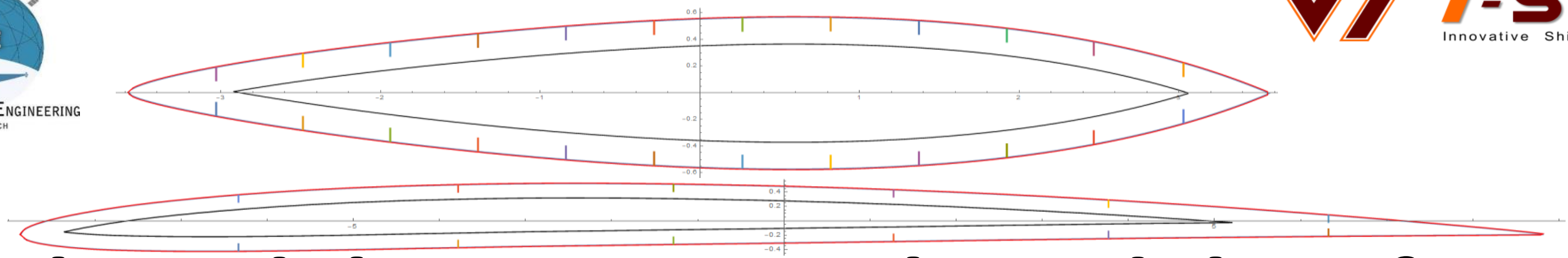
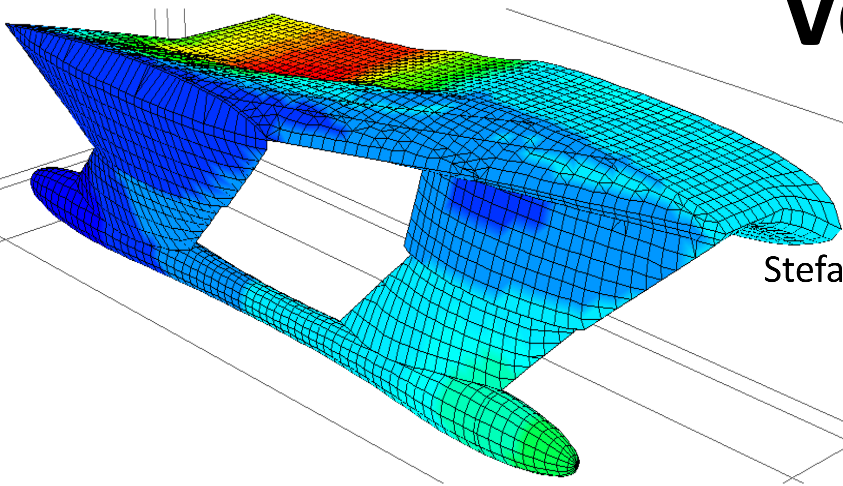
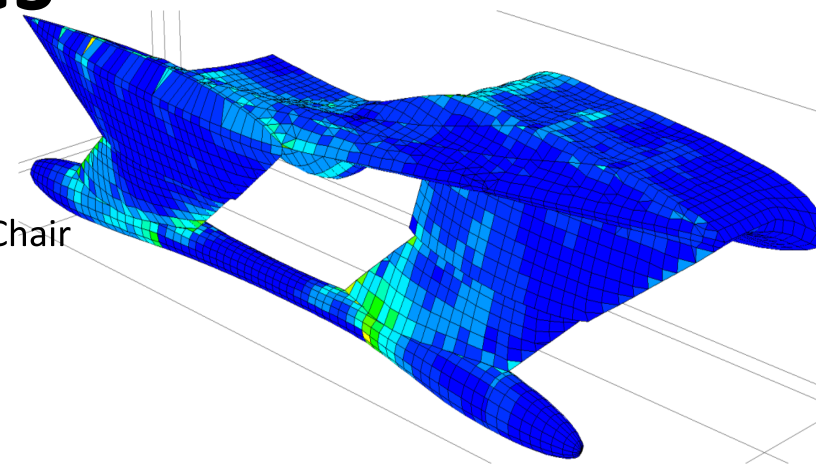


Multi-Fidelity Structural Modeling for Set Based Design (SBD) of Advanced Marine Vehicles



by Oliver Raj
27 April 2018

Stefano Brizzolara, Chair
Alan J. Brown
Seongim Choi



Presentation Outline

- Acknowledgements
- Thesis Focus
- Set Based Design
- HY2-SWATH Requirements
- Machinery, Equipment, Stores Loads
- AMVS Substructures and Plots
- AMVS Design Space Exploration
- AMVS Results
- MAESTRO Model Setup
- MAESTRO Model Results
- Conclusions
- Future Work
- References

AEROSPACE & OCEAN ENGINEERING AT VIRGINIA TECH

VT i-SHIP Innovative Ship Design Lab

Acknowledgements

- Dr. Stefano Brizzolara
- Dr. Alan Brown
- Dr. Seongim Choi
- Dr. Saad Ragab
- Dr. Rakesh Kapania
- Jim Shaughnessy
- Classmates
- Parents
- Sponsors (DARPA)

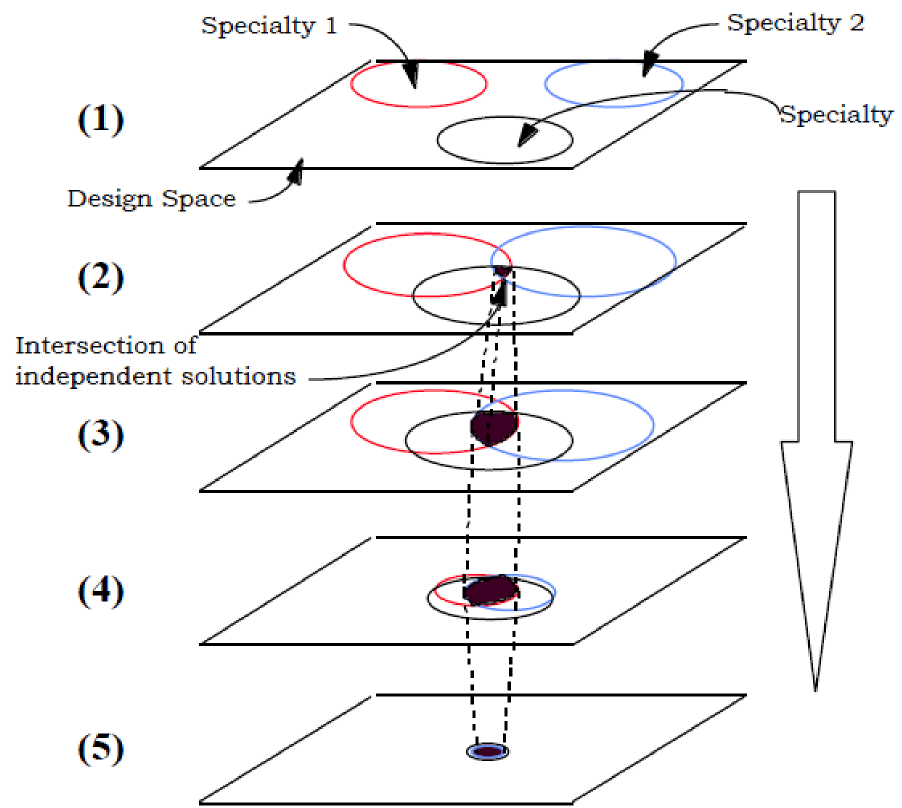
Thesis Fundamental Focus

- Development of a parametrically modifiable Advanced Marine Vehicle Structural (AMVS) module
  - Low-fidelity numerical 2D FEA applied to the concept ultra-high-speed Unmanned Surface Vehicle (USV) Hybrid Hydrofoil SWATH (HY2-SWATH)
  - Conduct preliminary design space exploration
    - Varying material, structural member dimensions, and structural member count
    - Demonstrate capability for module incorporation in global software manager for use in Set Based Design (SBD) method
  - Evaluate the structural feasibility of the HY2-SWATH structural design
- High-fidelity MAESTRO 3D FEA comparison of baseline reference HY2-SWATH to that calculated in AMVS module

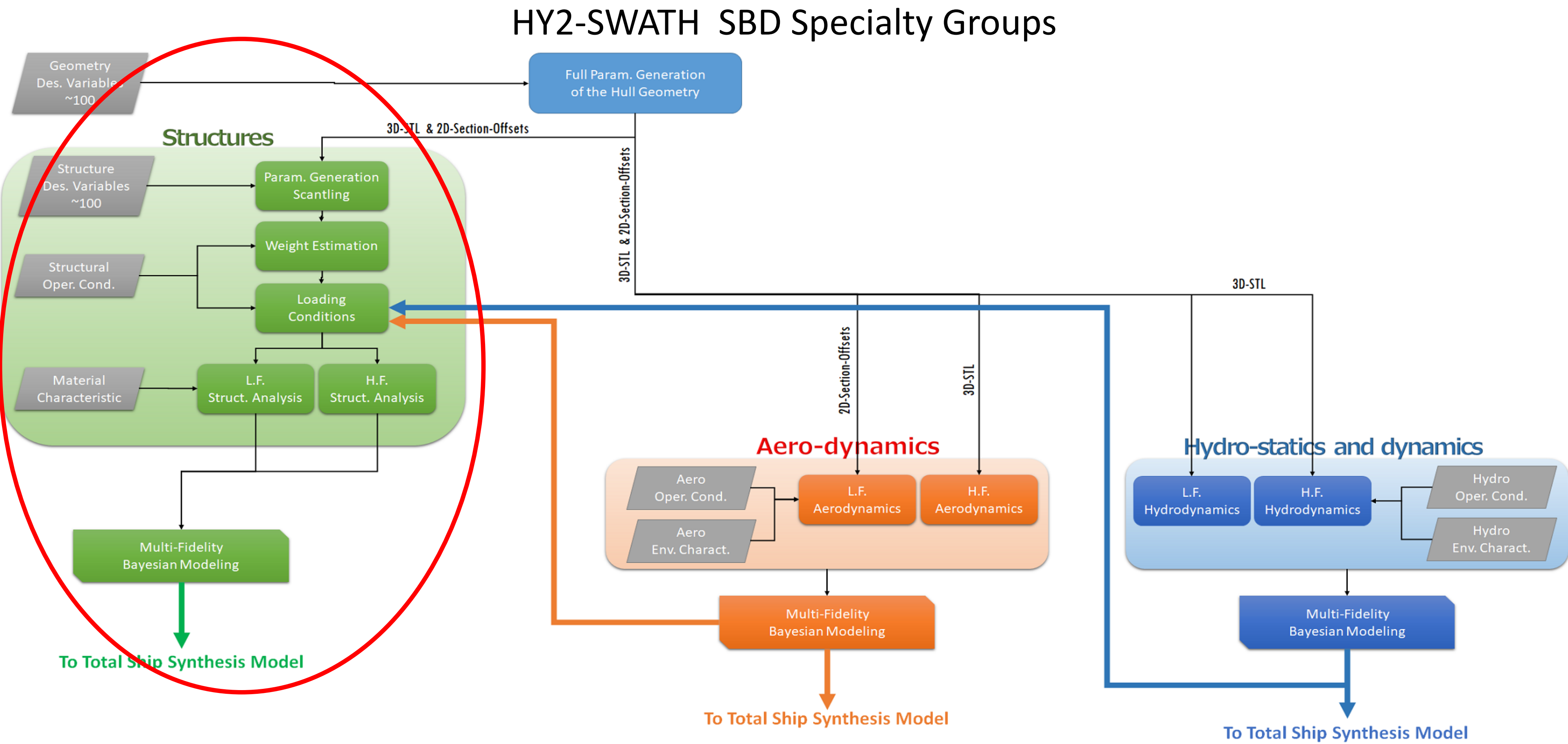
Set Based Design (SBD)

- SBD is summarized in three steps or phases as follows:
  1. Explore the design space
     A. Design space contains all possible solutions to design problem bounded by current and future-potential capabilities
  2. Identify overlapping solution set regions
  3. Refine feasible design regions

Set-Based Design Process [15]



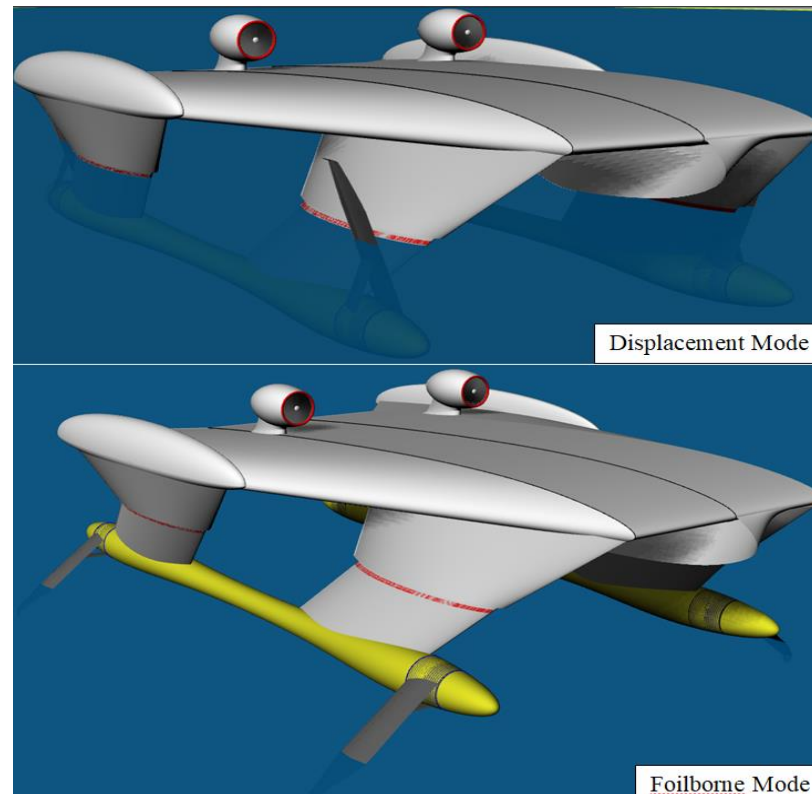
HY2-SWATH SBD Specialty Groups



HY2-SWATH Requirements

- Displacement Mode:
  - 8-25 knots
- Flying Mode:
  - 120+ knots
- Operate in sea state 3
  - wave heights of 1.67 – 4.08 ft. (0.5 – 1.25 m)
- Transport 3-5 MT payload
- Accomplish 5 day mission

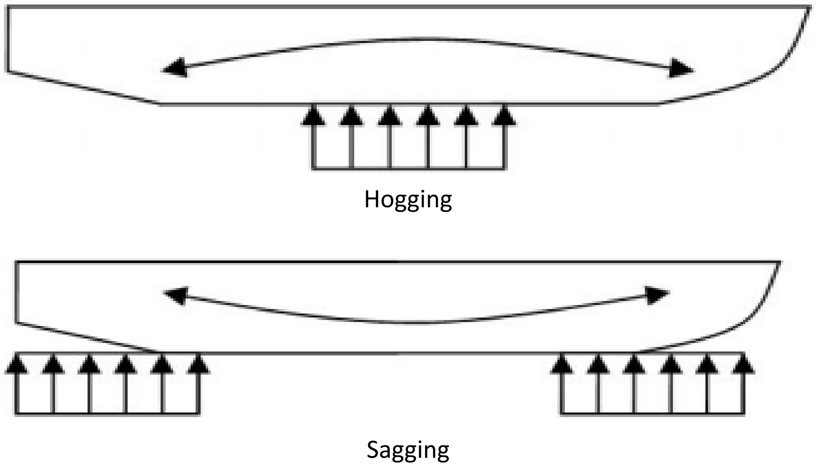
Displacement and Foilborne Operating Conditions



Structural Analysis Models

- Advance Marine Vehicle Structural (AMVS) low-fidelity model
  - FEA Euler-Bernoulli beam theory code written using 2D frame elements
- MAESTRO Marine high-fidelity model
- Analyzes the HY2-SWATH:
  - Buoyancy Mode
  - Flying Mode
  - Hogging Wave Condition (with slamming)
  - Sagging Wave Condition (with slamming)

Hogging and Sagging [14]



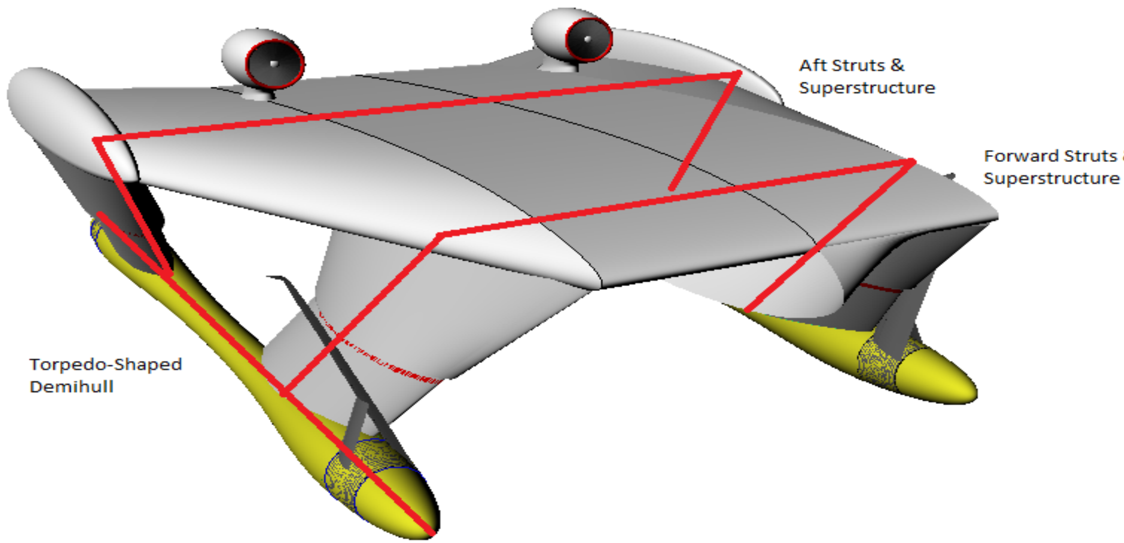
Reference HY2-SWATH Loads

Table contains the list of machinery loads, equipment loads, stores loads, and structural loads. "Loads" means forces and moments

