High Performance Yacht Design with Abaqus

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Abstract

Unified analysis platform is the core value for SIMULIA Abaqus with realistic simulation. This paper demonstrated a successful integration of design process with various design requests where CEL dominated slamming wave impact transient analysis, CFD deal with ventilation and thermal analysis, and CMA was in charged with composite structure layup and manufacturing process management. This unified platform dramatically decreased yacht design cycle time and brought highly accurate simulations with complex physical problems.

Keywords：Abaqus, CEL, CFD, CMA, yacht design, ventilation, thermal, composite layup

1. Introduction

The past twenty years have seen significant progress in the performance of motor and sail yachts, which has been partly driven by the use of polymeric composite materials. The science of structural design has moved forward in parallel. Better understanding of mechanical phenomena, together with wider availability of powerful tools like finite element analysis have contributed to this development [1].

In recent years, the application breakthrough is the implementation of numerical methods, such as finite element and finite volume. Numerical methods are qualified as a standard design tools and could be an official design report submission.

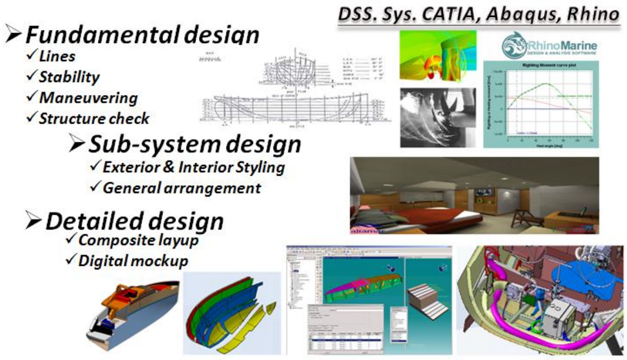
This research focused on an overall design solutions with unified Abaqus/CAE and its standard, explicit, and CFD solvers. A 72 feet power yacht is selected as a benchmark.

2. Research Motivation

Realistic simulation is the trend of design to raise product value and performance. There are 64 yacht companies, shipyards and naval architects adopted Dassault Systems CATIA PLM platform in recent three years [2]. Yacht customers distributed in 22 countries all around the world: England, Germany, Sweden, Norway, USA, Spain, Australia, France, Italy, etc. Customers include 34 naval architects and designer, 21 small yacht builders, and 9 large yacht builders.

In contrast, numerical simulation and the concept of digital design are still not broadly promoted in Taiwan. Lots of yacht companies even don't know there is a powerful tool that could immensely improve their design with shorter design cycle and better system integration.

In order to promote Dassault's PLM platform in Taiwan, a 72 feet yacht model was created from SIMULIA as a benchmark to integrate a broad field of design demands (Graph 2.1). There are still important aspects to discuss for yacht design like stabilities, maneuvering, drag calculation, lines design, NVH etc., but in this research we have to focus in some of them to dig deeply with mechanical insight and try to take them into practice for Taiwan's shipbuilding industries.



Graph 2.1 A broad view of yacht design

2.2 Research Framework

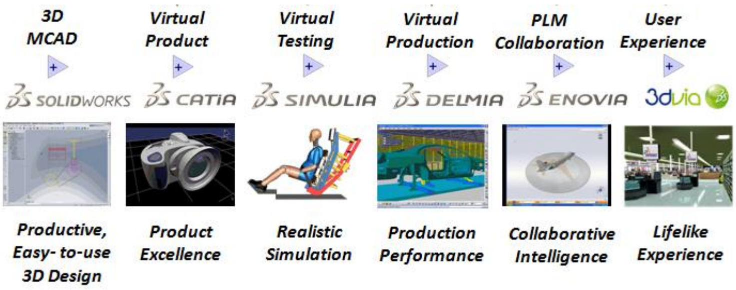
Three topics are discussed with different aspects of Abaqus' modules as followed:

(1). Abaqus/Explicit, CEL wave slamming impact & turning maneuvering analysis
(2). Abaqus/CFD, CFD ventilation & thermal analysis
(3). Abaqus/Standard + Simulayt, CMA composite structure layup analysis

3. Literature Review

3.1 3DExperience

Dassault Systèmes, the 3DEXPERIENCE Company, provides business and people with virtual universes to imagine sustainable innovations. Its world leading 3D design software, 3D Digital Mock-Up and Product Lifecycle Management (PLM) (Graph 3.1) solutions transform the way products are designed, produced, and supported.

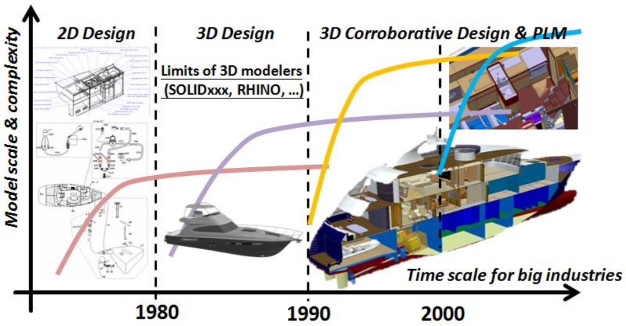


Graph 3.1 Dassault system PLM products

3.2 CATIA for Yacht

CATIA for yacht turn dreams into excellence and brought a huge revolution of how to design. Product design demand full filled and reached software capacities every 10 years (Graph 3.2).

