Analysis of the Design & Construction Methodologies for Carbon Composite Motor Yacht Superstructures

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1. Abstract

Composite hull and superstructure construction using fibreglass reinforcements has been a part of the motor yacht industry for several decades. However increasing demand for greater structural performance has required that motor yacht designers look for materials and composite layups that provide greater strength for equal or less layup thickness and weight.

Carbon fibres provide such a suitable option, however their cost and tendency to fail catastrophically without warning has meant that implementation in motor yacht structures requires surety that the performance of the final layup is as required by the demands placed on the hull or superstructure.

This thesis investigates the benefits and drawbacks of carbon in regards to material properties, structural design and the manufacturing process, focusing on sandwich laminate construction. Future trends in material use and production techniques will also be put forward, based on an historical trend of technology flow down from predominately the aerospace industry.

The investigation focuses on a comparison between the more standard E – Glass and Carbon fibre, and the advantages gained from using the higher performance reinforcement material with respect to.

1. Increased raw material properties, using simple beam theory
2. Advantages available from using carbon in superstructure design, using finite element analysis
3. Additional performance gains when combining carbon fibres with more refined laminate manufacturing methods.

Results show that carbon fibre offers an improvement over E – Glass in terms of reduced structural scantlings (Eg. reduced deck stiffener depth) and a corresponding reduced structural weight whilst offsetting its higher raw material cost to be a viable choice for modern yacht superstructures.

The thesis was conducted in conjunction with the development of a carbon fibre superstructure for a new class of motor yacht design with the Azimut Benetti group.

2. Introduction and Investigation

a. The Drive for Lighter Materials

Motor yachts design is primarily driven by demand for greater living space onboard and faster transit speeds, the former results in larger, heaver hulls needing more thrust to reach cruising speeds required to meet the latter. Hull structure is a significant part of a motor yachts weight and so designers constantly drive for lighter hull and superstructure weights to reduce engine power requirements and fuel consumption.

i. Steel → Aluminium → Fibreglass

One such avenue of improvement has been the advancement in material choice for construction. Metal materials have given way to composite structures, with smaller leisure boats today being almost solely built in glass reinforced plastics (GRP) (UNSW Course Notes, Taylor, 2006). The ease of application to mass production and cheap cost of materials without loss of mechanical properties has allowed GRP to become the dominant material in this sector.

TABLE 1 – RAW ISOTROPIC MATERIAL PROPETIES

Material	Steel	Aluminium	GRP	Carbon
Grade / Fibre	ASTM A131 – A	5083 – H321	E – Glass Fibre	Torayca T300
Density (kg/m^3)	7,850	2,660	2,580	1,760
Tensile Modulus (GPa)	140	70	72	230
Tensile Strength (MPa)	400	317	1,950	3,530
Shear Modulus (GPa)	80	26	30	12
Shear Strength (MPa)	280	190	1,125[1]	2,036[1]
Strain to Failure (%)	24.0	16.0	5.0	1.5

(1) Figures estimated using Von Mises relation $\tau = \sigma / \sqrt{3}$

Construction at the lower end of the leisure boats market is primarily driven by cost of manufacture to maintain competitiveness, and so materials used for the hull and superstructure are usually selected from the cheapest of the composite options available to the marine sector. E – Glass either in the form of chopped strand / mat or woven bi–directional fabrics are typically combined with cheaper unsaturated polyester or vinyl ester resins to form the laminate.

The matching manufacturing techniques used with these materials are equally cost driven, and will involve a minimal amount of investment in equipment for manufacture. Historically chopped strand spray or wet layups conducted by skilled and experience workforce is capable of providing a competitive solution. More demanding structural loads make use of Unidirectional E – Glass reinforcement and the resin infusion processes, which increases the concentration of load bearing fibres in the cured laminate.