Loads Applied			
Load	Quantity	Mass (Each, MT)	Reference Vessel Weight (Each, N)
Electric Motor	2	0.255 + 5% allowance	2,316.67
Payload	1	5	49,030
Wing-Superstructure	1	Calc. + 5% allowance	76,262.8 (AMVS); 85,866.5 (MAESTRO)
Cables and Pipes	1	0.65+ 5% allowance	6,692.6
Struts	1	Calc. + 5% allowance	43,672.6 (AMVS); 62,406.6 (MAESTRO)
Hull	2	Calc. + 5% allowance	15,799.75 (AMVS); 18,752.1 (MAESTRO)
Fore foil	2	1.535 + 5% allowance	15,804.8
Aft foil	2	1.57 + 5% allowance	16,165.2
Rotating Mech. Fore	2	0.125 +5% allowance	1,287.04
Rotating Mech. Aft	2	0.125 + 5% allowance	1,287.04
Elec. Nav. Equip.	1	0.5 + 5% allowance	5,148.15
Liquids	1	0.3 + 5% allowance	2,941.8
Fuel	1	Calculated	157,502.0
Gas Turbines	2	1.5 + 5% allowance	15,444.5
Genset	2	0.75 + 5% allowance	7,722.23

AMVS Substructure Frames

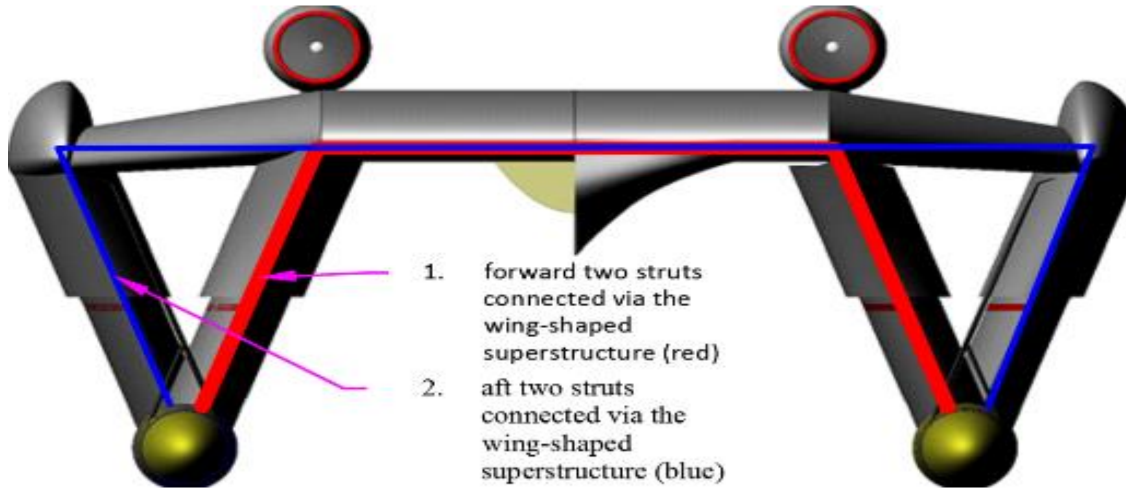
- Divided HY2-SWATH into three interdependent substructures.
- Together provide an accurate representation of whole vessel

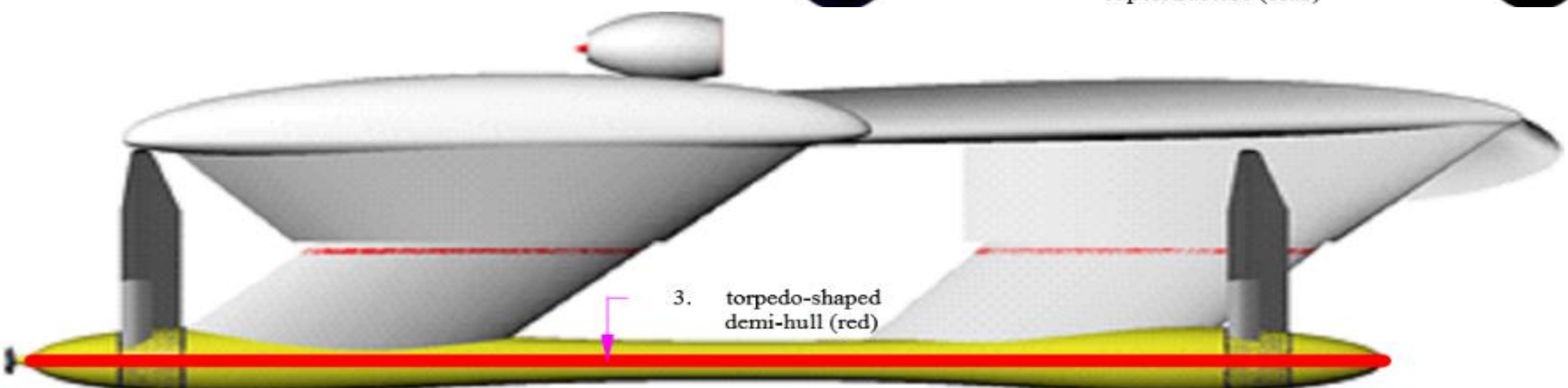


AMVS Substructure Frames (1)

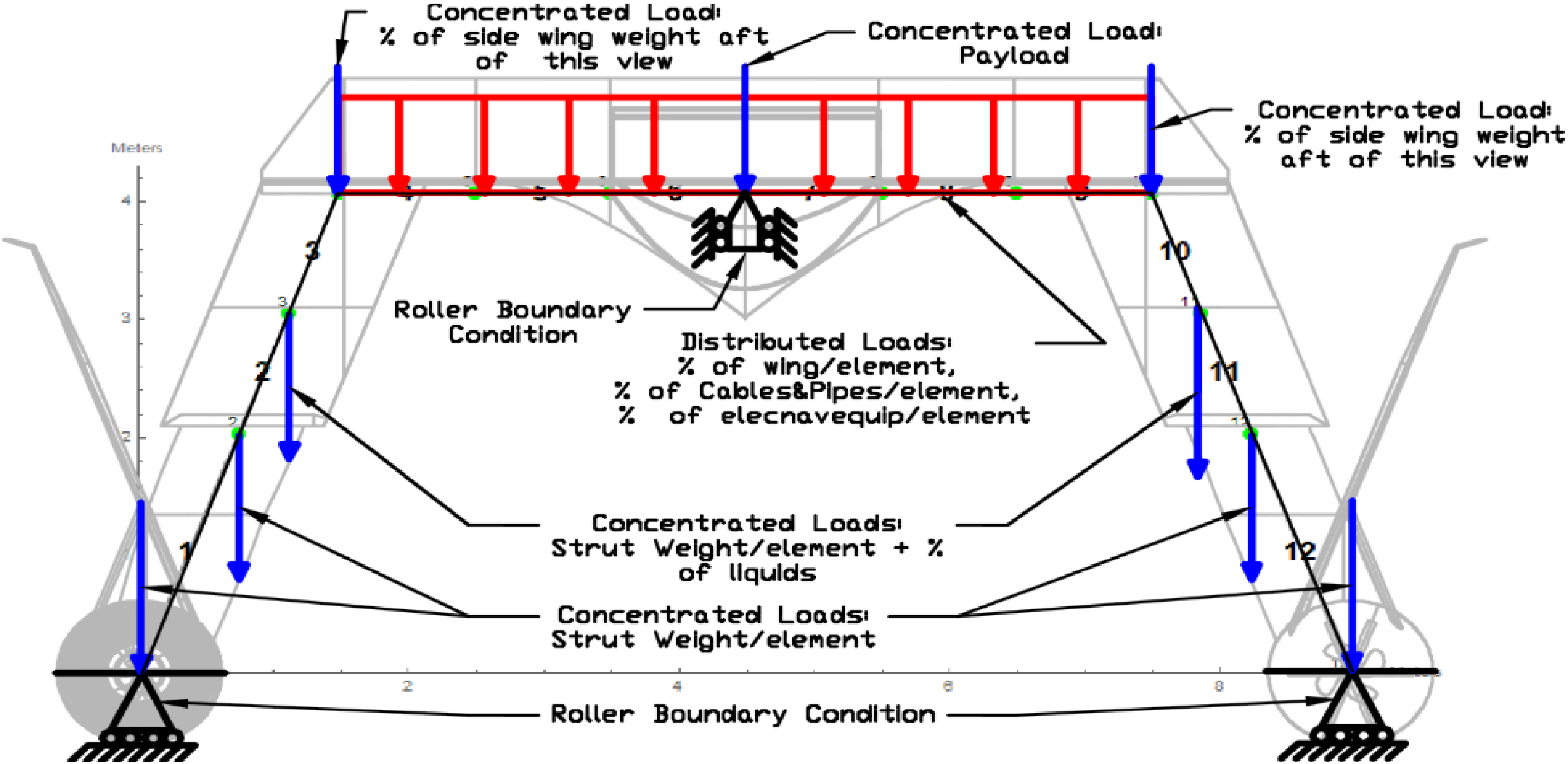
Divided into 3 substructure frames:

1. Forward two struts connected via the wing-shaped superstructure
2. Aft two struts connected via the wing-shaped superstructure
3. Torpedo-shaped demi-hull

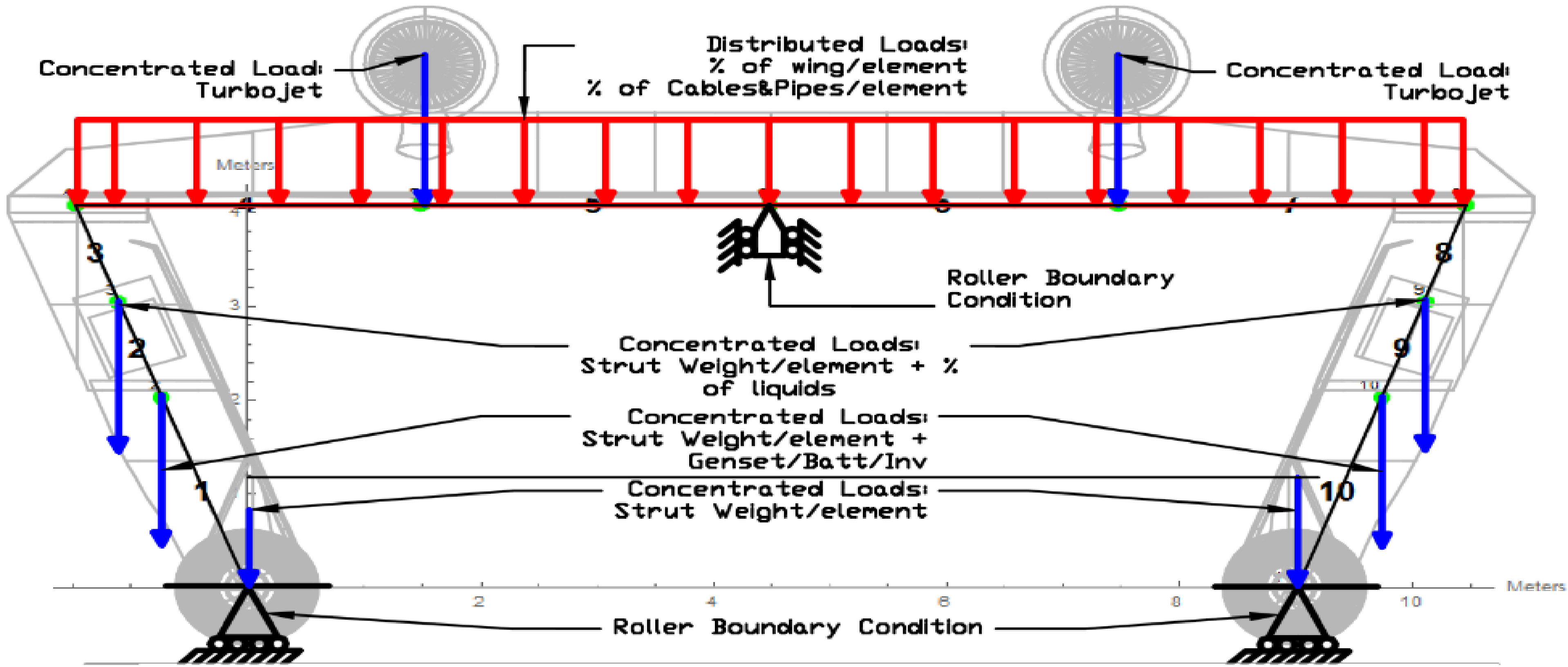




Substructure 1: Loads

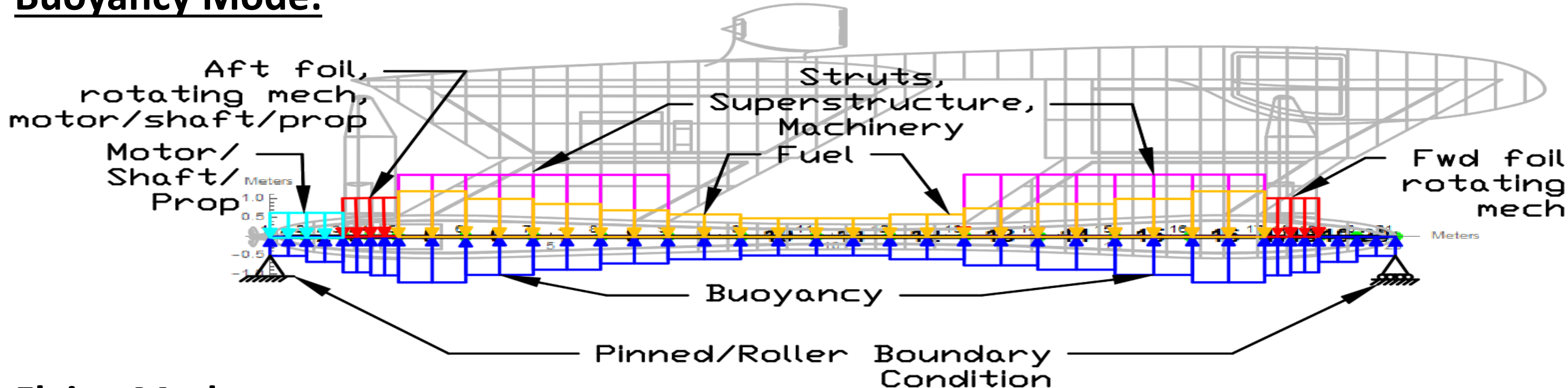


Substructure 2: Loads

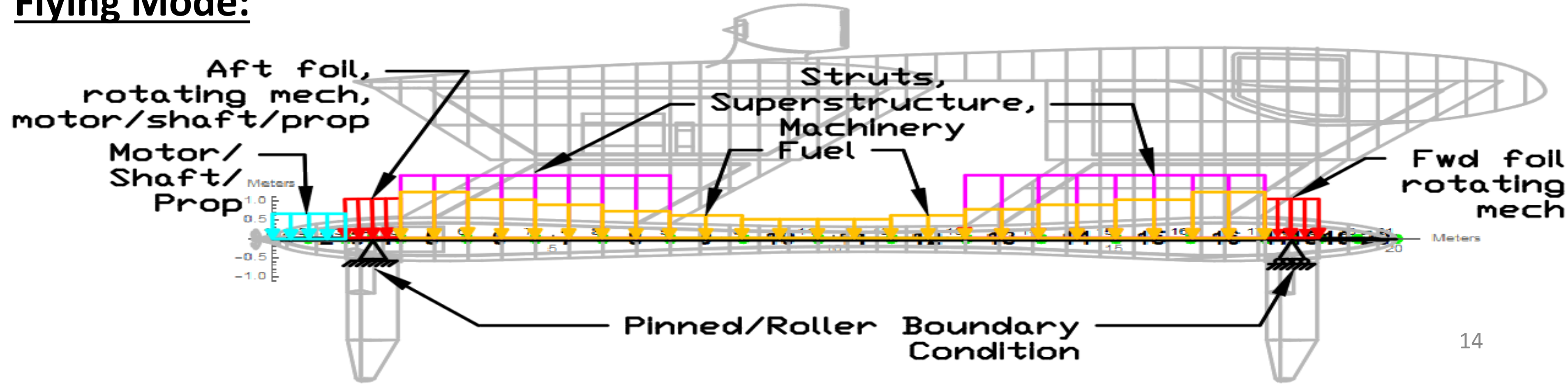


Substructure 3: Loads

Buoyancy Mode:

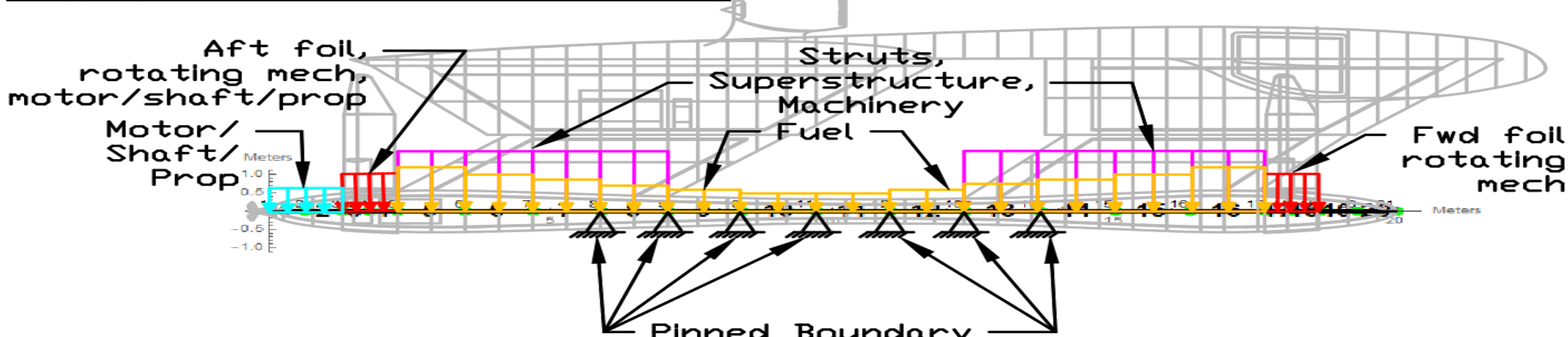


Flying Mode:

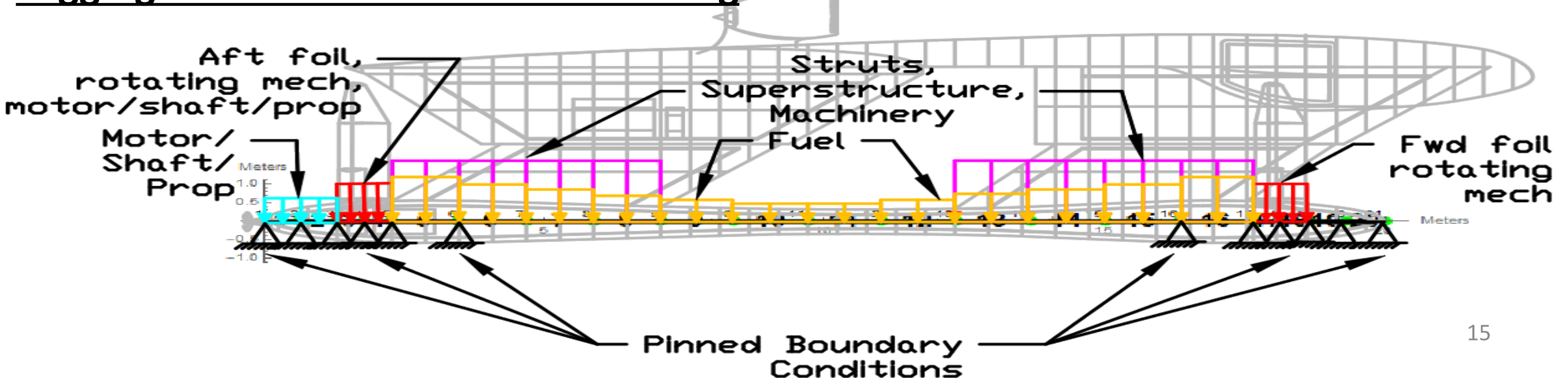


Substructure 3: Loads (1)

Hogging Wave Condition with Slamming

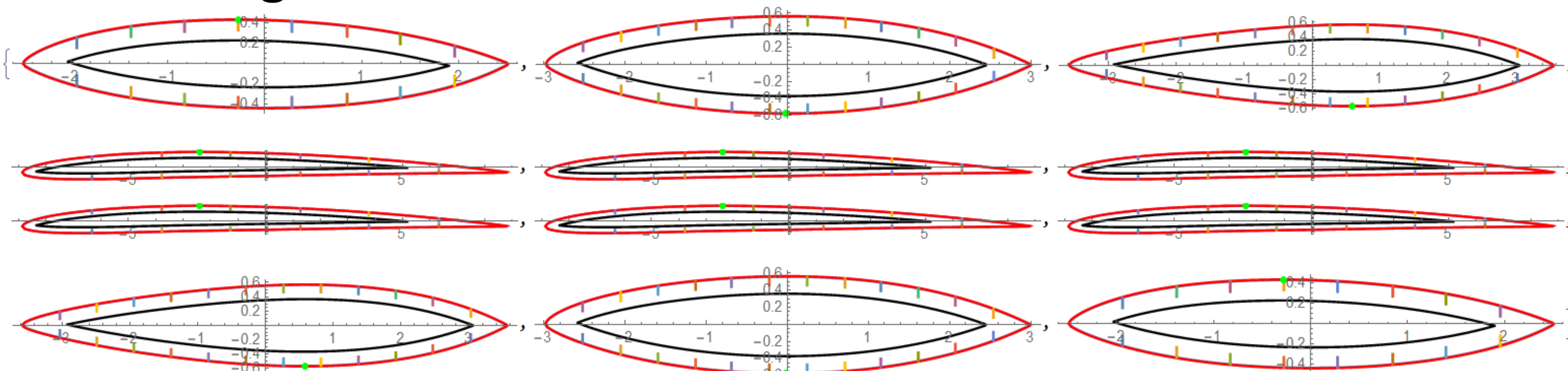


Sagging Wave Condition with Slamming



AMVS Module Element Cross-Sections

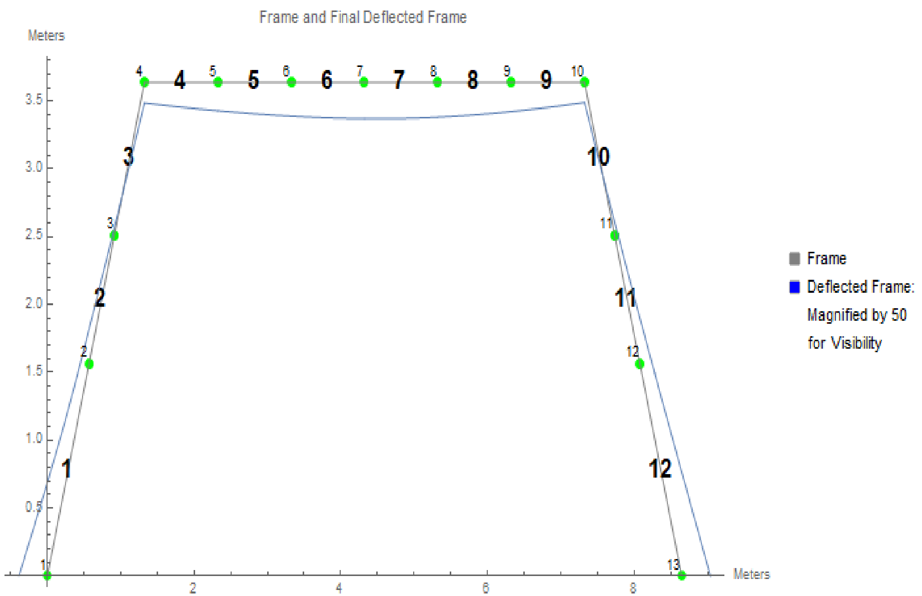
- Element cross-section parametric inputs:
  - Shell plating thickness
  - Number of longitudinal stiffeners and their dimensions
  - Ring stiffeners and their dimensions

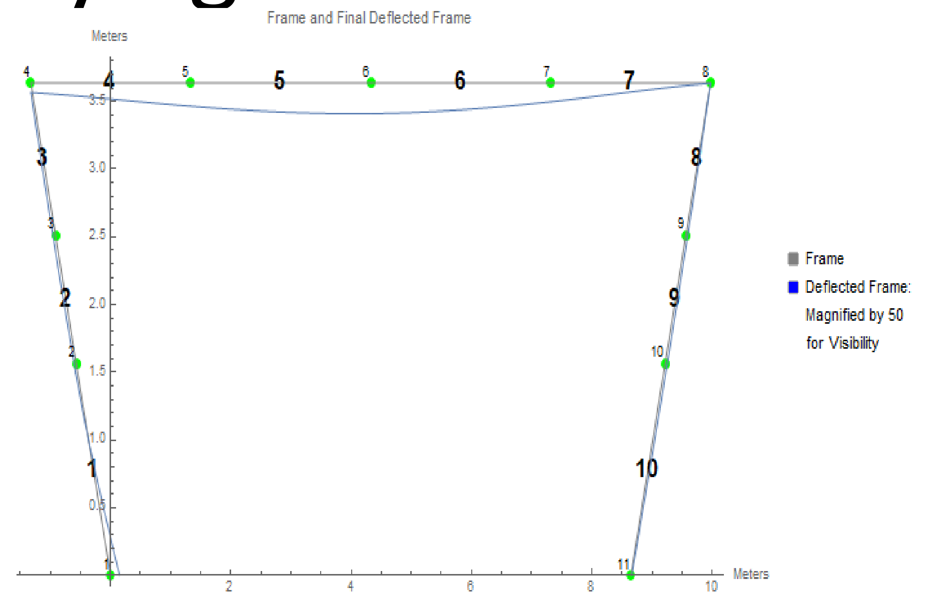


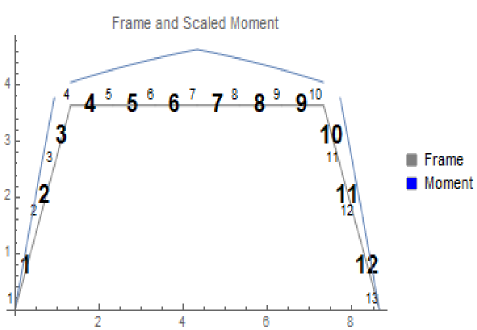
Forward Struts Frame Element Cross-Sections

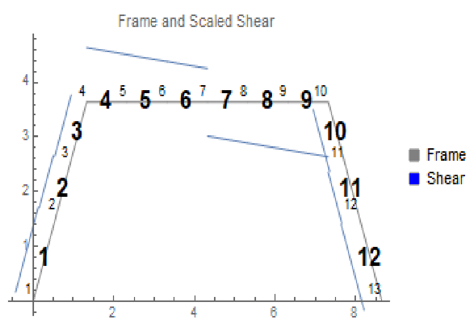
AMVS Module

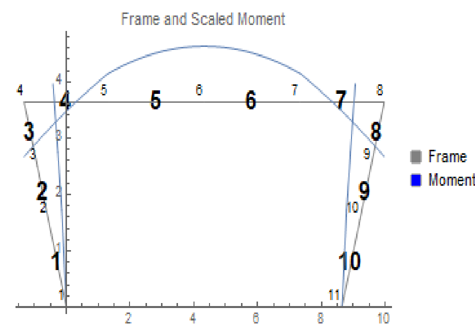
Reference Vessel Flying Mode Plots

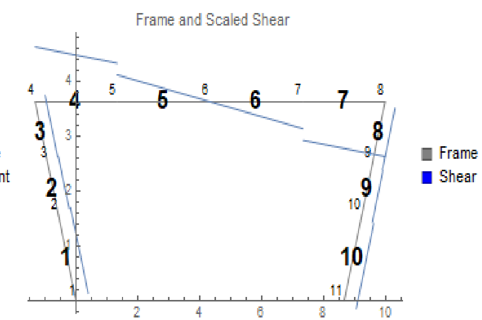






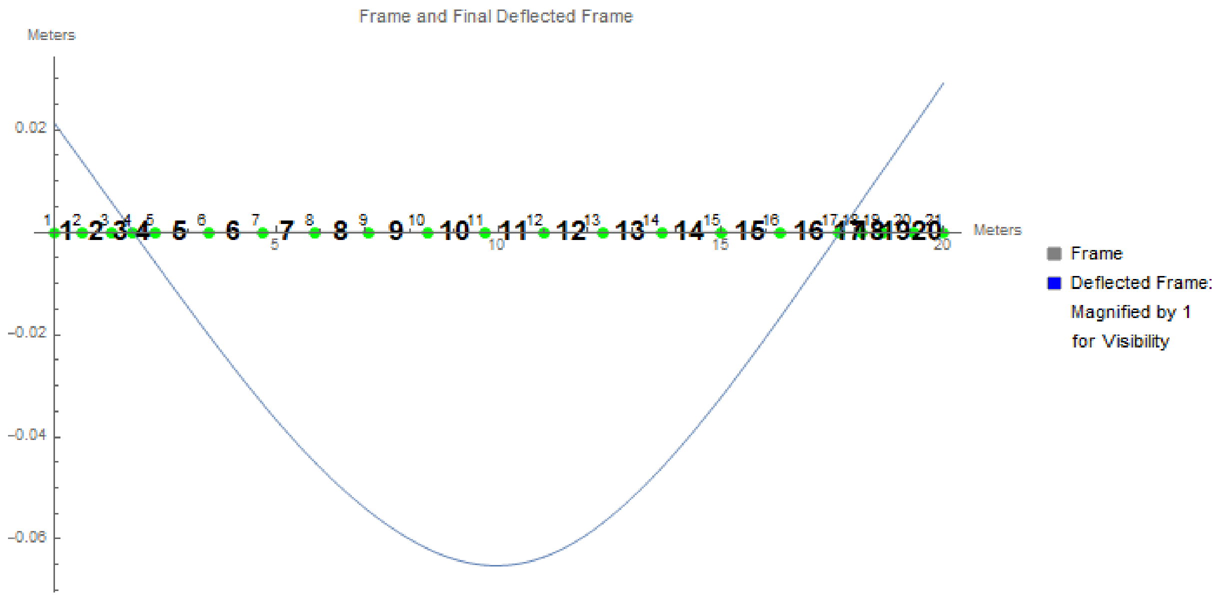


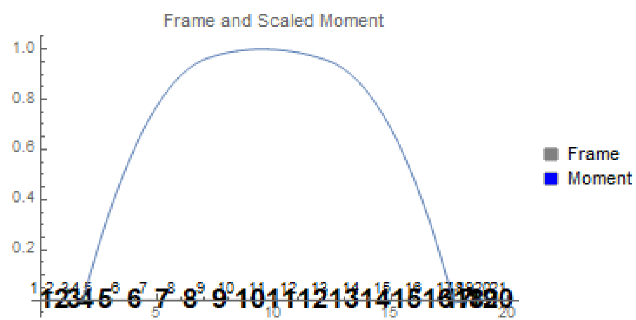


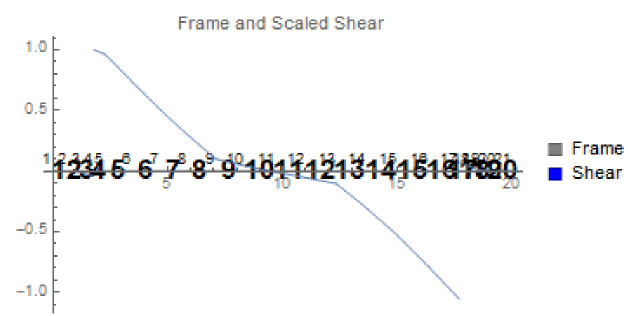


AMVS Module

Reference Vessel Flying Mode Plots (1)







Design Space Exploration

- Shell thickness varied from 4 – 7 mm
  - Flying mode hull elements 9-13 required an additional 6 mm to input shell thickness
  - Flying mode hull elements 8 & 14 required an additional 3 mm
- Material properties

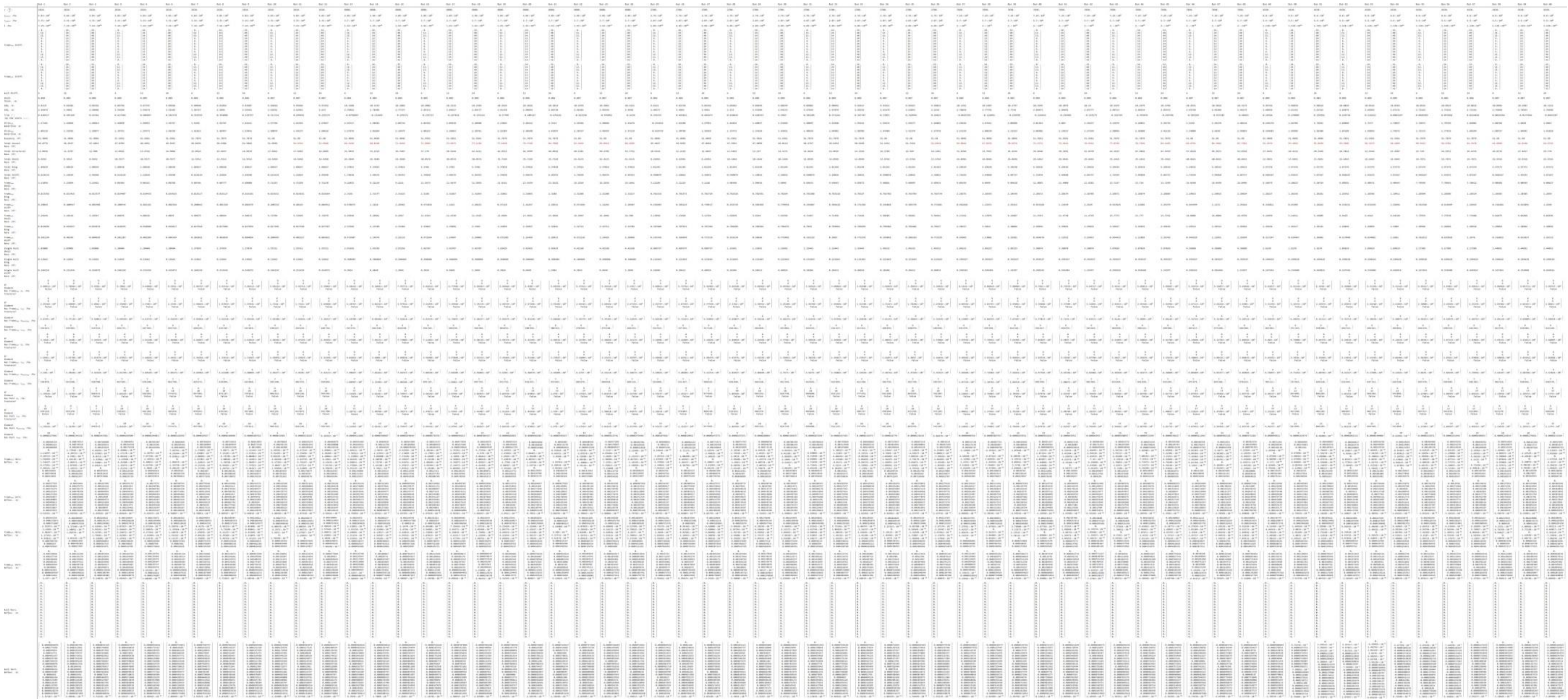
Material Property Parametric Inputs				
	ρ (kg*m^{-3})	σ_{yield} (MPa)	τ_{yield} (MPa)	E (GPA)
Aluminum 7075 - T6; 7075 - T651	2810	503	331	71.9
316L Steel	8000	205	370	193
Aluminum 6061 - T6; 6061 - T651	2700	276	207	68.9
AISI Type S20910 Stainless Steel, high strength	7890	725	570	200
Titanium Ti - 6 Al - 4 V (Grade 5), Annealed	4430	880	550	113.8