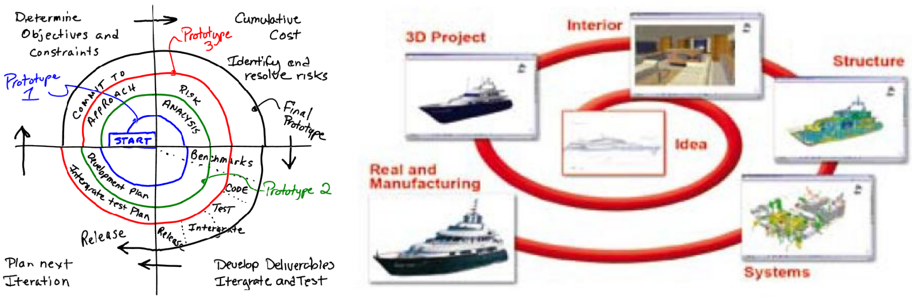
When the Small Boat market is facing hard competition on price and renewal, the strong demand on Super yacht market requires improvement on delivery time with high quality standards. This change is influencing the entire industry from designers and architects to shipyards and suppliers.



Graph 3.2 Dassault yacht design transformation

Facing tough, global competitions on price and style, yacht builders must be able to deliver more innovative products in a shorter amount of time with more iterating design cycles to make their design much more appealing (Graph 3.3).

To realize shipbuilding and yacht design to construction is a complex process. Engineers and manufacturers have to react to customers' demands as quick as possible while keeping costs low. The ability to simultaneously keep the balance between aesthetically pleasing style for a wide range of on-board features and performance negotiation is challenging. Technical barriers such as design proficiency, manufacturing cost and quality control are essential for companies to keep their competitive strength to against their rivals.



Graph 3.3 Yacht design spiral cycle [3]

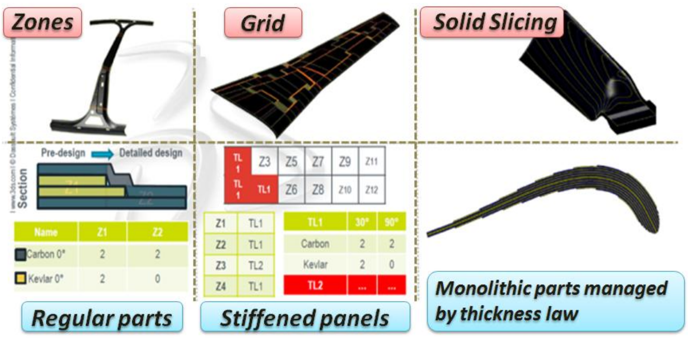
3.3 Composite Design Approaches & Simulayt

Simulayt's products help designers and engineers to integrate the design, analysis and manufacture of structures made from fiber reinforced materials to an unprecedented extent. By simulating the manufacture of these products, problems can be foreseen early in the development cycle and designs can be analyzed and improved to a greater extent within the available development budget.

In addition, the explosive growth of the high-performance composites market in automotive, marine and energy sectors has led to Simulayt's release of professional-level tools for design and analysis. Simulayt's involvement in multiple industry sectors and product development tools allows seamless communication between prime contractor right through to second-tier suppliers.

In general, there are three kinds of approaches (Graph 3.4) to model composite structure according to their structure configurations. The concept of zone modeling exaggerates its material distribution by geometrical features, and there is no obvious thickness variation across structure thickness direction. Structure topography played a much more important role to satisfy its stiffness requirements.

Grid modeling technique is used for large and flat panel with divisions under different structure stiffness and strength enhancement demands. The grid regions are partitioned manually due to engineer experiments and manufacturing feasibilities. The patterns of grid regions are independent to geometrical features where zone regions are.



Graph 3.4 Composite modeling approaches

Solid slicing technique is applied to where composite plies are laying on three dimensional structure like wheel rim [4], suspension mechanism connectors and the foundation of figure skating blade [5] (Graph 3.5). It's more component development oriented for this method where thickness variation gradient is much larger than the previous two.

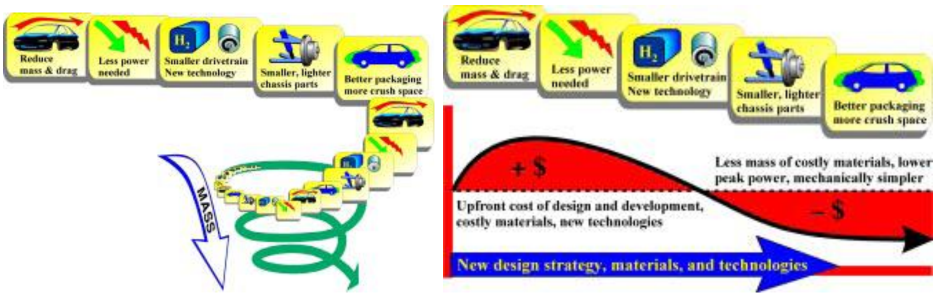
The composite layup pattern on every slice can be easily generated by CATIA and then be assigned to Abaqus with specified material properties and fiber orientation. Furthermore, the interface connects CATIA Composite and Abaqus CMA with compatible automatic data transfer which eliminates the possibilities of typo and tedious properties assignment layer by layer.

