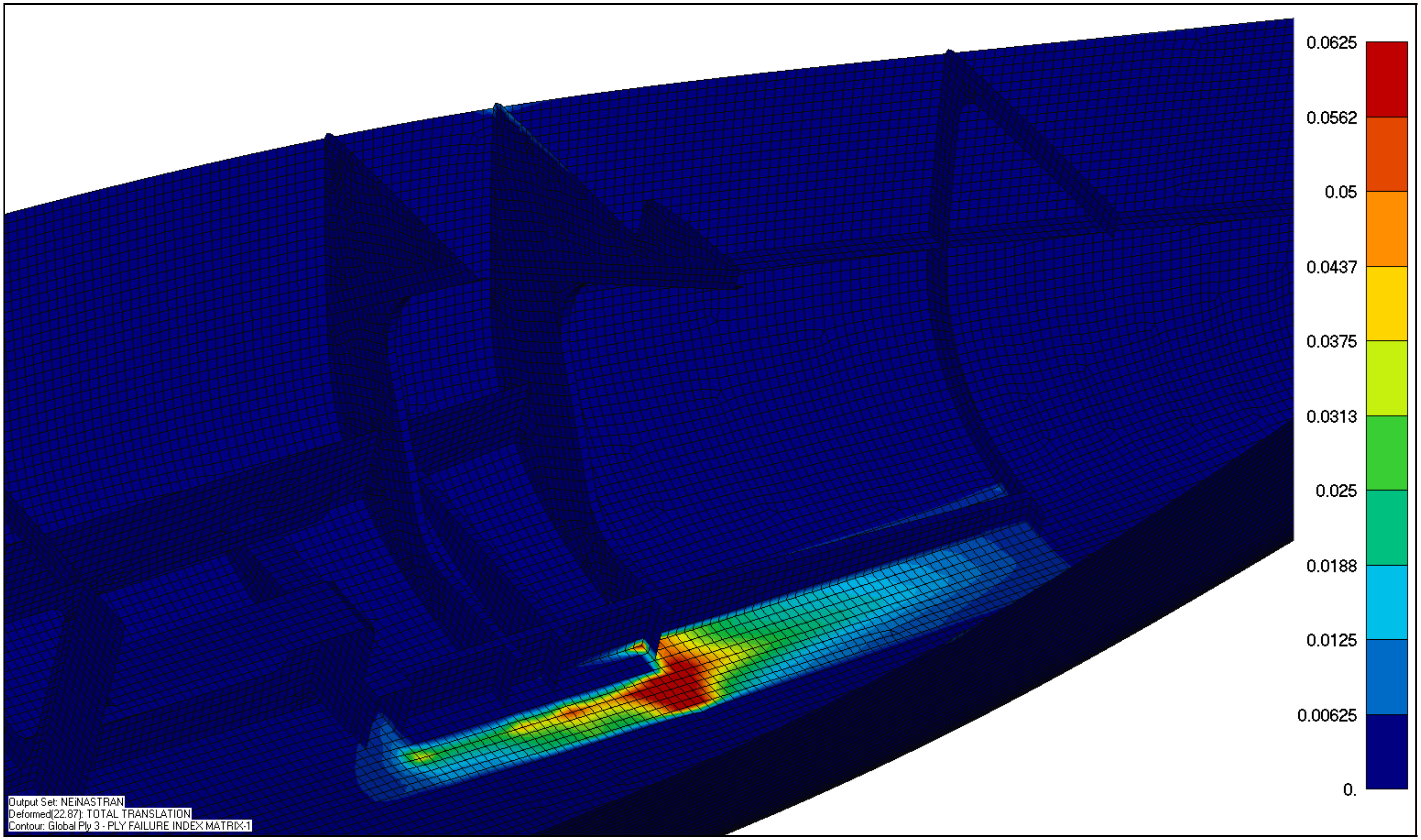

Figure 29 – Unidirectional ply, MCT FI (Matrix 1)