- Longitudinal stiffener count

Stiffener Count Parametric Input			
	Forward Strut Frame Stiffeners	Aft Strut Frame Stiffeners	Hull Frame Stiffeners
Run 1	(8, 12, 12, 6, 6, 6, 6, 6, 6, 12, 12, 8)	(8, 12, 12, 6, 6, 6, 6, 12, 12, 8)	6/element (20 elements)
Run 2	(16, 24, 24, 12, 12, 12, 12, 12, 12, 24, 24, 16)	(16, 24, 24, 12, 12, 12, 12, 24, 24, 16)	12/element (20 elements)
Run 3	(32, 48, 48, 24, 24, 24, 24, 24, 24, 48, 48, 32)	(32, 48, 48, 24, 24, 24, 24, 48, 48, 32)	24/element (20 elements)

Design Space Exploration (1)

- Data Results (Example)



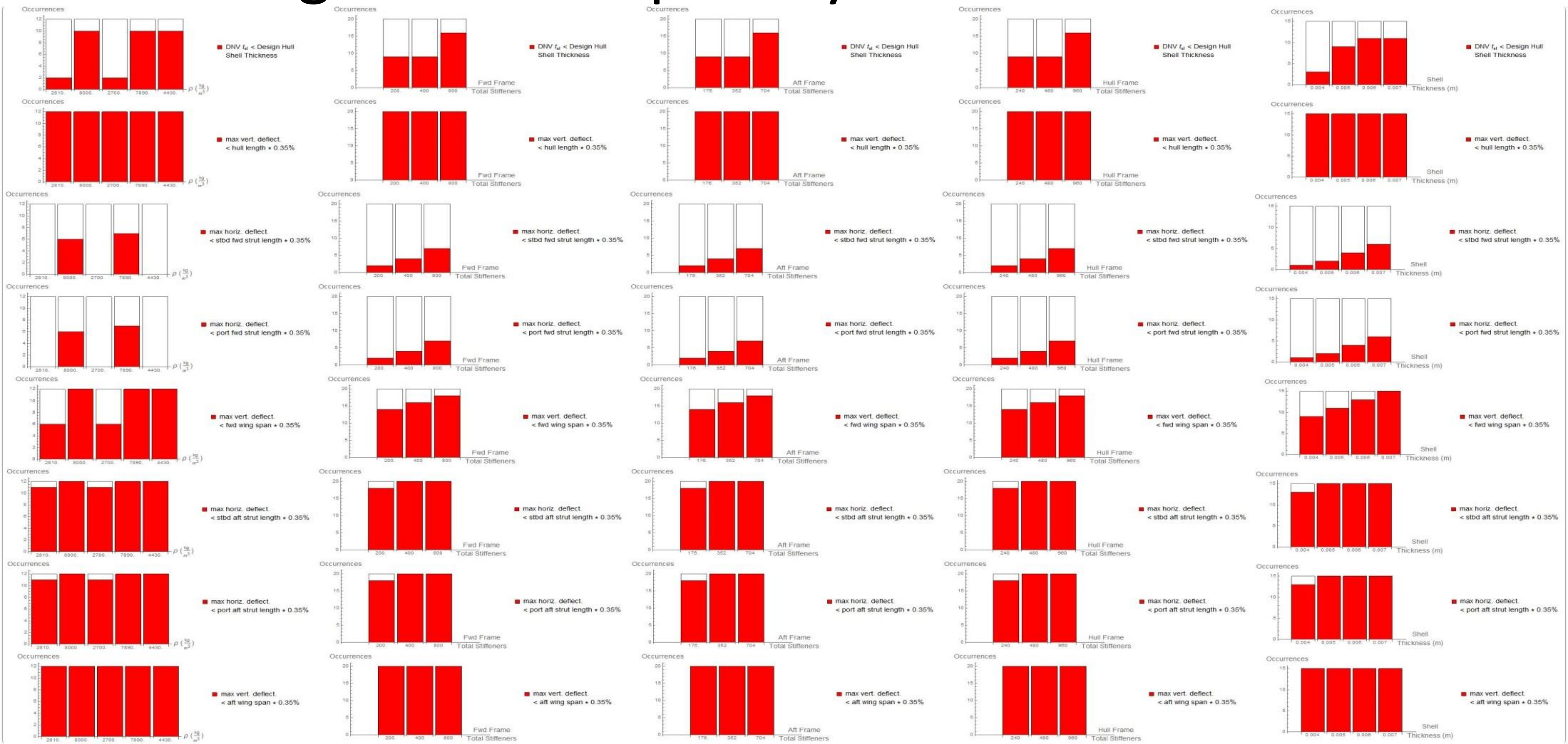
Design Space Exploration (2)

- Constraints (Example)

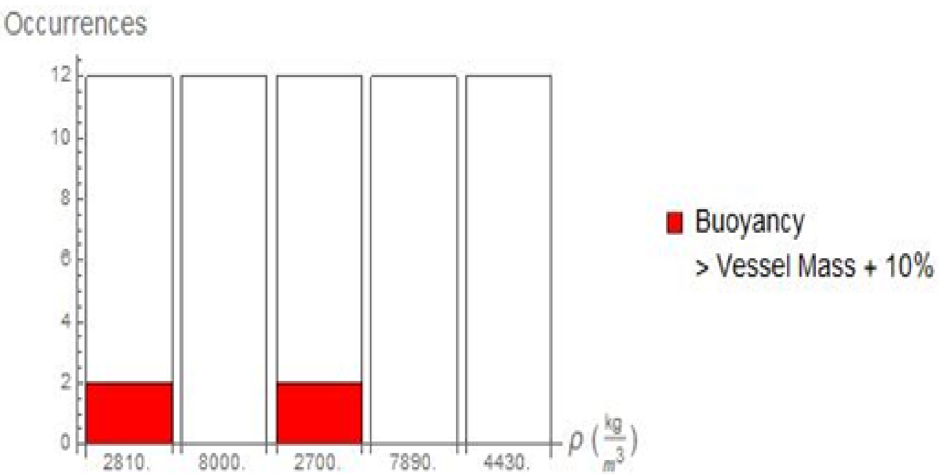
	Buoyancy Mode Operating Condition Constraints	
1	Buoyancy (initial waterline) > 1.1*weight	Initial waterline provides excess buoyancy. Constraint ensures vessel does not sink.
2	Abs(Trim angle) < 0.5°	Reduced drag, increased fuel efficiency and range
	Hull Frame	
3	Max vertical deflection of hull < total hull length *x%	Ensure hull vertical deflection does not cause failure
	Forward Struts Frame	
4	Max horizontal deflection < forward starboard strut length *x%	Ensure horizontal deflection of starboard strut does not cause failure
5	Max horizontal deflection <forward port strut length *x%	Ensure horizontal deflection of port strut does not cause failure
6	Max vertical deflection < forward wing span *x%	Ensure forward portion of the wing superstructure vertical deflection does not cause failure
	Aft Struts Frame	
7	Max horizontal deflection < aft starboard strut length *x%	Ensure horizontal deflection of starboard strut does not cause failure
8	Max horizontal deflection < aft port strut length *x%	Ensure horizontal deflection of port strut does not cause failure
9	Max vertical deflection < aft wing span *x%	Ensure aft portion of the wing superstructure vertical deflection does not cause failure
	Where x = 0.25% and 0.20%	

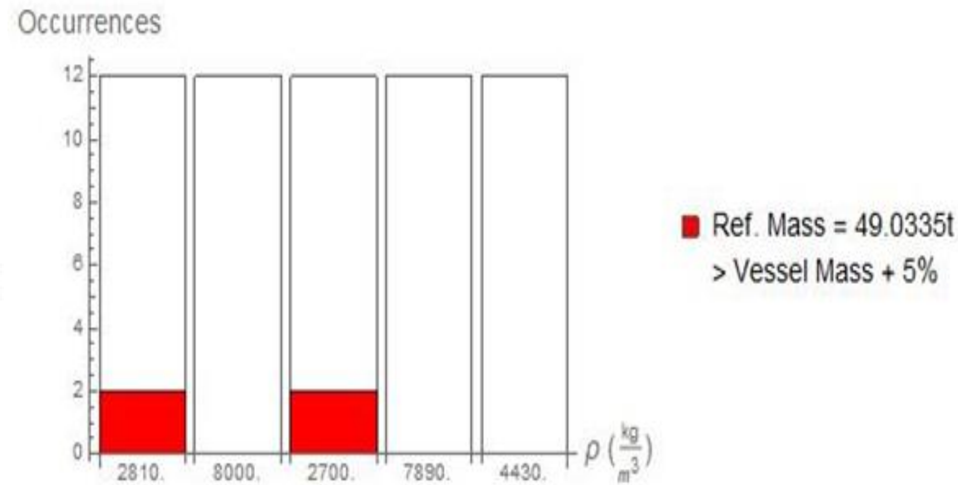
Design Space Exploration (2)

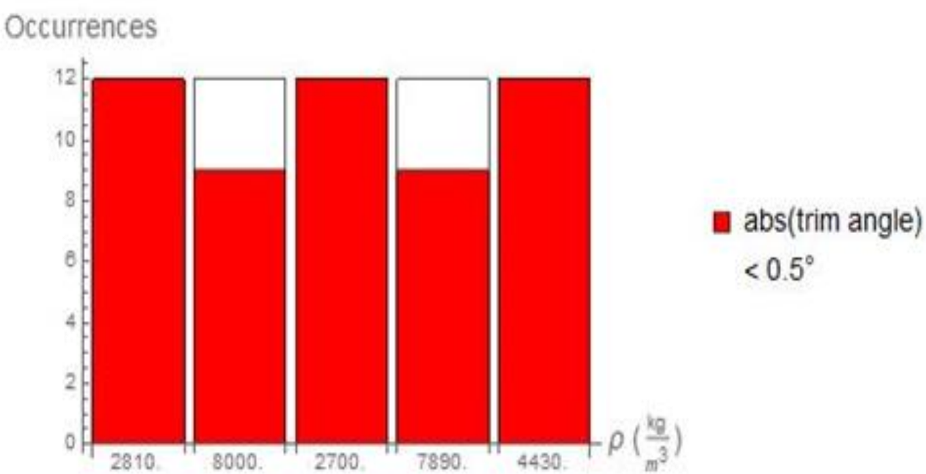
- Histograms to help analyze data

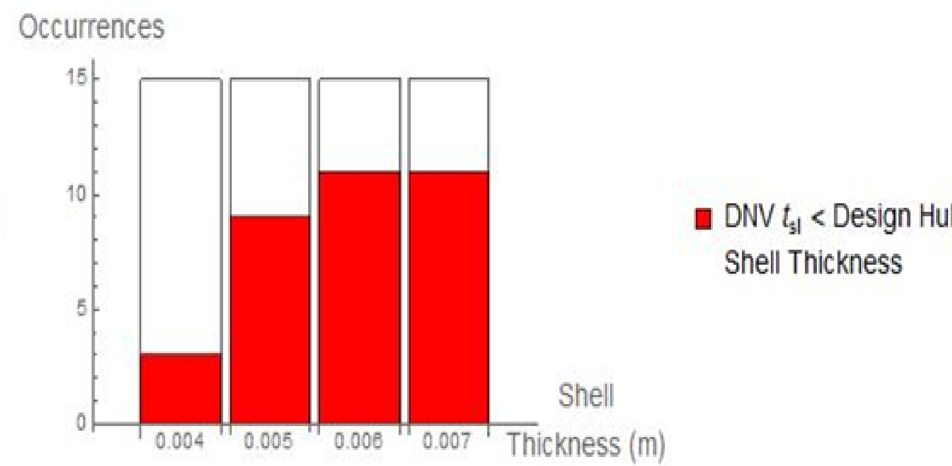


Design Space Exploration (3)



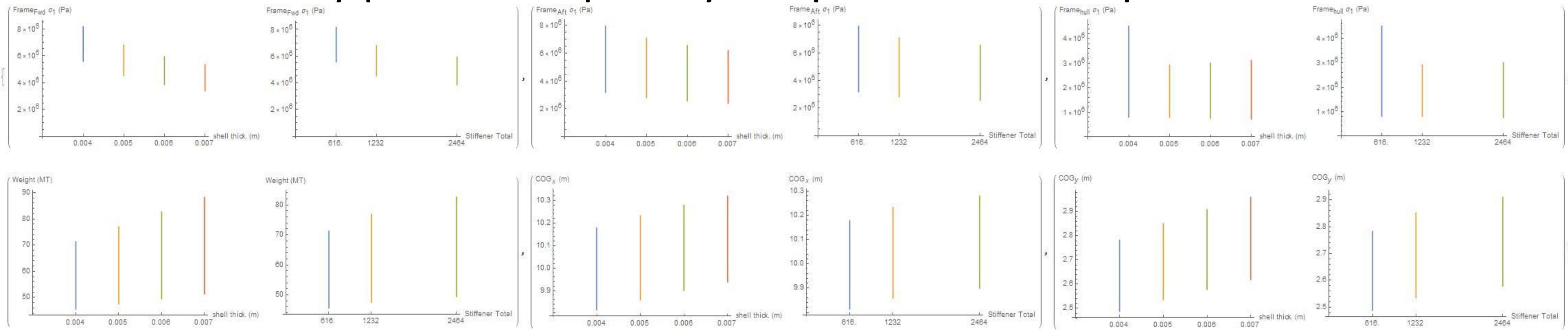


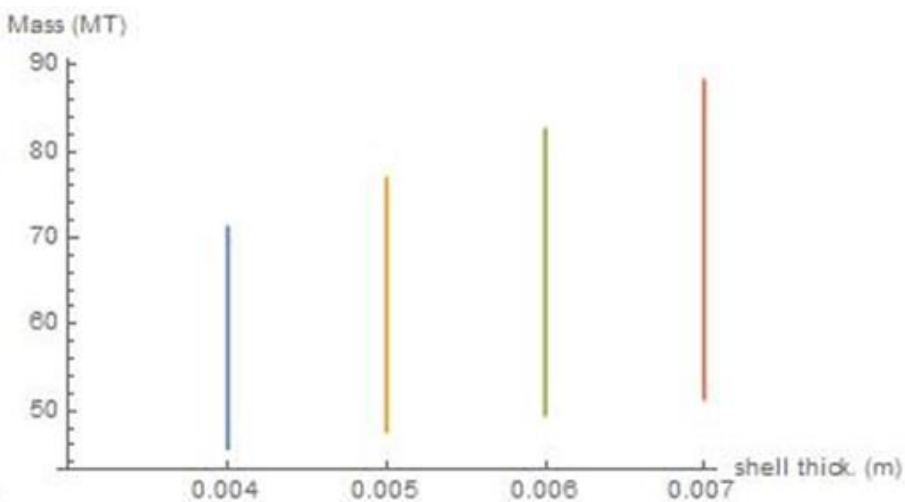


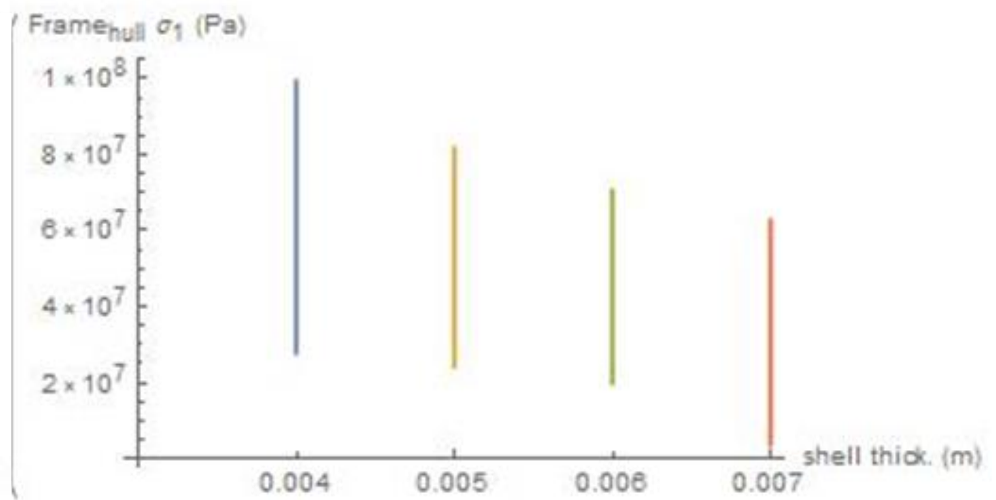


Design Space Exploration (4)