Graph 3.5 Three dimensional composite structures

3.4 Inherited Design Concepts

Lightweight structure is a crucial issue for all kinds of vehicular designs where its' prominent mechanical characteristics will accompany with vehicles along its' entire life. For examples, the decreasing of structure weight implied lower fuel consumption and lower take off speed for aircrafts, indicates a lower rolling resistance and higher acceleration performance for vehicles, and results a lower draught and drag force for vehicles (Graph 3.6). The advantages of lightweight structure are quite obvious but manufacturability and cost have to be counted into consideration to out this idea into practice.

Somehow, automobile, aircraft and ship design share very similar engineering techniques especially in numerical methods, material selections, system integration, power train design and multi-body mechanics. The design philosophies are the same: focusing on promoting performance. The concepts of lightweight structure design are much more mature in aircraft and automobile industries with their strict weight sensitive demands. There is still a long road for shipbuilding to implement these ideas to break their conservative design stereotypes.



Graph 3.6 Mass and cost decompounding [6,7]

For ultra-light hybrids, mass decompounding can also lead to a hidden benefit that unlocks the aforementioned economic paradox which is called cost decompounding (Graph 3.6). An ultra-light platform’s smaller drive system produces fewer kilowatts of average and peak power, which can decrease costs for components. Several automotive mechanical and electrical components can also be eliminated. Finally, recursive mass decompounding optimizes the automobile structure to its lowest possible mass, minimizing materials costs.

In principle, the extra cost of advanced materials and drive system technologies can thus be roughly offset by savings from their careful integration, elegantly frugal use of materials, and, ultimately, economies in fabrication, painting, and assembly [7,8].

For examples:

(1). While advanced steel offers at best 25 to 35% automobile structure mass reduction and aluminum 40 to 55%, GM's and Ford's composites experts have estimated a 50 to 67% reduction using automotive advanced composites [9,10] whose specific strength and stiffness 2 to 6 times higher than metals [8]. This maximizes mass and cost decompounding.

(2). The Advanced Composites Consortium built a Ford Escort glass composite front end using a manufacturability design and resulted in a 25% lighter structure than the original steel assembly one with the same packaging constrain. With no airbags, it passed all government crash tests, yielding superior performance [11].

(3). Head Injury Criterion scores were 31% below a 1995 steel Taurus design's with airbags (or 35% below an aluminum version's) [12]. Imagine what it could have done with clean sheet packaging and high performance materials like McLaren's carbon fiber F1 sports car, which drove away from a 30-mph fixed-barrier crash test. [13].

(4). The composite body panels of Renault's L'Éspace van had a 5 to7 fold lower tooling cost than an equivalent steel design [14].

3.5 Yacht Ventilation [15]

3.5.1 Passive Ventilation

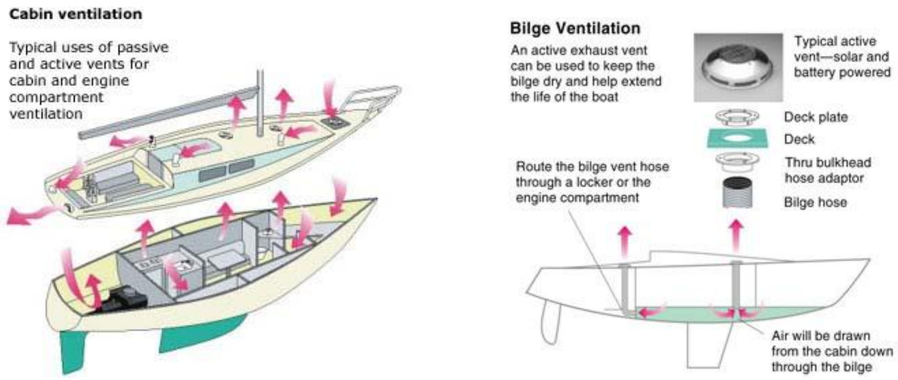
Passive vents include the traditional cowl vents, clamshell vents, louvered hatch boards, and the mushroom type vents. A cowl vent may include a water trap or dorade box. The dorade box is a water trap that was designed by the Sparkman and Stephens design group and first used on a sailing yacht called Dorade. A passive vent works reasonably well on a nice breezy day, but on those hot, still days in August, they do not move much air. They also work well as intake vents for systems that include active vents.