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd…

Comparing MCT to Tsai-Wu for deck biaxial plies (Fig. 18 vs. 26) and longitudinal unidirectional plies (Fig. 19 vs. 27):

- Note: MCT failure index is quadratic with SQRT(FI) = 1/SF; So for instance FI = 0.0625 equates to SF = 4; Thus contour scale for MCT failure index ranges from 0 (blue) to 0.0625 (red) for direct comparison to Tsai-Wu and LaRC02 plots

- For both biaxial and unidirectional plies, overall contours from MCT are similar in nature to those from Tsai-Wu, but magnitude of predicted damage is quite a bit higher (~2.5x), particularly for the biaxial plies

Comparing MCT to LaRC02 for deck longitudinal unidirectional plies (Fig. 20 vs. 27):

- LaRC02 predicts more widespread and slightly higher magnitude of damage, most likely due to consideration of fiber buckling (i.e. buckling load failure is more dominant than compressive strain failure)

POST PROCESSING – FAILURE THEORY RESULTS COMPARISON, ctd...

Comparing MCT to Tsai-Wu for hull longitudinal unidirectional plies (Fig. 23 vs. 28/29):

- Similar trend to that seen for LaRC02
- Tsai-Wu prediction of smeared ply damage is similar to combination of fiber and matrix damage predicted by MCT

Comparing MCT to LaRC02 for hull longitudinal unidirectional plies (Fig. 24/25 v 28/29):

- MCT also predicts matrix failure dominates (although slightly higher magnitude of damage)
- MCT failure tilted even more toward matrix failure than LaRC02

POST PROCESSING – FAILURE THEORY SELECTION

- Preceding comparison of failure theory results begs the obvious question:
  - Which one is right?
- Unfortunately, no simple answer to this question
- Development and validation of composites failure theories is an area of intensive ongoing research
- "World Wide Failure Exercise" (WWFE) by Soden, Hinton and Kaddour most notable attempt at establishing a baseline set of criteria for comparing predicted results from various failure theories to actual laminate test data

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POST PROCESSING – FAILURE THEORY SELECTION, ctd…