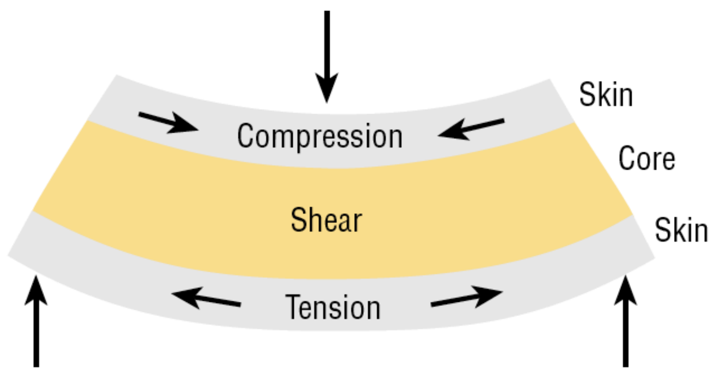
ii. Fibreglass → Carbon Fibre

For typical motor yachts designs below 30m in length, fibreglass and manufacturing methods mentioned above provided sufficient stiffness and strength for the global loadings that are experienced longitudinally along the boat with minimal penalty for weight, layup complexity and manufacturing cost. However as vessel length grows the increasing global bending loads require thicker, heavier, more complex E – Glass layups to support the vessel structure. These higher loads increase the value of using the higher modulus, more expensive carbon fibre as reinforcement material.

iii. Sandwich Construction

When the objective of a structural element is to carry bending loads (As is the primary objective of decks / hull plating structures), the principal property of the deck / stiffener cross section is its 2nd moment of inertia, and tensile /compression strength at the beam extremes.

FIGURE 1 – SANDWICH CONSTRUCTION: DESIGN LOADS



(1) Gurit Technical Paper – "Guide to Composites"

The use of sandwich construction in composites allows for placement of the high modulus, high strength materials at the cross section extremes, where tension and compression forces are greatest. The material 'sandwiched' in between the reinforcement is usually lightweight, with high shear properties, as shear stresses are highest at a beams neutral axis.

b. Carbon Fibre Benefits

i. Stiffness

The most noticeable gain when using carbon fibre is the stiffness of the material, with Carbon's modulus over 3.0 times that of E – Glass and 1.6 times that of a typical marine grade steel. The technical advantages of this property are more prevalent in structures where deformation affects vessel performance (Sailing rigging, propulsion shafting etc), however low deck deflection is an important aesthetics criterion for larger luxury yachts, and carbon provides the stiffness to minimise these deflections.

ii. Ultimate Strength

Secondary to the high modulus value is carbon's tensile strength, where the ultimate strength of carbon is 1.8 that of its E – Glass rival. This higher ultimate strength is significantly beneficial given that when the designer has reduced the thickness of a sandwich plate by replacing E – Glass with carbon, the bending stress extremes will be greater for the thinner equivalent modulus carbon sandwich. The higher allowable stresses negate the reduction in laminate thickness.

c. Carbon Fibre Setbacks

Carbon fibre is not however, without its setbacks, both with regards to the mechanical properties and material costs. These disadvantages must be considered when investigating the feasibility of using carbon fibre in motor yacht structures.

i. Catastrophic Failure, Impact Strength

The stiffness of carbon fibre can also present a safety risk, with minimal strain to failure making it difficult to detect damage from excessive loading before the laminate reaches its ultimate failure loading. Laminate fatigue in the form of transverse micro-cracking (Separation of resin and mis-aligned fibres) can occur unseen within internal layers of the laminate, with no external sign of damage.

As such carbon fibre is usually implemented in structural design with fibre materials that are more impact resistant (Eg. Aramid) where strain under such impact loads is possible without such a high risk of catastrophic failure.

The high stiffness also allows the designer to reduce the thickness of the structure plate (Or reinforcement skins in Sandwich construction). With skin thicknesses as low as 0.3mm any impact damage may cause instant failure across the full laminate section. It should be noted that impact loading risks are more relevant to hull constructions, and so is not as significant a factor in superstructure construction.

ii. Cost

The complex process of manufacturing the raw carbon fibres involves a long and harsh chemical process. Usually carbon chains are created through polymerisation, oxidation and carbonisation stepped processes, where all stages involve chemical reactions requiring high temperatures and strictly controlled atmospheric conditions. When compared to the E-Glass production, which involves only a high temperature melt and controlled extrusion process, the complexity of the carbon process makes it a more costly reinforcement option (Guide to Composites, Gurit, 2003).