Graph 3.7 Passive ventilation system

3.5.2 Active Ventilation

These are usually mushroom type vents, with a powered fan installed inside the vent body. These are usually solar powered, but there are a couple of units available that are powered from the ship's 12 volt system. There are even units available that offer both solar and 12 volt power sources. Day and Night solar vent uses the sun's energy to run the fan during the day and charge battery, which will run the fan at night. Most of the active vents have interchangeable fan blades that allow them to be used either as exhaust or intake vents.

A proper ventilation system will exchange the air within the cabin about once an hour. An average 35' cruising sailboat will have an interior volume of about 1,200 cubic feet. The airflow ratings of the various passive vents range from 350 to 600 cubic feet per minute (cfm). The airflow ratings of a powered vent range from 700 to 1,200 cfm. This suggests that a minimum of two vents for exhaust and two vents for intake are required to properly ventilate a boat of this size. Smaller boats will need fewer vents, and vice versa.



Graph 3.8 Cabin & bilge ventilation

4. Yacht Integrated Analysis

4.1 Objective Yacht

Basically, yachts with similar length overall will have similar specifications so that we choose Monte Carlo Yachts 70 as a benchmark to provide more detailed specifications (Chart 4.1) for SIMULIA S72 as performance and calculation references. The Monte Carlo Yachts 70 (Graph 4.1) has a distinctive style. Every aspect of the yacht's design and manufacture has been meticulously executed.

Chart 4.1 MCY 70. Specifications [16,17]

General Spec.			
Length Overall	69' 11"	Dry weight	39 ton
Beam	17' 9"	Fuel Cap.	1,057 gal.
Draft	5' 0"	Water Cap.	222 gal.
Deadrise/Transom	N/A	Bridge	20' 8"

Max. headroom	N/A	Clearance
Building Material		
VTR, Kevlar®, carbon		
Engine Spec.		
Std. power	2 x 1200-hp MAN V8 with ZF POD 4000	
Speed		
Max. speed	33 kn (V8 1200 POD)	
Cruise speed	26 kn (V8 1200 POD)	

Graph 4.1 Monte Carlo Yachts 70 [16]

4.2 CEL Wave Slamming Impact & Turning Maneuvering Analysis

4.2.1 Model Description

In wave slamming analysis, a wave is generated by inflow velocity boundary assignment with periodic amplitude. The inflow velocity is 12m/s (23.3knots). The ship is gradually moved downward until reaching its' specified design water line. Before the ship is on its' ready position, the inflow velocity remains the same, and then assigned with periodic amplitude. Zero pressure outflow boundary is assigned on the opposite side of the inflow boundary surface. Zero normal velocity is settled on the other surfaces as wall condition.

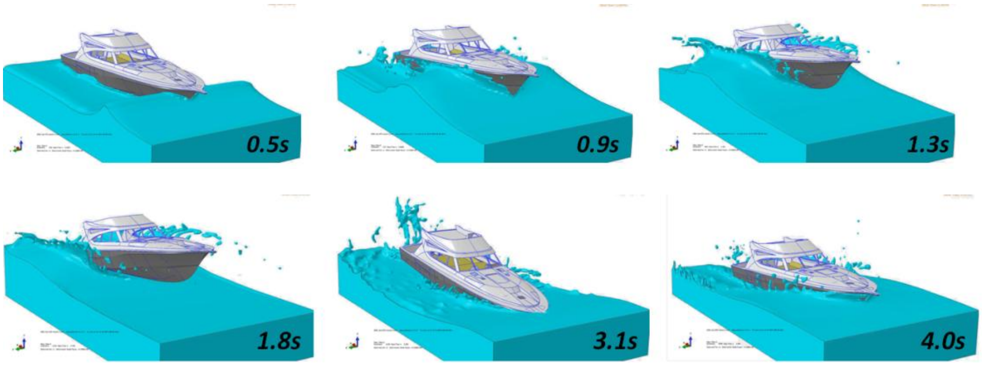
In turning maneuvering analysis, a steady inflow with constant velocity 12m/s is assigned on the inflow boundary surface. The other surfaces remained the same as in wave slamming analysis. A back and forth angular displacement is assigned with displacement control to trace the resistance variation during the turning.

Reaction force, reaction moment, displacement, velocity and acceleration are recorded on the mass center of the yacht in history output to examine the dynamic performance of the yacht. Otherwise, slamming contact pressure on the hull is also output to examine the structure loading under transient impact.