- Sensitivity plots to help analyze input variables impact on stresses







AMVS Reference HY2-SWATH Displacement/Stress Results

AMVS Max Displacement Results Summary						
Load Case	Forward Frame Location	Forward Frame Displacement (mm)	Aft Frame Location	Aft Frame Displacement (mm)	Hull Frame Location	Hull Frame Displacement (mm)
Buoyancy Mode	Node 7	-5.33	Node 6	-4.50	Node 10	0.752
Flying Mode	Node 7	-5.33	Node 6	-4.50	Node 11	-65.1
Hogging	Node 7	-21.0	Node 6	-17.78	Node 21	-43.0
Sagging	Node 7	-21.0	Node 6	-17.78	Node 11	-14.9

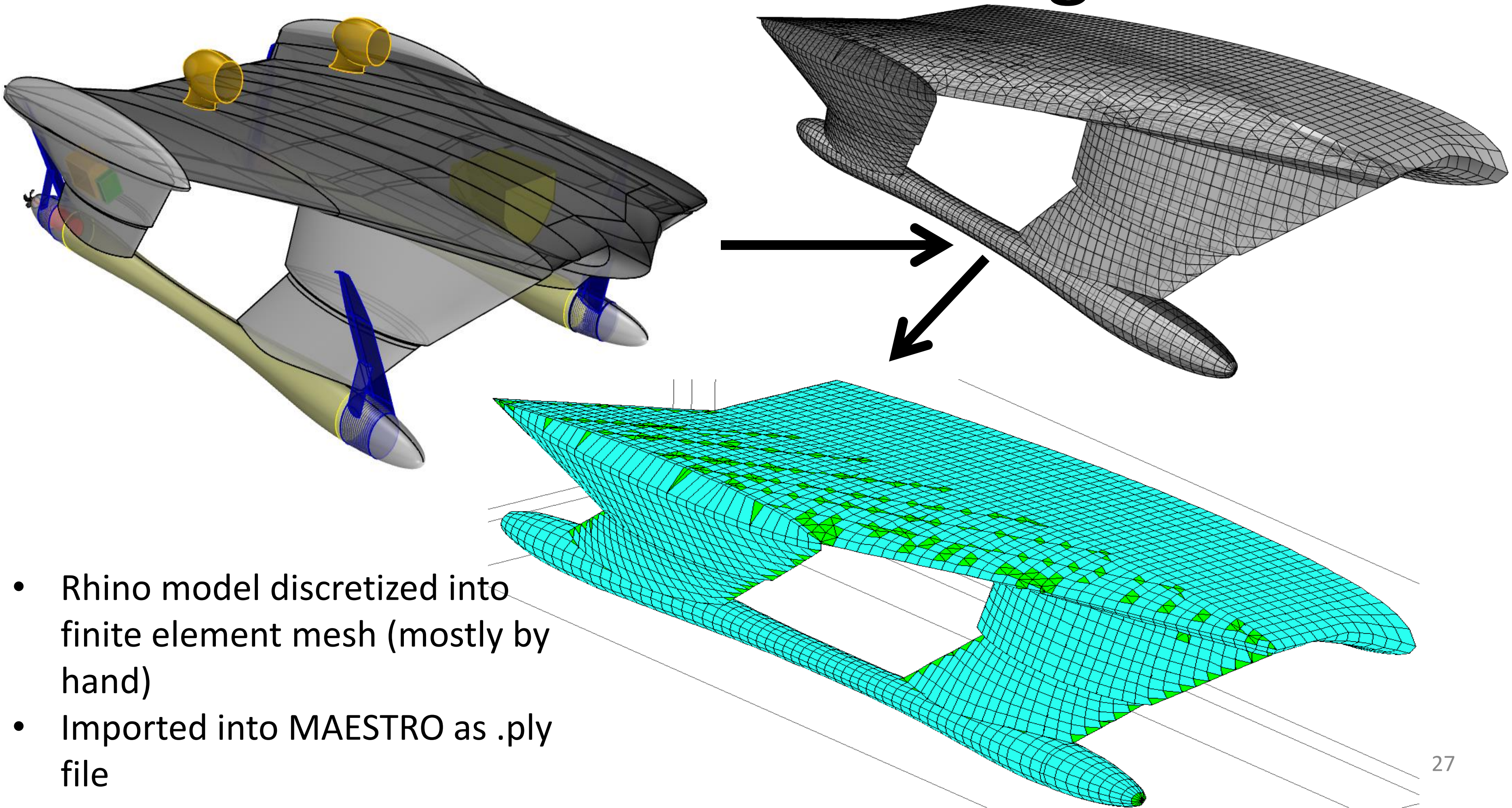
AMVS Max Von Mises Stress Results Summary						
Load Case	Forward Frame Location	Forward Frame Stress, σ_{VM} (Pa)	Aft Frame Location	Aft Frame Stress, σ_{VM} (Pa)	Hull Frame Location	Hull Frame Stress, σ_{VM} (Pa)
Buoyancy Mode	Element 6	$3.931*10^6$	Element 5	$2.653*10^6$	Element 10	$1.037*10^6$
Flying Mode	Element 6	$3.931*10^6$	Element 5	$2.653*10^6$	Element 11	$7.614*10^7$
Hogging	Element 6	$1.553*10^7$	Element 5	$1.047*10^7$	Element 7	$6.933*10^7$
Sagging	Element 6	$1.553*10^7$	Element 5	$1.047*10^7$	Element 6	$4.02*10^7$

AMVS Von Mises Stress Statistics				
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. (μ ± σ)
Buoyancy Mode	$3.903*10^6$	$1.332*10^6$	$1.149*10^6$	2.27
Flying Mode	$7.615*10^7$	$1.622*10^7$	$2.445*10^7$	2.45
Hogging	$6.933*10^7$	$1.236*10^7$	$1.562*10^7$	3.65
Sagging	$4.020*10^7$	$1.371*10^7$	$1.199*10^7$	2.21

MAESTRO High-Fidelity Model

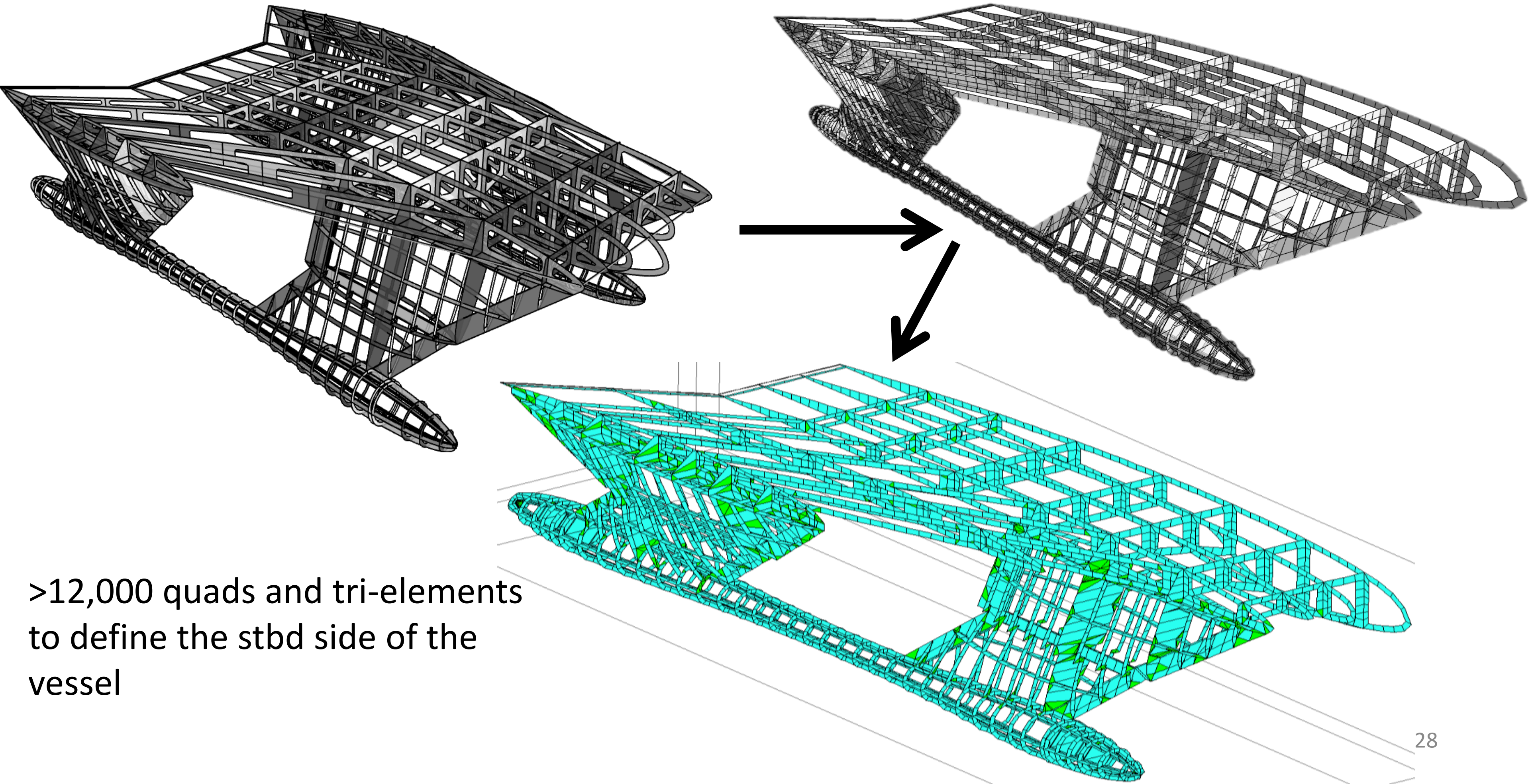
- Rhino model was converted to a mesh (quad and tri-elements) and imported into MAESTRO
- Material properties and structural element thicknesses applied
- Same machinery/equipment/stores loads applied to the AMVS module were applied to the HF model.
- Structural loads calculated by MAESTRO

MAESTRO Shell Plating Mesh



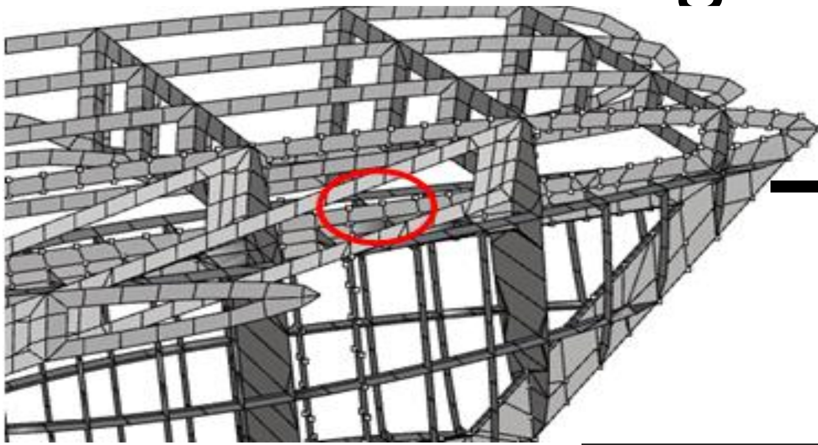
- Rhino model discretized into finite element mesh (mostly by hand)
- Imported into MAESTRO as .ply file

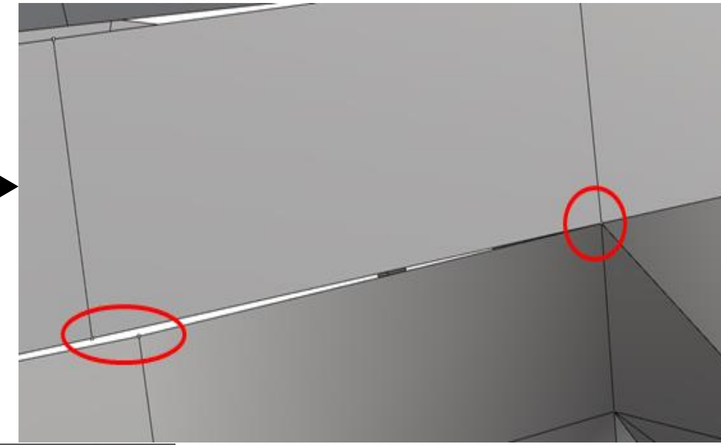
MAESTRO Internal Structure Mesh

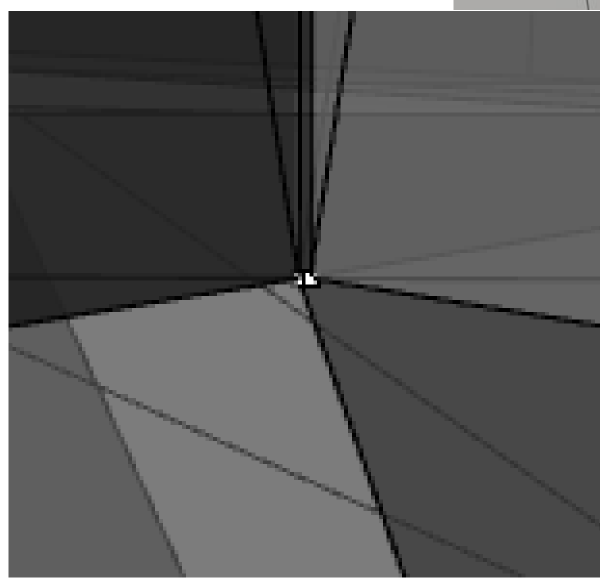


>12,000 quads and tri-elements to define the stbd side of the vessel

Node Free Edges and Discontinuities







MAESTRO Material Properties and Thickness

Aluminum 7075 Material Properties

Material

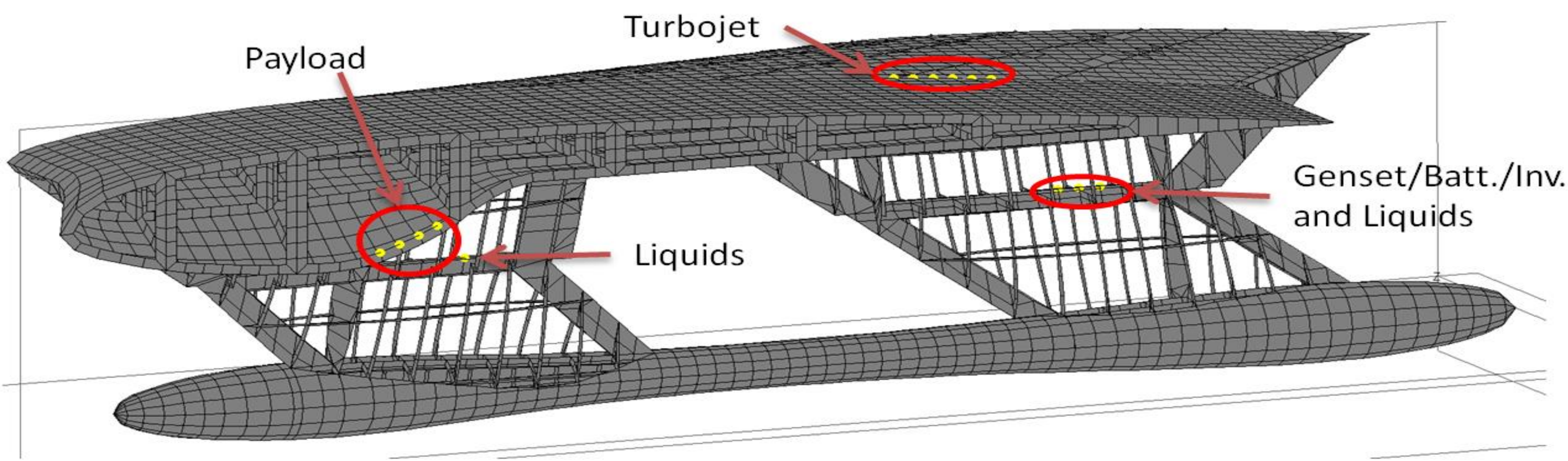
Name: Al 7075-T6 | ID: 2 | Type: Isotropic

Name	Value
Young's Modulus Ex(N/m^2)	7.19e+10
Poisson Ratio	0.33
Density(kg/m^3)	2950.5
Yield Stress(N/m^2)	5.03e+08
Ultimate Tensile Strength(N/m^2)	5.72e+08