To counter the higher raw material cost of carbon the designer must place the higher performance reinforcement effectively in the structure to affect its full potential. Areas of high tension are typical priorities for carbon fibre placement. To ensure correct placement of the higher performance material, a more complex and costly structural analysis must be conducted to correctly identify regions requiring carbon.

iii. Equivalent Resin Strength

Under tension loading, composite materials fibre reinforcements will carry the vast majority of the load through the structure, which in the case of carbon shows a dramatic improvement in the tensile properties of cured laminates. However, under compression the risk of fibres buckling in a variety of modes is mitigated by the ability of the resin to maintain fibre orientation through its stiffness and fibre adhesion.

As loadings on vessels are predominately cyclical in nature structures must have capability to withstand both tension and compression. Therefore where carbon fibre brings advantages to tension loads there must also be equivalent resin properties to withstand equal but opposite compression loadings.

Implementation of carbon fibre currently requires costly high performance resins (typically epoxies) to meet this demand. Chemically, carbon fibres are less compatible with vinyl ester and other non – epoxy resins during the curing process due to the absence of functional groups on the surface of the carbon capable of working through a subtraction reaction. Where non-epoxy resins polymerise through subtraction condensation reactions (H_2O lost in polymerisation), epoxies bond through addition reactions, which is compatible with functional groups present on the carbon surface.

Research is currently underway into nano material infusion of resins to further improve the cured compression properties – See chapter on future production techniques.

3. Current Use of Carbon in Motor Yachts

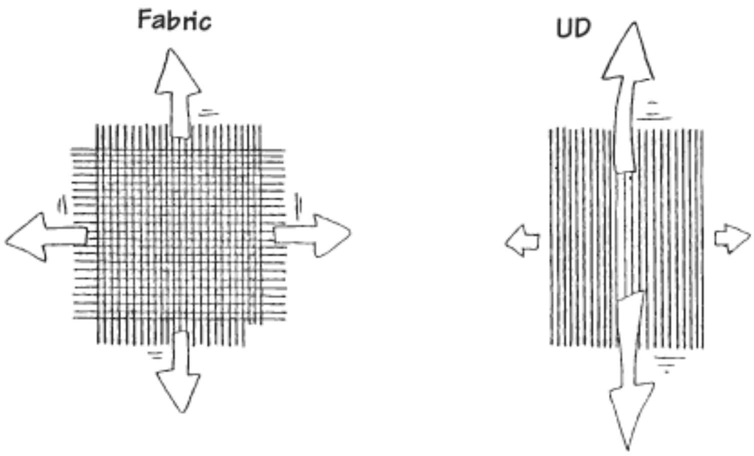
The following section details findings on the current use of carbon in motor yacht structures, following the material through from the supplier to the cured laminate manufactured on the shipyard site.

a. Typical Carbon Use

i. Materials Supplied to Yard

Carbon fibre when used in motor yacht construction as a composite material typically arrives at the shipyard in the form of various fabrics, either with or without pre-impregnated resin. The orientation of the fibres in these fabrics determines the stiffness and strength of the final laminate layer and are typically laid up in such a way such that the primary strength direction of the fabric is orientated to match the primary design loadings expected. This is a key advantage of using composites generally, and is particularly significant for carbon fibres given the increased material properties and associated higher cost.