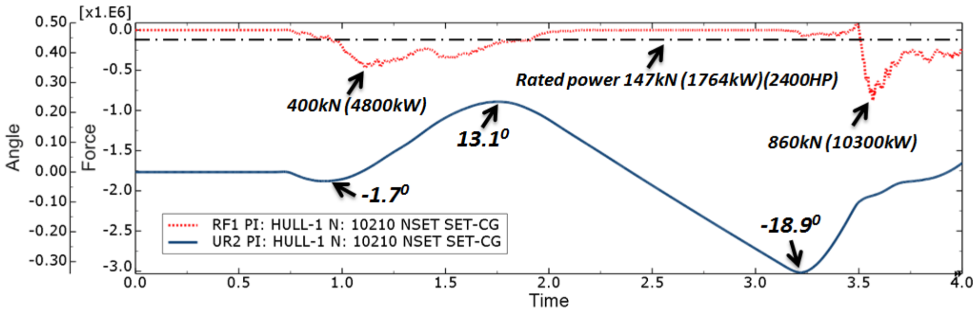
4.2.2 Wave Slamming Result

After seconds of wave propagation, the yacht sustained 400kN reaction force which is about 2.7 times maneuvering resistance and reaching its maximum positive trim angle 13.1^0. At 3.1 second, the yacht reached another austere condition when falling down to the water and a much more severe resistance force 860kN which is 5.8 times maneuvering resistance is sustained. Trim angle variation between 13.1^0 and -18.9^0 is observed. The slamming process is demonstrated as (Graph 4.2) and the history output is shown as (Graph 4.3).

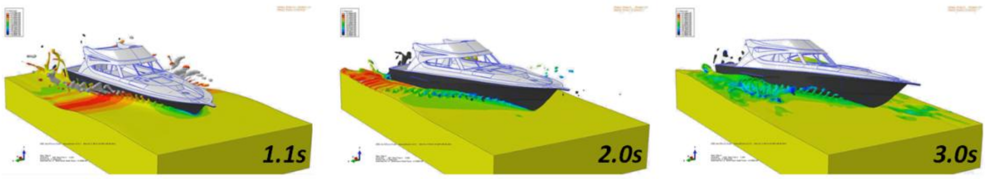
During the turning analysis, roll , trim and turning angle are observed. Resistance force variation is also counted in. The peak resistance force 390kN which is 2.65 times the maneuvering resistance happened when the yacht just finished its turning command. There is a 2 second roll angle response delay after the finishing of ramp turning command and a 1.5 second delay after the turning recovery command. It is interesting that the maximum resistance did not appear when the yacht is fully turned but happened on the end of turning. There is also an over-turning phenomenon after the recovery command is over and the over-turned roll angle is almost the same as the positive toll angle but with shorter response time. The turning process is demonstrated as (Graph 4.4) and the history output is shown as (Graph 4.5).

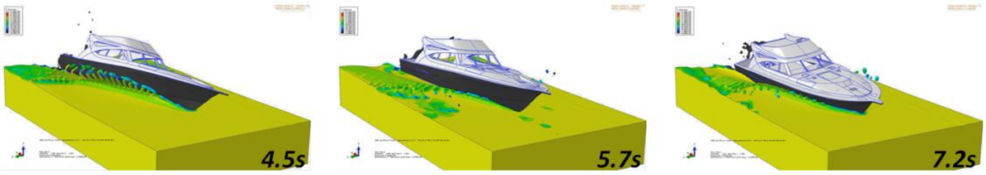


Graph 4.2 Yacht wave slamming and motion analysis process

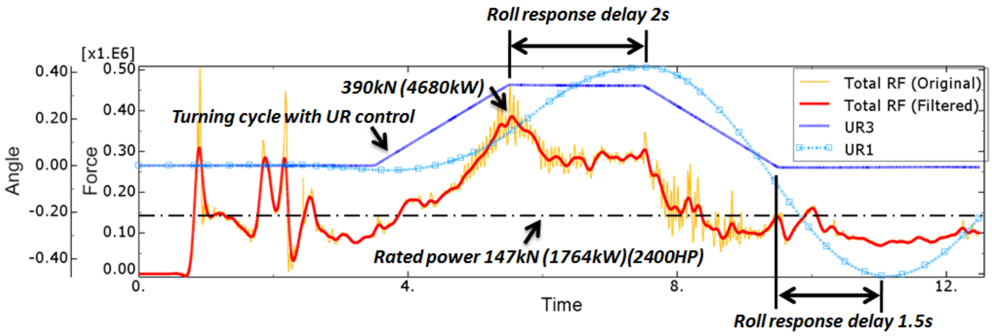


Graph 4.3 Yacht resistance force and trim angle history output





Graph 4.4 Yacht maneuvering and turning analysis process (velocity field)



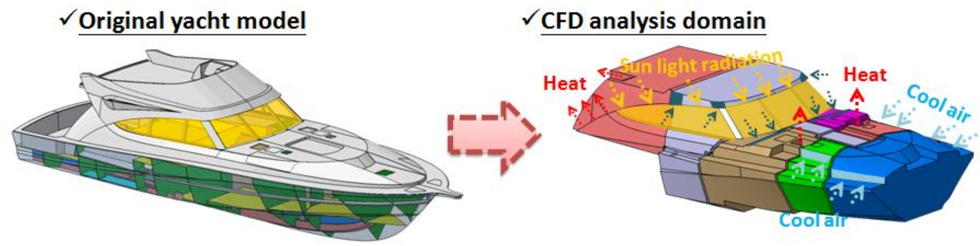
Graph 4.5 Yacht turning cycle, rolling angle and resistance history output

4.3 CFD Ventilation & Thermal Analysis

The understanding of conduction-convection heat transfer phenomenon results in more accurate ventilation system specification estimation and vent arrangement.