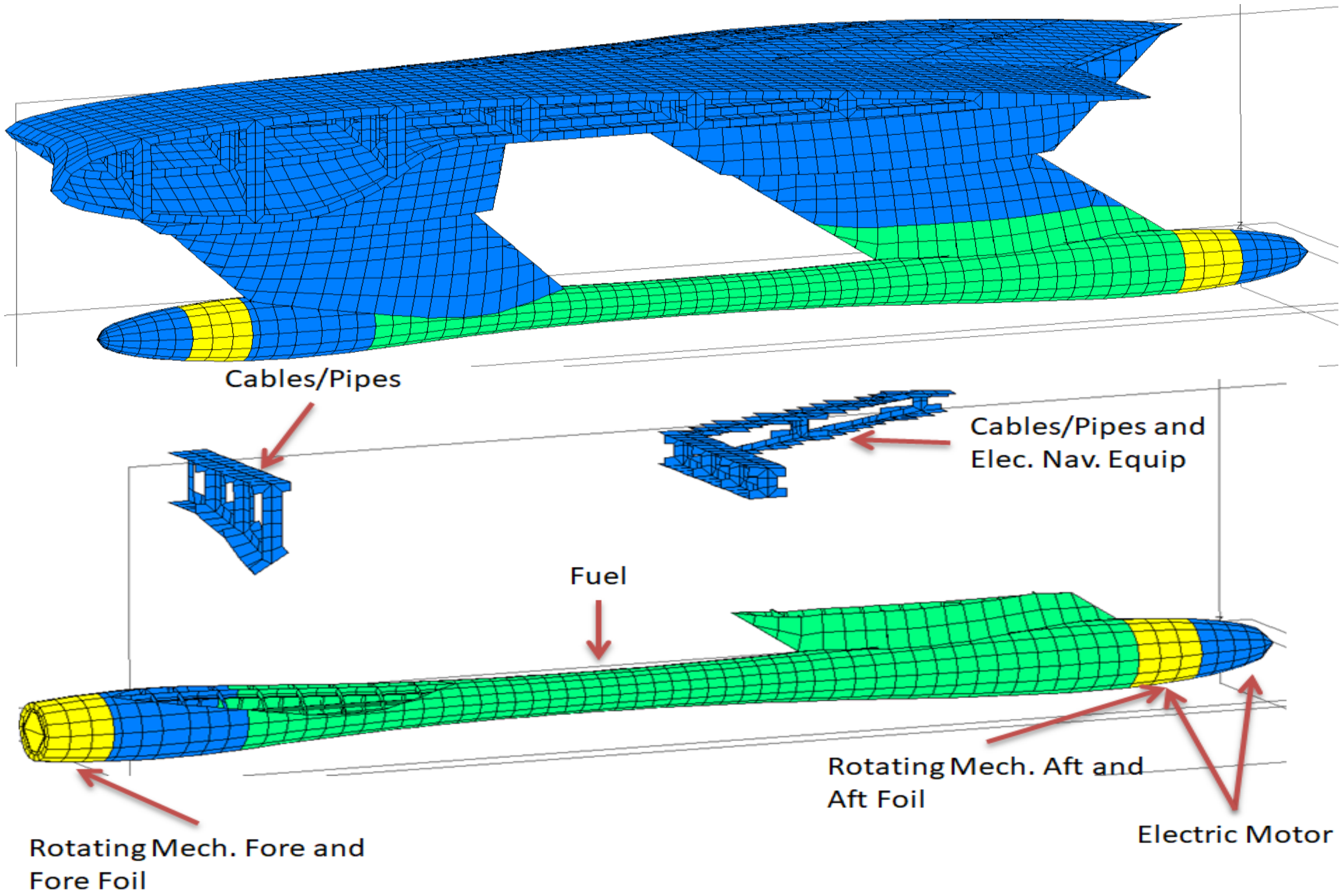
ID	Name	Material	#Layers	Thickness(mm)
1	Null Plate Prop	ST24	1	0
2	6mm Al 7075 (default)	Al 7075-T6	1	6
5	6.35mm Al 7075 (girders/rings)	Al 7075-T6	1	6.35
3	9mm Al 7075 (hull shell)	Al 7075-T6	1	9
4	12mm Al 7075 (hull shell)	Al 7075-T6	1	12

Concentrated Loads

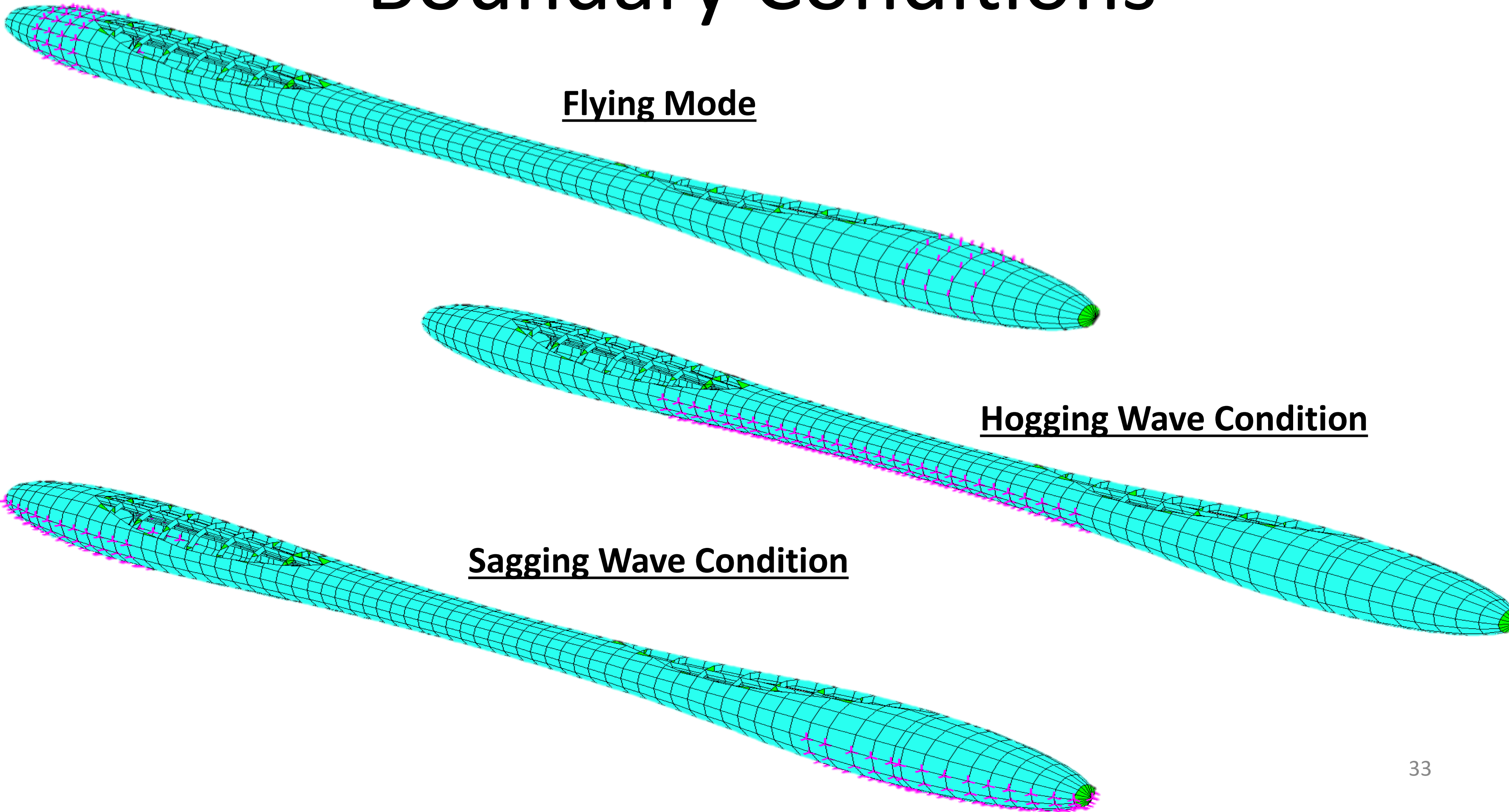
- The reference vessel loads applied in the AMVS module were applied to the MAESTRO model. (Best for comparison purposes)
  - Concentrated loads remained concentrated and distributed loads remained distributed (which also made logical sense going 2D → 3D)



Distributed Loads



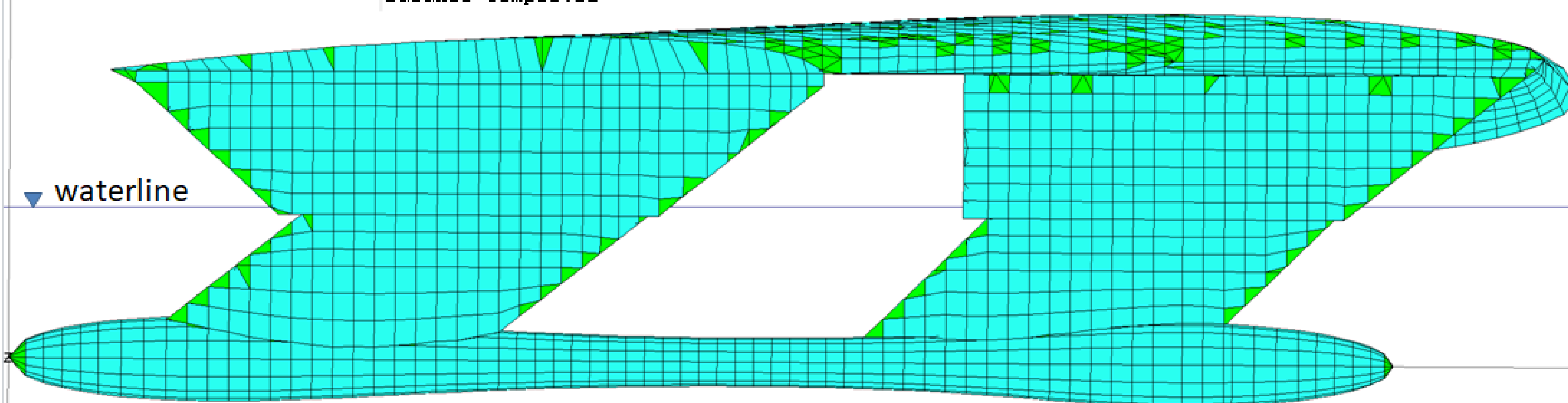
Boundary Conditions



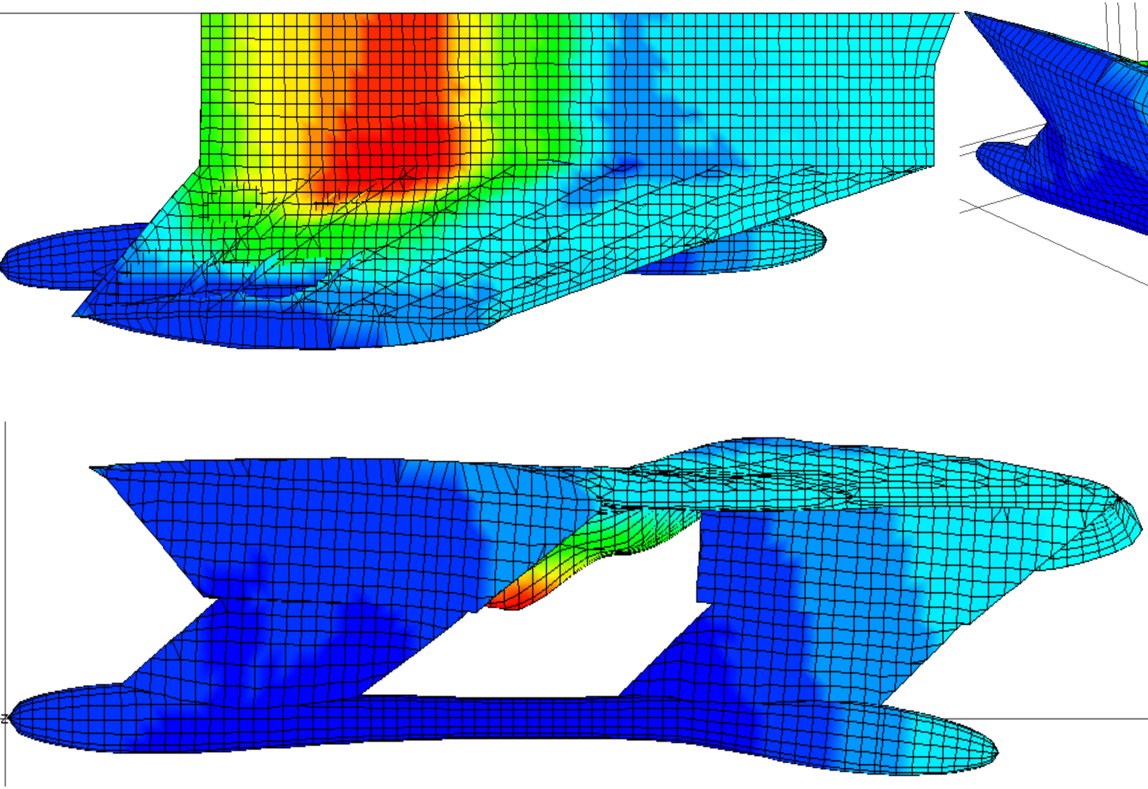
Balance the Vessel (Buoyancy Mode)

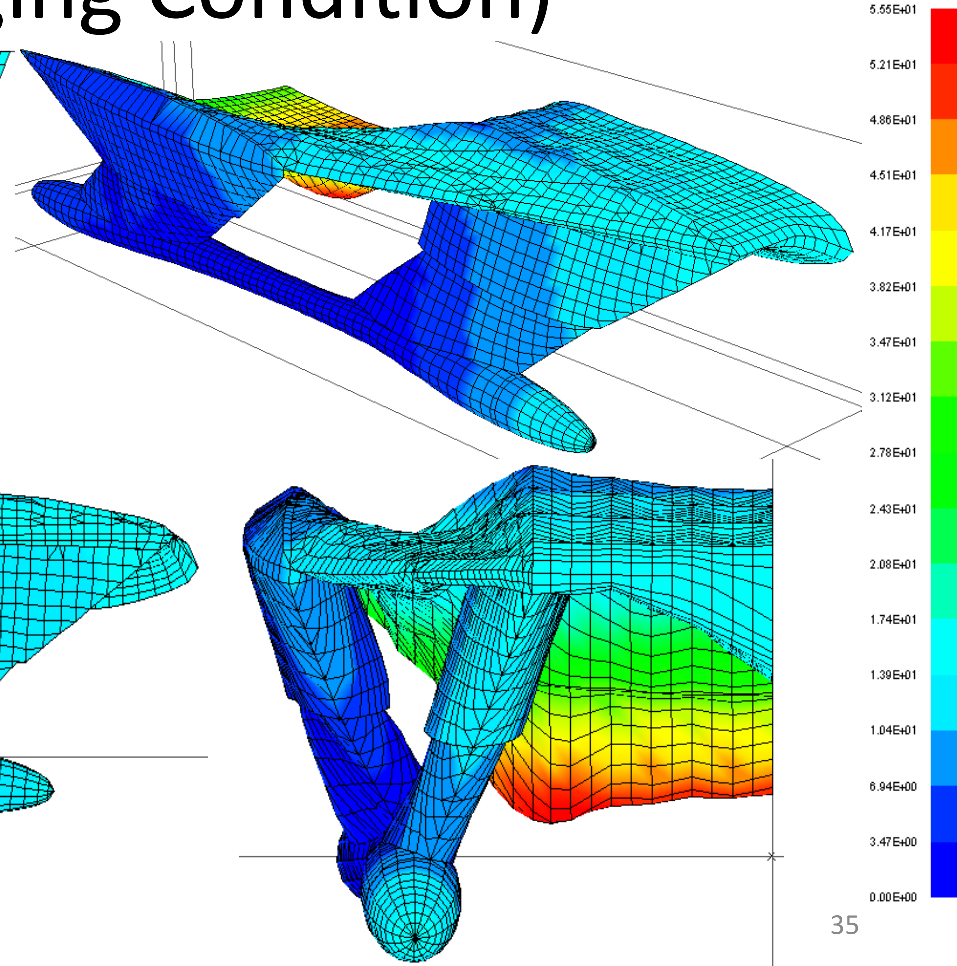
```
***Information Only. No effect on FE-Analysis***
*Displacement= 527529 N, Volume=52.4349 m^3
*The following parameters are in the Ship Coordinate system:
*Center of Buoyancy: xCB= 10411.5 mm, yCB=644.096 mm, zCB=0 mm
*Center of Gravity:  xCG= 10391 mm, yCG=1827.82 mm, zCG=0 mm
*Center of Flotation: xCF= 11748.1 mm, yCF=2252.13 mm, zCF=0 mm
*Trim Angle(Deg)=-0.375233
*Fore Draft Point (mm)=(19537.011,  2303.141,  3660.728)
*Aft  Draft Point (mm)=( 3764.859,  2199.847,  5299.683)
*Fore Draft Point at z=0 (mm)=(19537.011,  2303.141, 0)
*Aft  Draft Point at z=0 (mm)=( 3764.859,  2199.847, 0)
*Distance to origin =-2175.143 mm
*BMT= 7885.98 mm
*BML= 10048 mm
*It=4.13501e+14 mm^4
*Il=5.26866e+14 mm^4
*GMT=6702.14 mm
*GML=8864.16 mm

Balance Completed
```



MAESTRO Reference Model Displacement Results (Hogging Condition)