FIGURE 2 – FABRIC OR UNIDIRECTIONAL LOADCASES

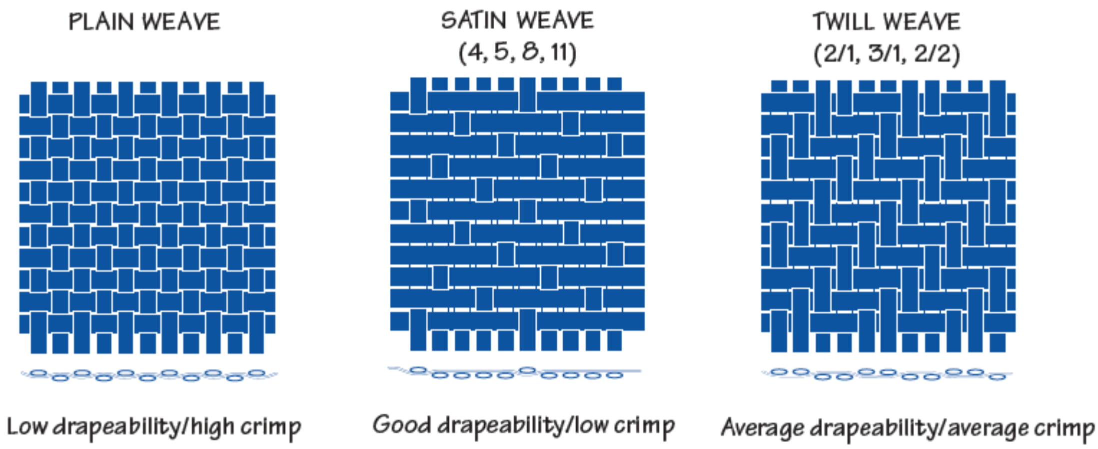


(1) Hexcel Composites Prepreg Brochure

Within the fabric group there are further options available to the designer based on variation and complexity in the stitching technique. Taking much of the lead from the textile industry, a variety stitching techniques alter a fabrics drapeability (ability to place fabric over curved surfaces) and crimp (orientation of the fibres as they pass over / under cross-stitching yarn. Ultimately marine structure require fabrics with high drapeability and low crimp – high drapeability for ease of fitting to the curvature of frequently complex structural shapes and low crimp to ensure fibres are orientated as straight as possible prior to loading and to provide a smoother surface finish.

In general, the fabric styles available vary around the number of warp / weft fibre passes before a stitching pattern is repeated. A greater number of fibre strands passed over before a weave allows the fibre to be straighter (lower crimp) and frees up the fibres to deform as required to match the surface of the mould (high drapeability).

FIGURE 3 – BI-DIRECTIONAL FABRIC STYLES AVAILABLE



(1) Hexcel Composites Prepreg Brochure

As always with composites, each fabric style has advantages and disadvantages and it is important to strike the balance required by the design. Satin, for example, has high drapeability and low crimp but has an inbuilt asymmetry between the top and bottom faces of the fabric. Whereas the top fabric face will have fibres predominately in warp the underside of the fabric will have predominately weft fibres. When creating a multiple satin fabric layups, care must be taken to ensure this imbalance does not result in additional interlaminar shear stresses between the layers by matching fibre orientations face to face (warp face to warp face and vice versa).

Where a more local, unidirectional amount of fibres are required, the reinforcement can also be supplied in tape form. Fibre tapes allow for strong, straight, continuous reinforcement and are usually applied along deck and hull stiffeners, where the load is primarily in a single direction. The tape fibres also have less cross – reinforcement, and so do not suffer crimp issues as they pass over /under cross-stitching.

TABLE 2 – FABRIC PROPERTIES

Material	E – Glass		High Strength Carbon	
Fabric Type	Woven	Unidirectional	Woven	Unidirectional
0º Tensile Modulus (GPa)	20	43	70	130
0º Tensile Strength (MPa)	600	1,100	800	2,000
90º Tensile Modulus (GPa)	19	8	65	9
90º Tensile Strength (MPa)	550	35	750	80
0º Compressive Modulus (GPa)	17	42	60	115
0º Compressive Strength (MPa)	550	900	700	1,300
90º Compressive Modulus (GPa)	16	10	55	10
90º Compressive Strength (MPa)	500	150	650	250
In-Plane Shear Modulus (GPa)	4.2	4.0	5.5	4.4
In-Plane Shear Strength (MPa)	55	60	80	95
0º Interlaminar Shear Strength (MPa)	50	75	70	80