4.3.1 Model Description

This model examines a transient heat transfer of a yacht ventilation process in its cabins. A buoyancy-driven natural convection and conduction of air itself were considered. A constant heat flux and temperature from the windows to simulate solar radiation was assigned. Heat is thus transferred from the window surfaces to the ambient air through convection process. Several inflow and outflow vents are assigned. Inflow temperature is 15^{o}C with 0.5m/s intake velocity. Outflow surfaces are assigned with zero pressure boundary condition.



Graph 4.6 CFD analysis domain, inflow and outflow boundaries

Ventilation design target is to find a better vent arrangement that minimize the compressor requirement. In this example, a constant heat rate Q of cooled air flows in the cabin, a constant heat dissipation q from solar radiation is assigned, and two different vent arrangements are compared. Under such conditions the product of inflow speed and inflow vent area is constant to guarantee a constant energy input.

The heat dissipation assignment and boundary conditions are listed as below.

$$E = Q\Delta t = mC_p\Delta T = \rho VC_p\Delta T \quad (4.1)$$

$$Q = mC_p\Delta T / \Delta t = \rho VC_p\Delta T / \Delta t = \rho AvC_p\Delta T \quad (4.2)$$

where

E=energy(J)	*m=flow mass(kg)*	*t=time(s)*
Q=heat rate(W)	*v=flow velocity*	*Cp=specific heat(J/g/K)*
q=heat flux(W/A)	*V=flow volume*	
T=temperature(K)	*A=area(m²)*	

Chart 4.2 Air material constant at 298K (25^{o}C)

Density ρ *(kg/m^3)*	1.127	Conductivity κ *(W/m/K)*	0.026
Dynamic viscosity μ $(Pa \cdot s)$	$1.81\text{x}10^{-5}$	Specific heat C_p*(J/kg/K)*	1012
Expansion coeff. β *(1/K)*	$3.43\text{x}10^{-3}$		

Chart 4.3 Heat dissipation and boundary conditions

Heat source	*Heat flux q ($J/s/m^2$)*	Boundary conditions	*Temp. (^0C)*
Solar radiation	342	Initial ambient	35
		Inflow	15

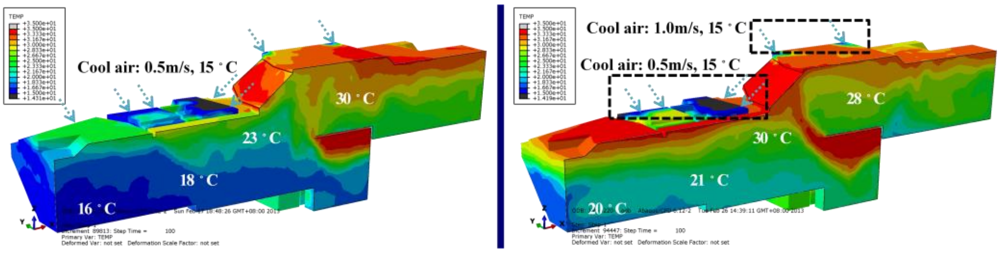
Chart 4.4 Temperature sensing index

Ambient temperature *(^0C)*	Human's feeling
<21.9	Cold
22.0~24.9	Nice and cool
25.0~27.9	Comfort
28.0~30.9	Warm
>31.0	Hot

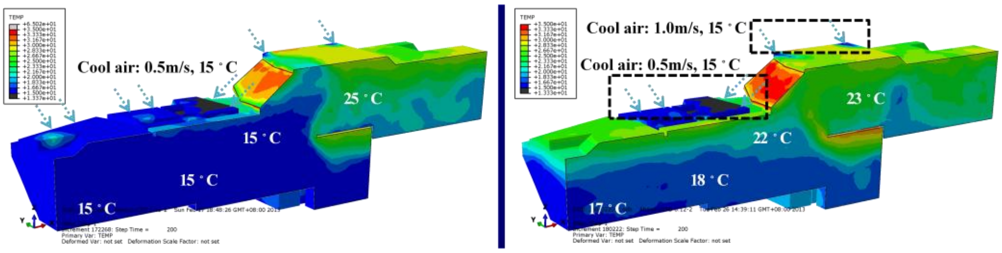
4.3.2 Analysis Result

As showed on (Graph 4.7 to Graph 4.10), there are ten inflow vents where four in the front cabin, two in the mid cabin and four in the cockpit. The inflow velocity is $0.5m/s^2$ for all the vents and total intake areas are $3.218m^2$. A constant flow rate is $1.609m^3/s$ in the yacht is assigned.