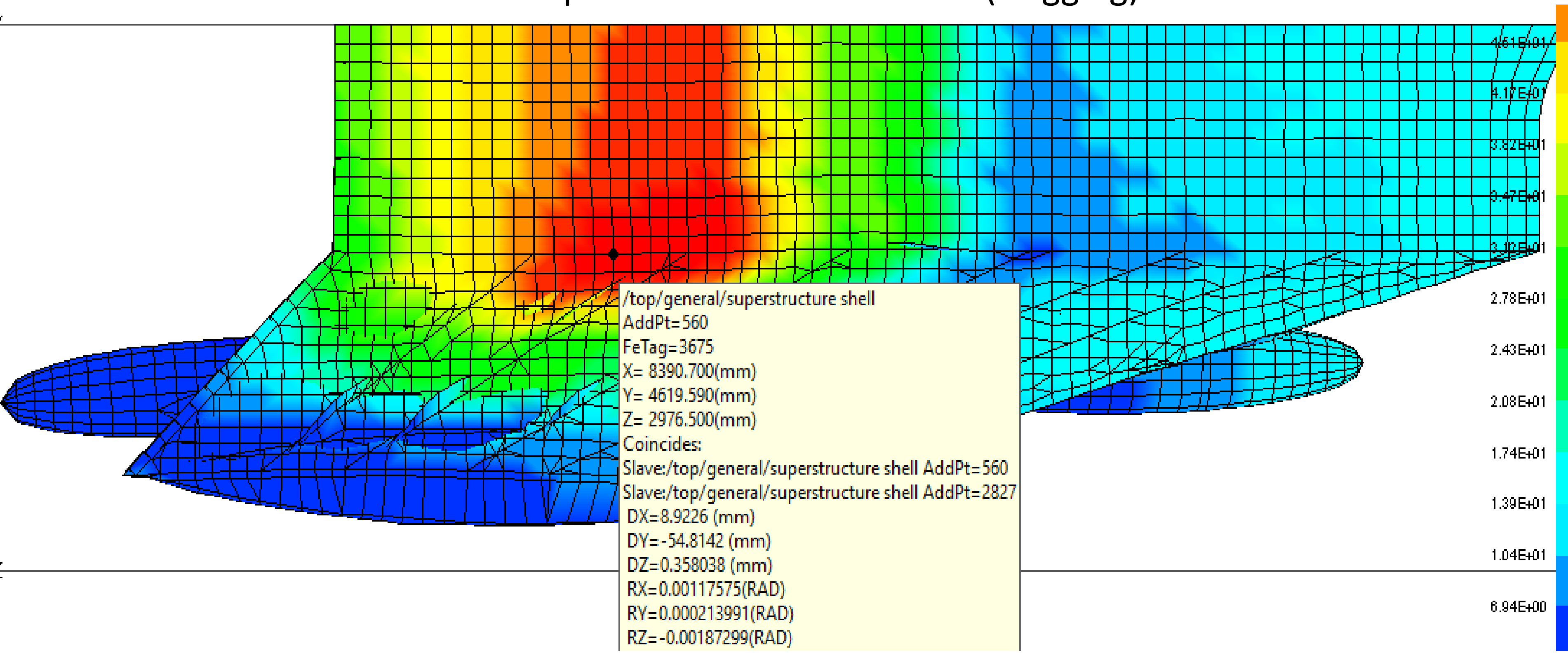




Displacement magnified by 42x factor
Displacement in mm

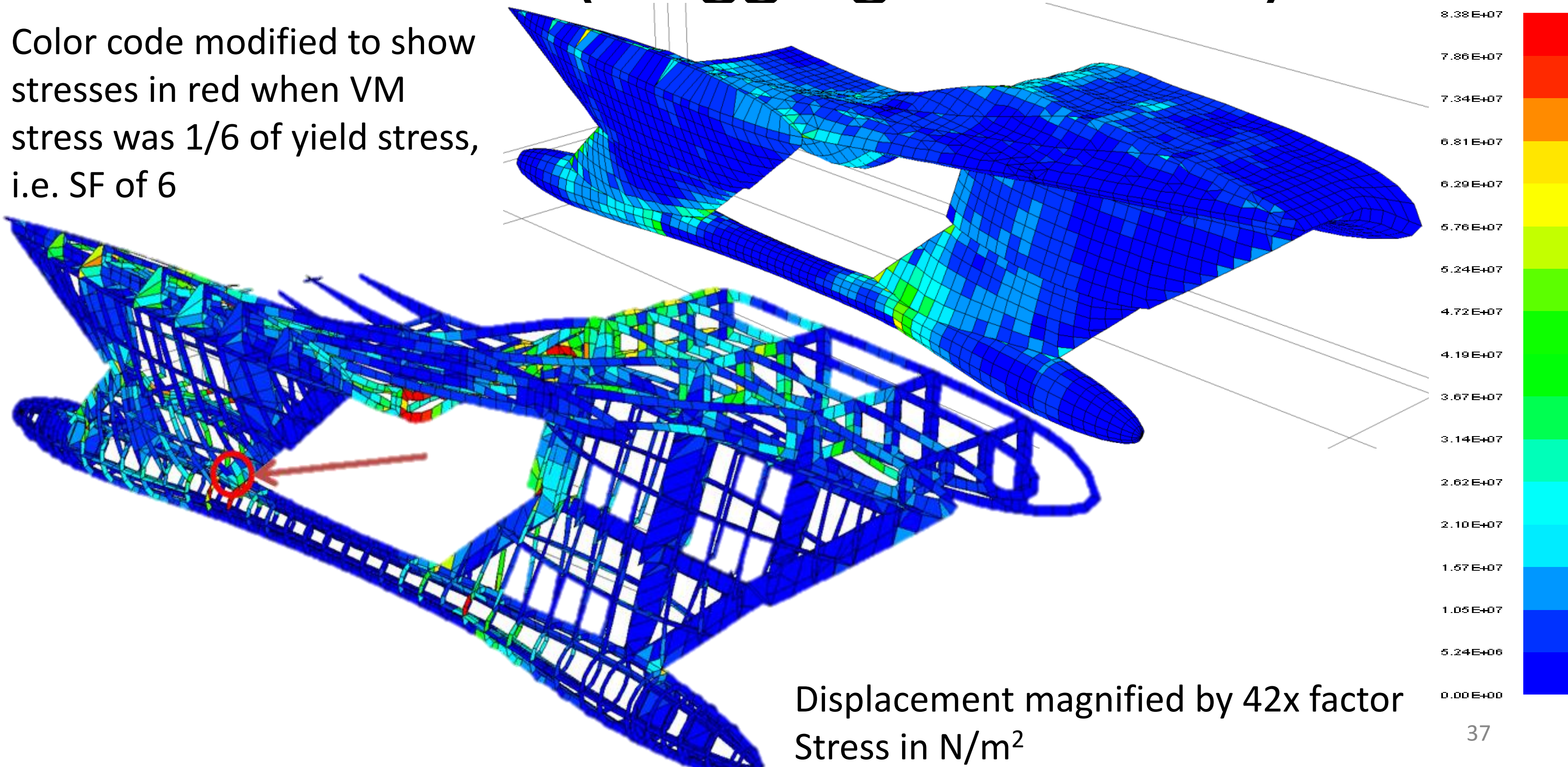
MAESTRO Reference Model Displacement Results (Hogging Condition) (1)

Max Displacement Node Location (Hogging)



MAESTRO Reference Model Stress Results (Hogging Condition)

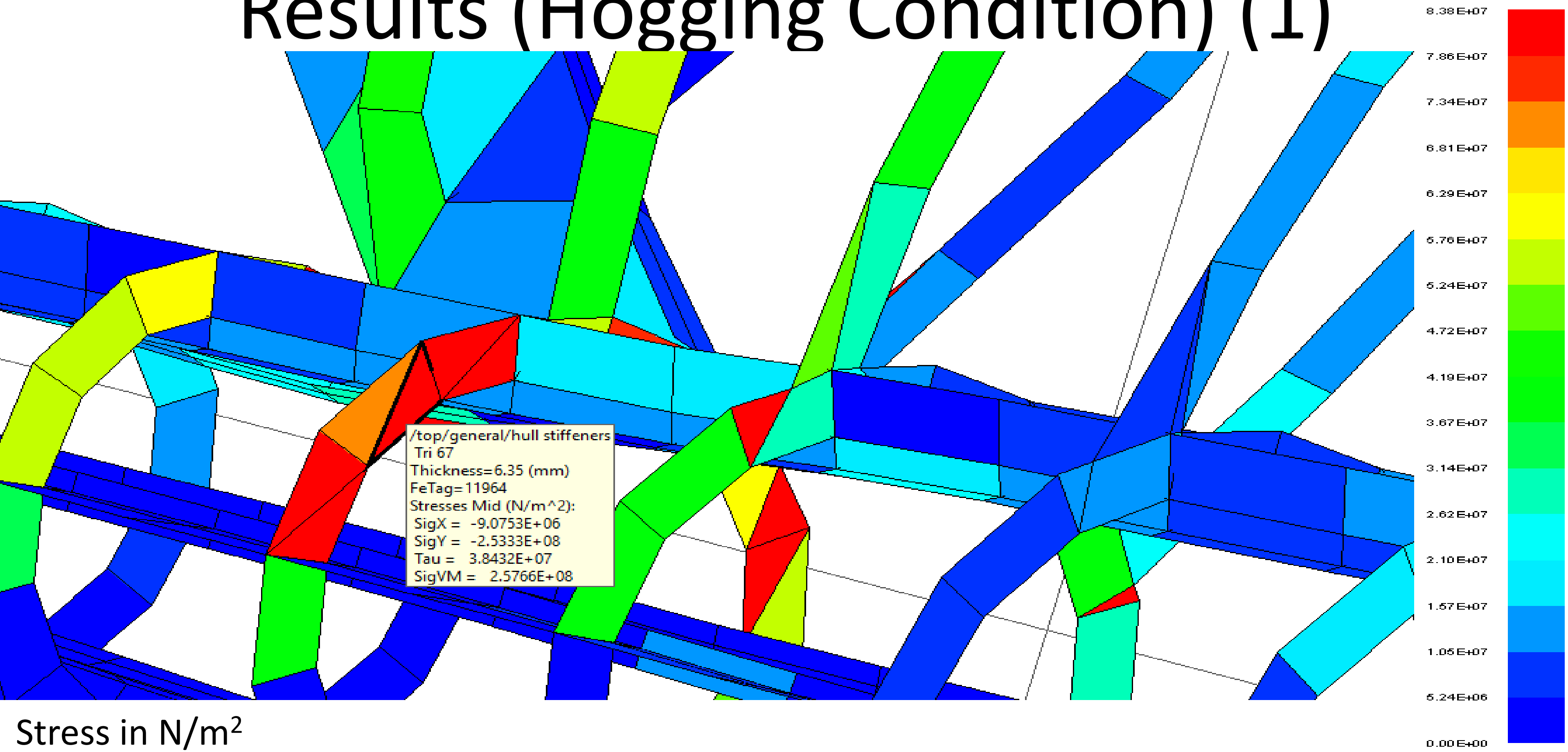
Color code modified to show stresses in red when VM stress was 1/6 of yield stress, i.e. SF of 6



Displacement magnified by 42x factor

Stress in N/m^2

MAESTRO Reference Model Stress Results (Hogging Condition) (1)



Stress in N/m^2

MAESTRO Reference HY2-SWATH Displacement/Stress Results

MAESTRO Max Displacement Results Summary		
Load Case	Displacement Location	Displacement (mm)
Buoyancy Mode	FeTag 10693	34.50
Flying Mode	FeTag 3675	-15.49
Hogging	FeTag 3675	-54.81
Sagging	FeTag 3675	-54.34

MAESTRO Max Von Mises Stress Results Summary			
Load Case	Stress Location	Max Stress (Pa)	Safety Factor
Buoyancy Mode	Strut Stiffener - Tri 298 - FeTag 12042	$5.36*10^7$	9.38
Flying Mode	Hull Stiffener - Tri 56 - FeTag 11968	$1.20*10^8$	4.19
Hogging	Hull Stiffener - Tri 67 - FeTag 11964	$2.58*10^8$	1.95
Sagging	Hull Stiffener - Tri 56 - FeTag 11968	$1.94*10^8$	2.59

MAESTRO Von Mises Stress Statistics				
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. (μ ± σ)
Buoyancy Mode	$5.361*10^7$	$2.858*10^6$	$3.528*10^6$	14.39
Flying Mode	$1.201*10^8$	$3.106*10^6$	$3.755*10^6$	31.13
Hogging	$2.577*10^8$	$1.038*10^7$	$1.359*10^7$	18.22
Sagging	$1.939*10^8$	$9.412*10^6$	$1.173*10^7$	15.74

Conclusions

- AMVS module design space exploration of 60 different HY2-SWATH variations for four load cases
  - Flying mode hull stress/displacement largest of four load cases
  - Four feasible solutions found!
    - Limited primarily by the buoyancy provided by the hull, material used, and the hydrofoils' designed lift

Conclusions (1)

- MAESTRO Reference HY2-SWATH was feasible for all load cases with a minimum stress safety factor of 1.95
  - Hogging wave condition with slamming showed the largest displacement and stress
    - Max displacement in the superstructure at turbojet location
    - Max stress in the hull near aft strut

Conclusions (2)

- The models displacements generally correlated to each other
  - Largest displacements were in the wing-shaped superstructure - location of the turbojets
    - High-fidelity model - turbojets caused largest displacement overall in flying mode, hogging, and sagging load case scenarios.
    - Low-fidelity model – largest displacement overall seen in the hull at midship in flying mode
      - Turbojets caused largest displacement in substructure 2 (aft strut frame) for hogging and sagging load case scenarios.
      - The AMVS module analyzed the hull in a slightly more severe configuration – in absence of strut and superstructure, yet loaded as if they (and all internal machinery) were present.
      - Useful to consider a closed longitudinal frame to include the hull, struts and superstructure.

Conclusion (3)

- The models VM stresses generally correlated to each other
  - MAESTRO model calculates a much larger range of stresses and an order of magnitude greater max stress
  - Average and the standard deviation are similar in their OOM

AMVS Von Mises Stress Statistics				
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. (μ ± σ)
Buoyancy Mode	$3.903*10^6$	$1.332*10^6$	$1.149*10^6$	2.27
Flying Mode	$7.615*10^7$	$1.622*10^7$	$2.445*10^7$	2.45
Hogging	$6.933*10^7$	$1.236*10^7$	$1.562*10^7$	3.65
Sagging	$4.020*10^7$	$1.371*10^7$	$1.199*10^7$	2.21

MAESTRO Von Mises Stress Statistics				
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. (μ ± σ)
Buoyancy Mode	$5.361*10^7$	$2.858*10^6$	$3.528*10^6$	14.39
Flying Mode	$1.201*10^8$	$3.106*10^6$	$3.755*10^6$	31.13
Hogging	$2.577*10^8$	$1.038*10^7$	$1.359*10^7$	18.22
Sagging	$1.939*10^8$	$9.412*10^6$	$1.173*10^7$	15.74

Future Work

- AMVS Module
  - Conduct larger design space exploration
    - Incorporate in global software manager
    - Incorporate additional ship analysis modules
    - Modify more variables (already capable)
  - Consider analysis of additional frames
  - Reinforce structurally weaker areas

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Future Work (1)

- MAESTRO HF model
  - Automate the vessel creation and analysis
  - Reinforce structurally weaker areas
  - Refine mesh
  - Create wave load cases with intrinsic wave functions
    - Compare against DNVGL wave load cases

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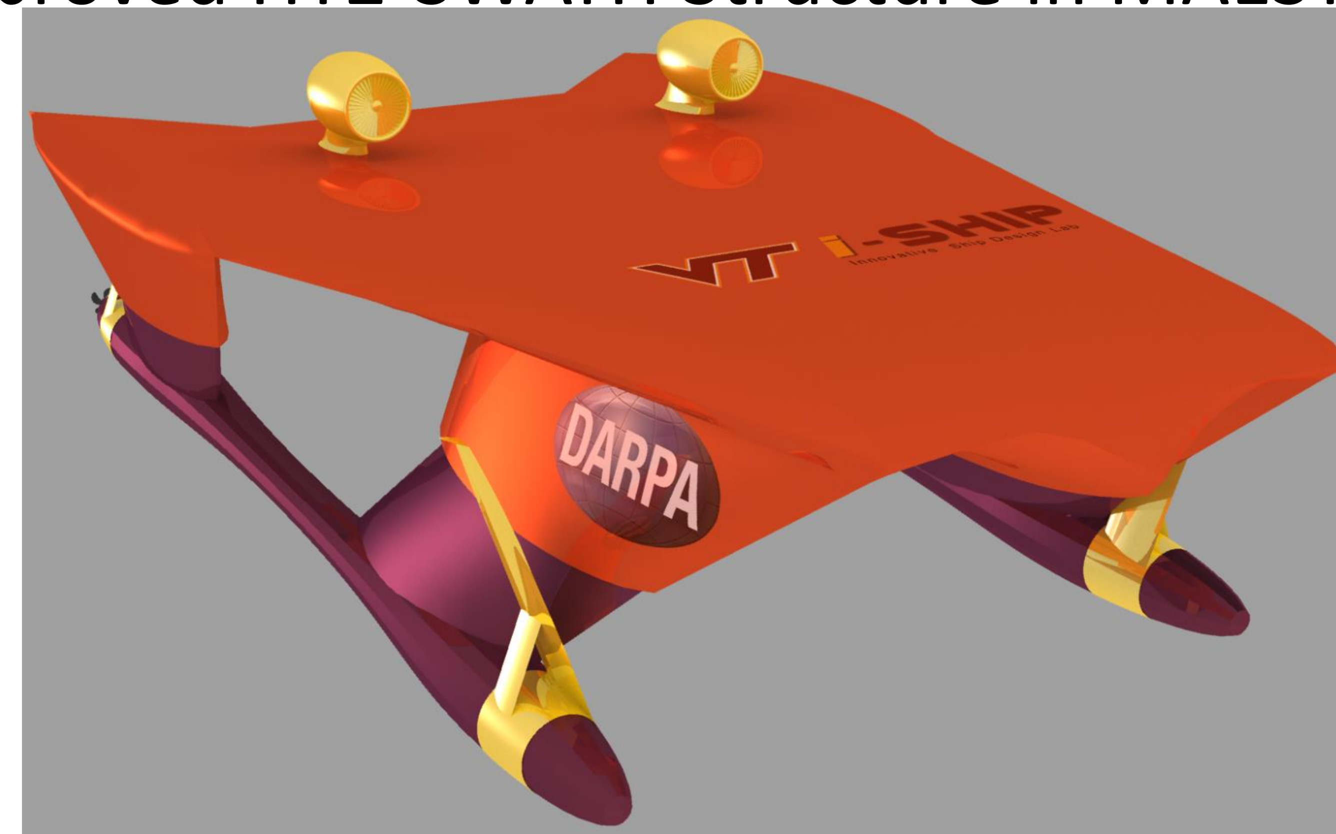
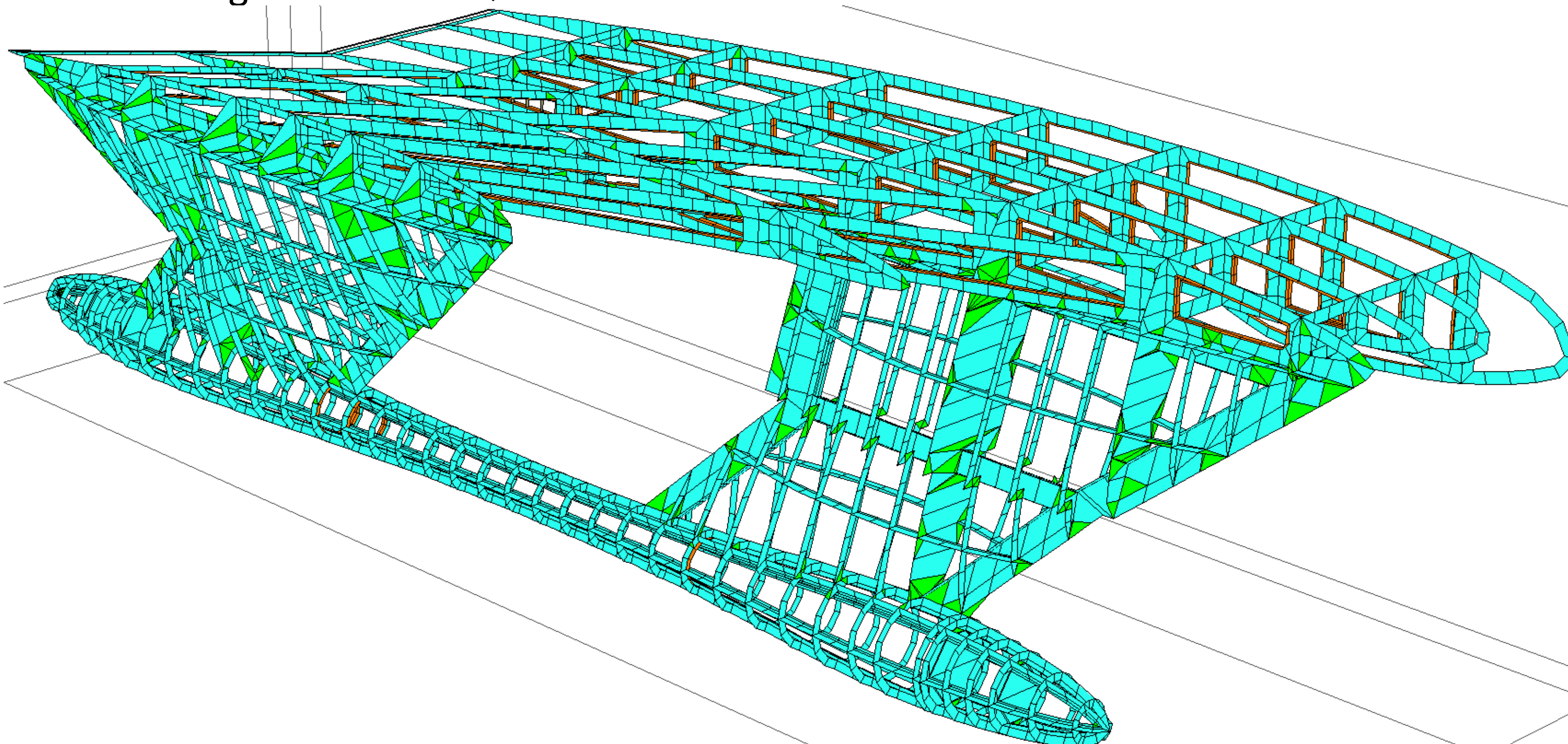
Backup Slides