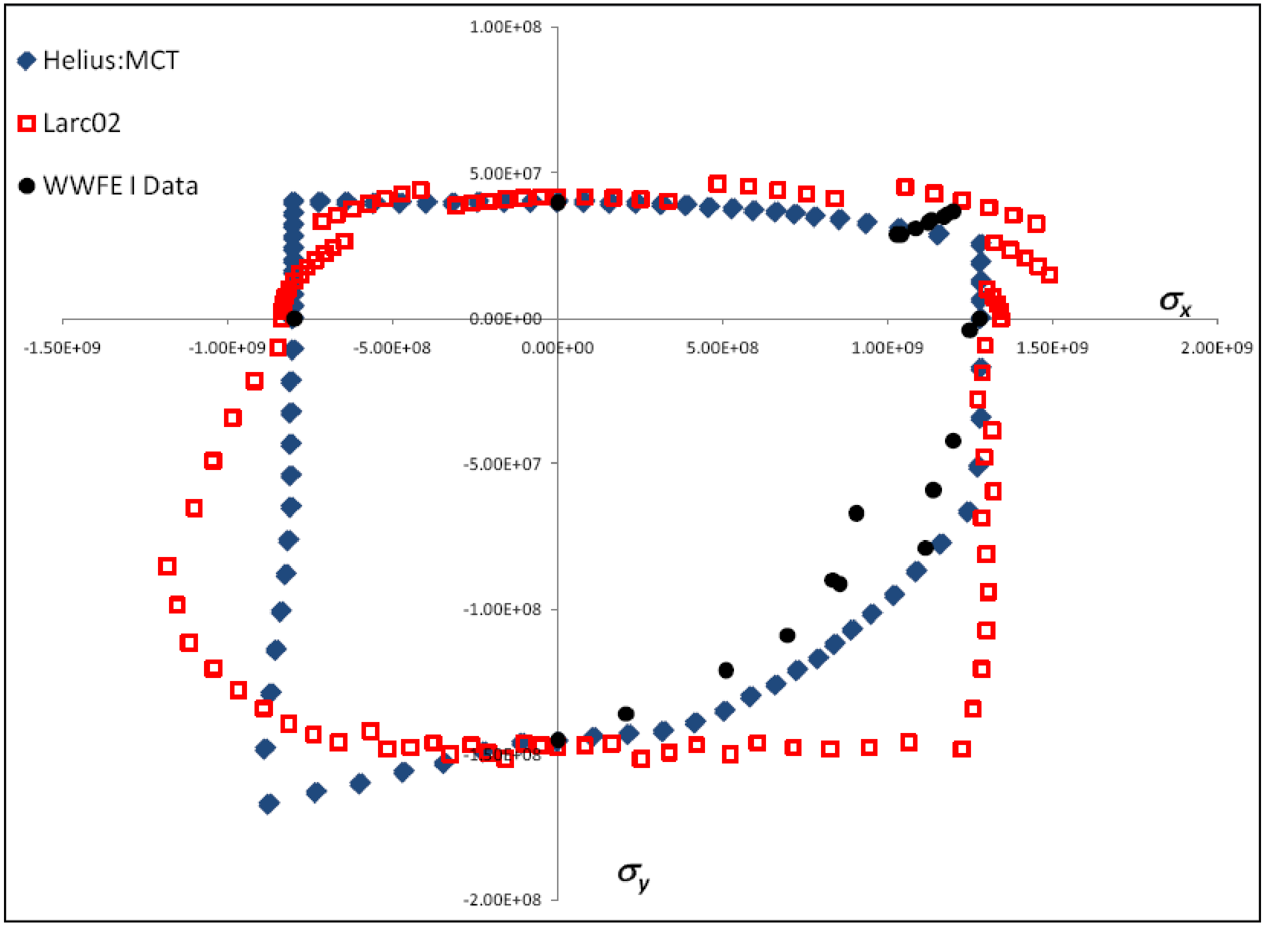

Figure 30 – σx:σy Failure of 0° E-Glass/Epoxy Lamina – MCT vs. LaRC02 vs. Test Data (Firehole Technologies)

POST PROCESSING – FAILURE THEORY SELECTION, ctd…

- In theory, could select different failure theories to assess different areas of model based upon accuracy for dominant local failure modes
- Might be OK for small models; Too cumbersome for large models with hundreds of different laminate zones
- Practical approach:
  - Utilize Tsai-Wu for initial review to evaluate maximum (of all plies) failure indices; Quickly identifies hot spots in model
  - Utilize LaRC02 and/or MCT depending on ply type (unidirectional or biaxial) to extract constituent fiber and matrix stresses and evaluate hot spots in more detail
  - Utilize Max. Stress and principal stress vectors to identify stress flow and aid in placement of unidirectional reinforcements
  - Adjust laminates to meet targets and iterate

20th CSYS: ADVANCEMENTS IN THE APPLICATION OF FINITE ELEMENT ANALYSIS TO THE OPTIMIZATION OF COMPOSITE YACHT STRUCTURES

TIPS & RECOMMENDATIONS

- FEA is not a replacement for sound engineering best-practices
- FEA should be used as a supplement to fundamental structural design approaches based on first principles and/or scantlings
- FEA can provide a more detailed understanding of both the global and local structural response to applied loads
- FEA can be used for optimization of global deflection and strength as well as for localized studies such as panel deflection & strength, beam/stiffener/girder sizing, assessment of critical fittings & attachments, etc…
- 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

20th CSYS: ADVANCEMENTS IN THE APPLICATION OF FINITE ELEMENT ANALYSIS TO THE OPTIMIZATION OF COMPOSITE YACHT STRUCTURES

TIPS & RECOMMENDATIONS

- FEA should only be performed by someone competent and experienced enough 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 properly, FEA is unmatched as a tool for composites optimization

ARISTON TECHNOLOGIES

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- Advanced Failure Analysis: HELIUS:MCT