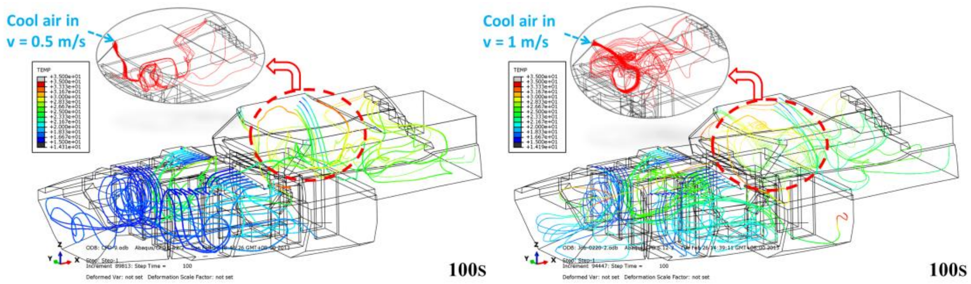
The left graph demonstrated the appropriate design that the maximum temperature difference between frontal cabin and cockpit would reach a 10 degree level around 200s conditioning operation. The right graph demonstrated a modification design that decreased the frontal cabin ventilation intake area and increased cockpit vent intake flow velocity as a compensation to maintain a constant intake flow rate. Under 200s, a much more satisfied result was showed where the temperature difference was within 5 degree which provided a better temperature homogeneity and comfort. CFD calculation is a crucial process to evaluate air conditioning arrangement.



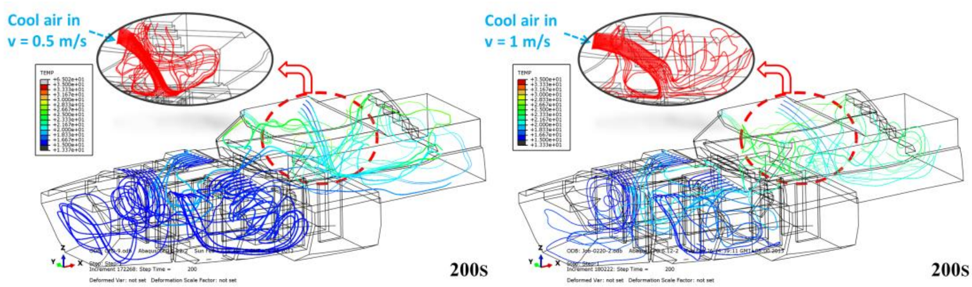
Graph 4.7 Temperature field comparison with different ventilation arrangement at 100s



Graph 4.8 Temperature field comparison with different ventilation arrangement at 200s



Graph 4.9 Streamline comparison with different ventilation arrangement at 100s



Graph 4.10 Streamline comparison with different ventilation arrangement at 200s

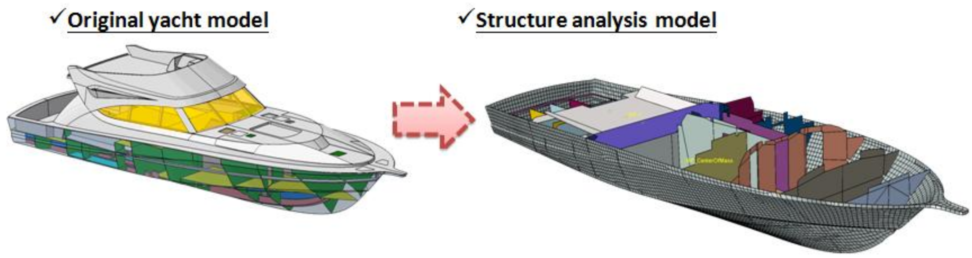
4.4 CMA Composite Structure Layup Analysis

CAM design model was desired to provide a better composite ply layup arrangement and management with fiber warping consideration during layup. In this analysis, only hull structure was modeled with CMA whose features are much suitable to examine fiber layup process feasibility.

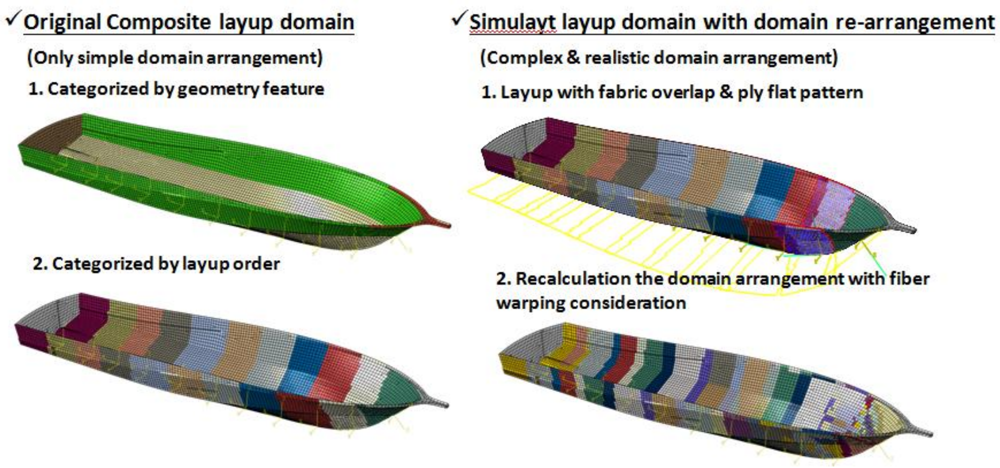
4.4.1 Model Description

A shell model was created with deletions of small features that may cause distorted element. The connections between hull, bulkheads, deck floors and walls were assigned with tie constrain without initial position adjustment (Graph 4.11).