Improved HY2-SWATH Structure in MAESTRO:



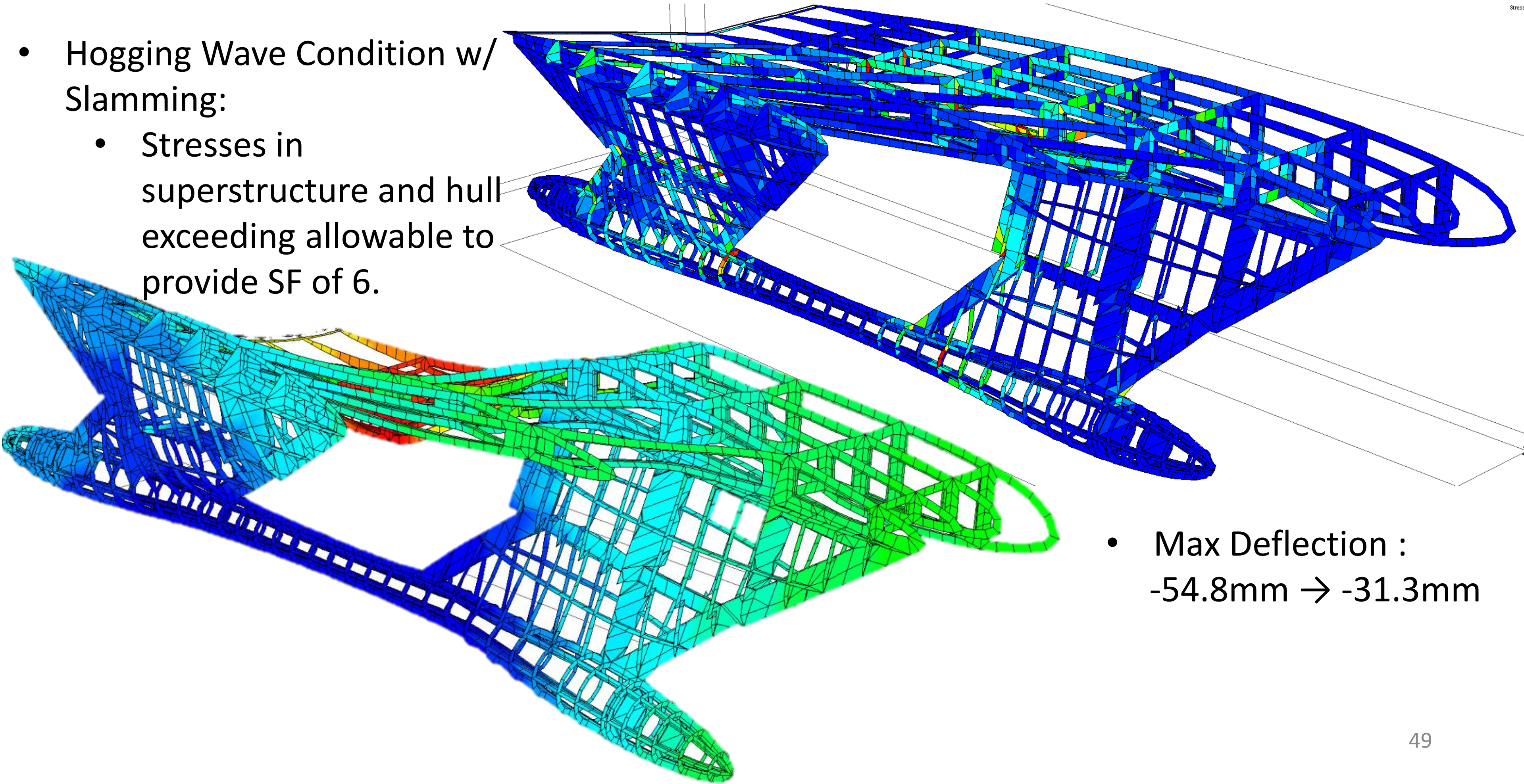
HY2-SWATH V2.0

- Goal: Reduce large deflections and high stress areas to achieve SF of 6
    - Addition of flanges in the superstructure and some in hull:
        - Weight: 53.76 MT→ 55.12 MT



HY2-SWATH V2.0 (1)

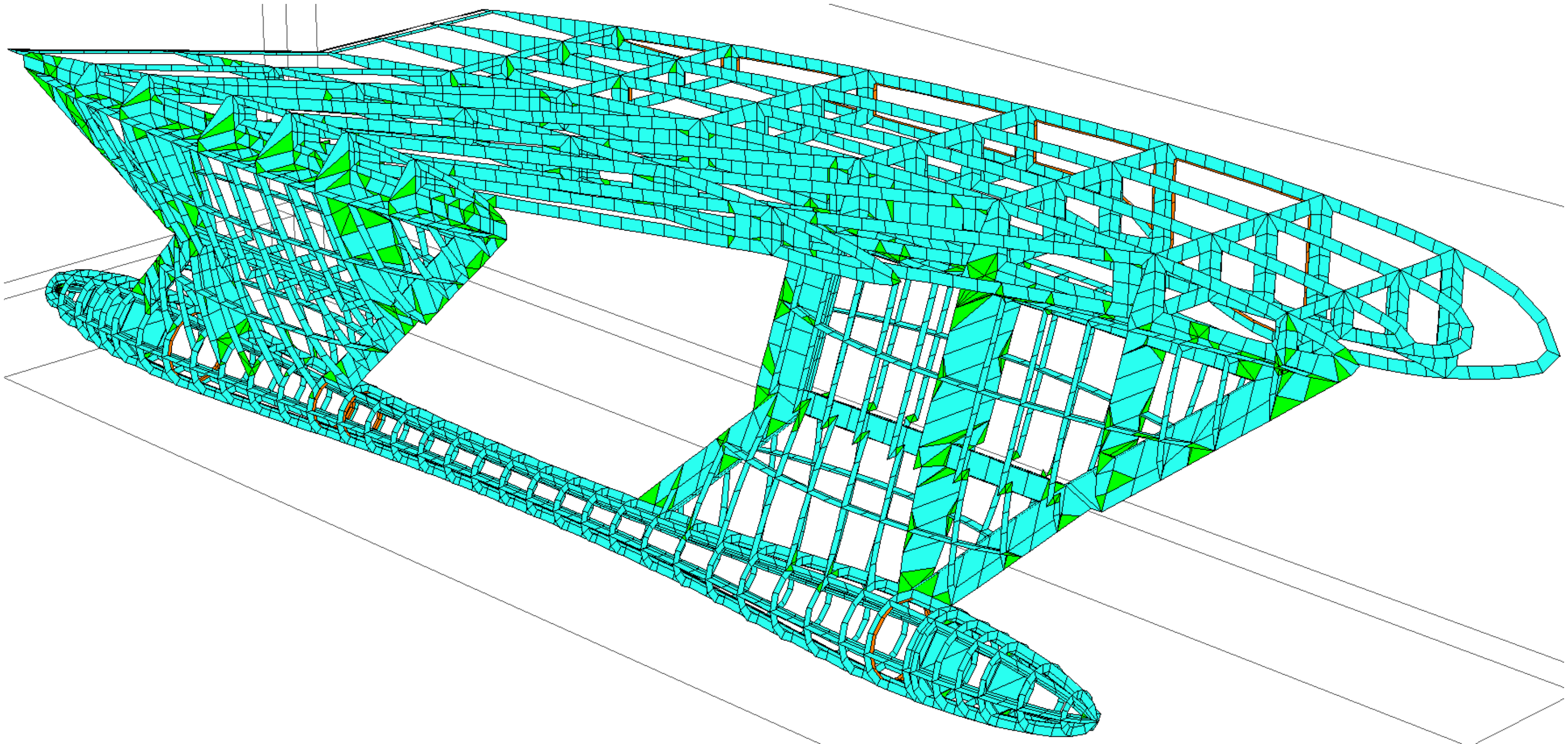
- Hogging Wave Condition w/ Slamming:
  - Stresses in superstructure and hull exceeding allowable to provide SF of 6.



- Max Deflection : -54.8mm → -31.3mm

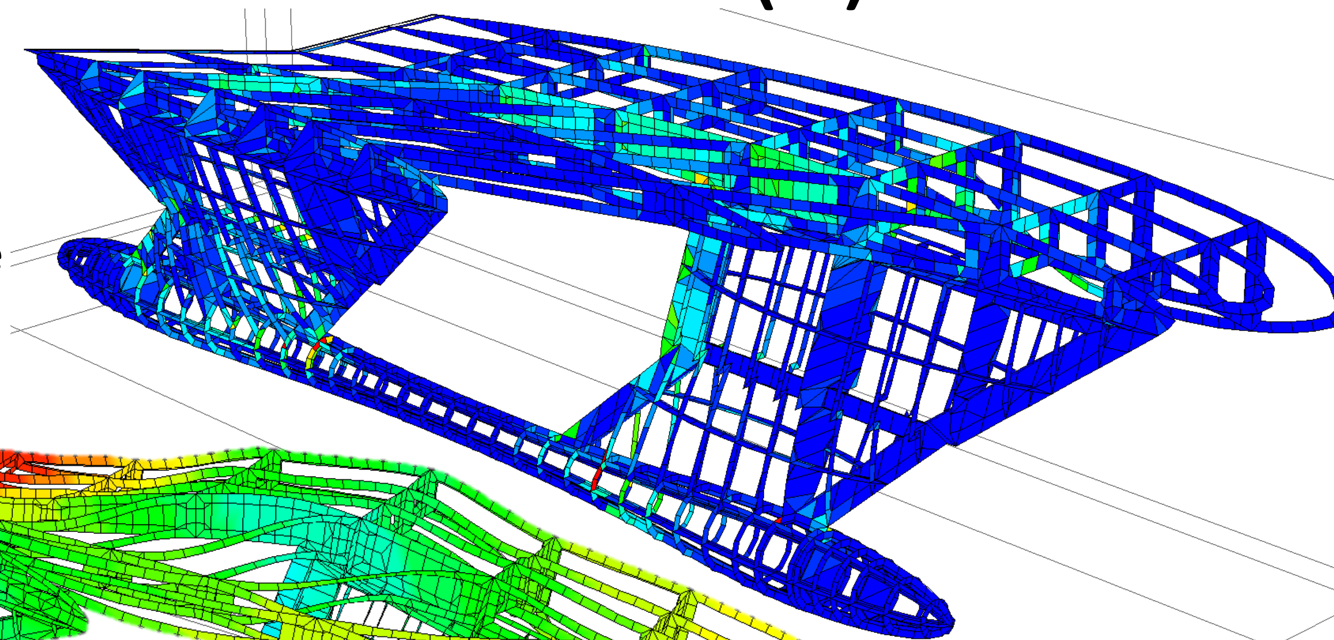
HY2-SWATH V2.1

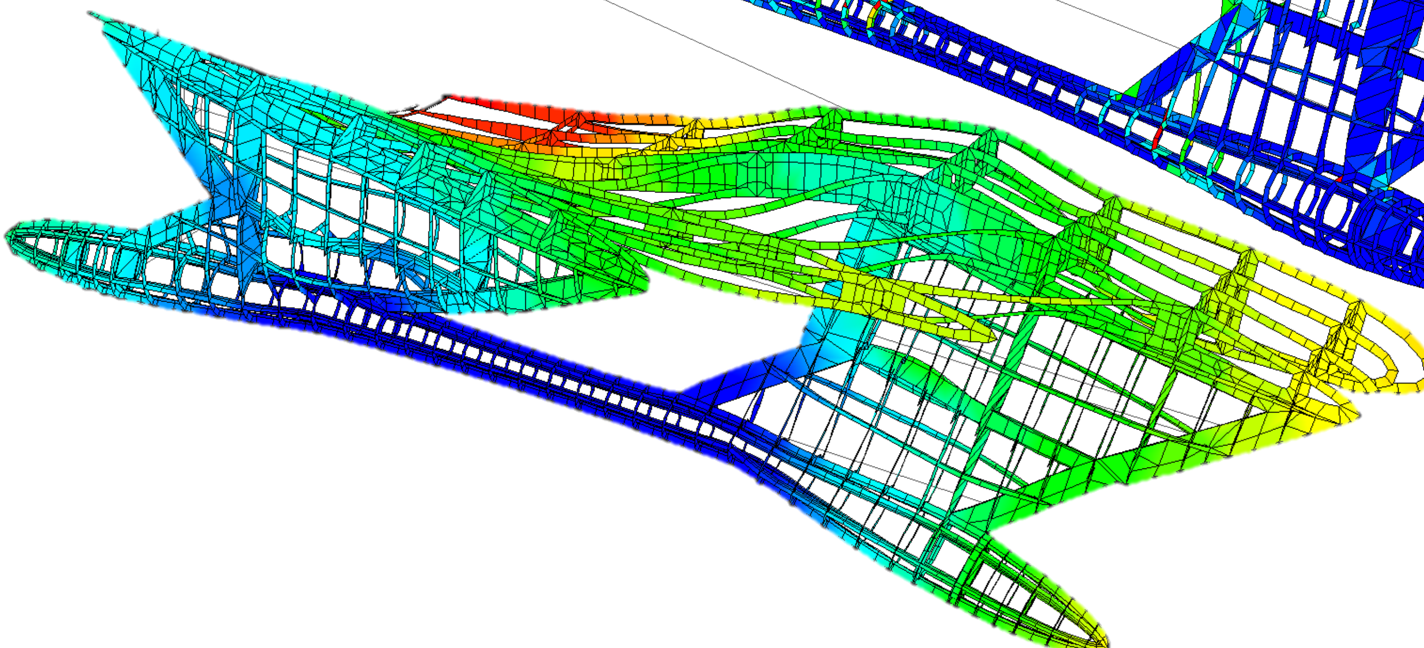
- Goal: Reduce large deflections and high stress areas to achieve SF of 6
  - Removal of most flanges in the superstructure
  - Addition of solid bulkheads in superstructure
    - Weight: 53.76 MT→ 54.09 MT



HY2-SWATH V2.1 (1)

- Hogging Wave Condition w/ Slamming:
  - Stresses in the hull exceeding allowable to provide SF of 6.





Max Deflection :
-54.8mm → -16.8mm