A trivial hydrostatic pressure was assigned with inertial relief. The differences between these two models were the considerations of fiber warping and overlap effect where traditional composite layup approach implied a fiber orientation mapping without rotation along geometrical feature and Simulayt counted it into its' calculation. Also, the multi-selection function in Simulayt brought it much more easily to assign complex or duplicated layup. The section properties difference were showed as (Graph 4.12).



Graph 4.11 Structure analysis shell model

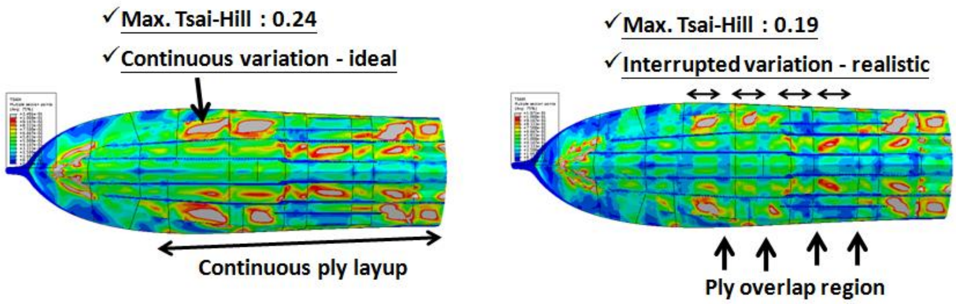


Graph 4.12 Traditional composite layup & Simulayt layup comparison

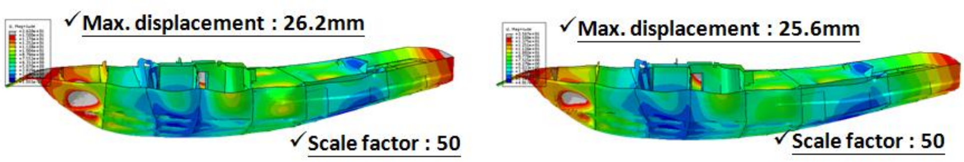
4.4.2 Analysis Result

Both stress and strain distribution demonstrated different patterns that there is stress/strain discontinuity and overlap reinforcement that the Tsai-Hill criteria and max. displacement decreased about 20% and 2.2% which implied the increasing of stiffness (Graph 4.13, Graph 4.14). The same tendency also could be observed under the increasing of modal frequency that sagging and lateral bending mode consecutively increased 3.8% and 3.3%.

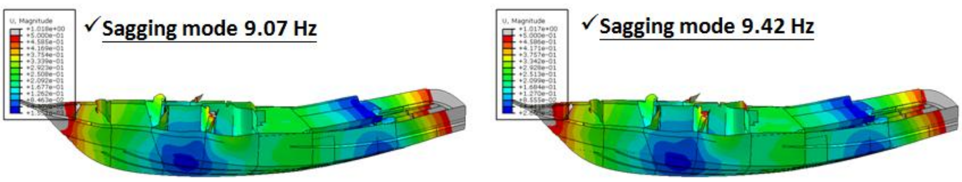
The realistic layup arrangement provides much more design space and flexibility with the increasing of stiffness and strength to guarantee a light weight structure more easily.



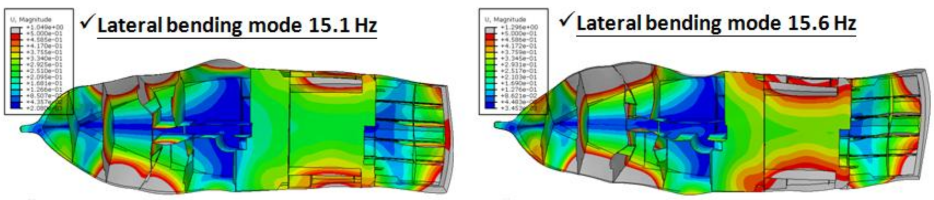
Graph 4.13 Tsai-Hill distribution comparison between composite layup & Simulayt



Graph 4.14 Displacement comparison between composite layup & Simulayt



Graph 4.15 Sagging mode comparison between composite layup & Simulayt



Graph 4.16 Lateral bending mode comparison between composite layup & Simulayt

5. Discussions & Conclusions

Yacht maneuvering and turning performance was evaluated under CEL, air conditioning vent arrangement modification was achieved by CFD, and composite layup with fiber warping consideration was examined with CMA. Although there are satisfactory results on each engineering item, it is hard to realize a unified model to achieve analysis with such a field divergence. Except this issue, Abaqus is great for integration design to improve vehicular performance and proficiency.

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