(1) Hexcel Prepreg Technology, Epoxy resin cured laminate properties

As mentioned previously in the section on carbon fibre setbacks, a final laminate is only as strong as its weakest component. Comparing the 90º tensile strengths for the unidirectional fabric in Carbon and E – Glass failure occurs at almost an identical stress level, and both unidirectional fibres have near equal 90º modulii. As such the above unidirectional laminates only gain significant tensional properties from the move to carbon. To create a more all-rounded set of mechanical properties, the resin must have greater cured properties to prevent failure against the laminate orientation.

As a result of the almost infinite possibilities provided by varying the reinforcement setup there are an equally infinite number of options available to the structural designer. The structure can be optimised to uniquely reflect the position of specific loadings on the deck structure, minimising excess structure that results in reduced superstructure weight and material costs. The relative laminate weakness in compression can to an extent be mitigated by correct material placement.

ii. Standard Production Setups

Pressurised curing techniques such as vacuum bagging or resin infusion improve the fibre volume fraction (FVF) of the final laminate above that of an open mould processes, such as those mentioned above, and so provides an improvement in the cured laminate performance. Since the required production quantities decrease as the yacht (and therefore mould) length increases, there is minimal demand for a production process that is faster than individually vacuum bagging each setup as required.

Usually makeshift ovens are constructed around the larger moulds to encourage the formation of the linking bonds required to solidify the matrix. These ovens are typically not capable of temperatures beyond 70ºC and so the resin choice is restricted to those with lower curing temperatures.

The lower curing temperatures increases the required curing time and reduces the final strength and stiffness of the laminate, as the lower temperature reduces the number of cross – links between polymer chains chemically created that provide the cured resin with the ability to transfer forces between the polymer chains at the molecular level.

iii. Bigger is Better

The common use of carbon composites in standard motor yacht design is currently reserved for larger, custom new builds. Greater longitudinal loads, reduced budget constraints and a desire for weight reduction of the ships structure result in shipyards 'upgrading' from the cheaper glass fibres to carbon. Most of these constructions are single builds and thus allow for a greater scope of design work to be conducted optimising the superstructure for each unique case and material choice.

Some major yards are however beginning to use carbon in the more mainstream class production yachts, initially in superstructures where the reduction in weight benefits both powering and stability of the motor yacht. Both Sunseeker and Azimut Benetti yachts have begun including carbon fibre across their range of class vessels with the primary objective of reducing topside weight. A secondary objective to this improvement in stability is the aesthetics of carbon fabric when used with a transparent gelcoat.

b. Specific Customer Requirements

Carbon can also be selected as the main reinforcement material based on a specific customer requirement, which forces the designer to select the stiffer, more expensive material. Two such examples of specific requirements are mentioned below with respect to the motor yacht case studies.

i. Lightweight Requirement (Ermis^2)

FIGURE 4 – 38M LENGTH ERMIS^2 CAN ACHIEVE 55 KNOTS

(1) Humphreys Yacht Design

The 38m Ermis^2 yacht makes prominent use of carbon fibre in order to reduce overall structural weight. The requirement from the owner for a maximum speed in excess of 55 knots meant that all weights were kept to a minimum. Carbon and Aramid were the predominant fibre reinforcement choices for the yacht, combining the stiffness of carbon with the impact toughness of the Aramid fibres. The result was a lightweight hull and superstructure that lowered resistance at high speed.

ii. Stiffness Requirement (Laurel)

The higher modulus of carbon results in a stiffer structure when compared to the geometric equal in E – Glass. The added stiffness and strength allows for the possibility of smaller beam depths, reducing the space required between decks for structure.

The 73m superyacht Laurel makes significant use of carbon fibre in its superstructure, with key superstructure beams incorporating unidirectional carbon fibre tape. A requirement from the owner for a low profile yacht meant service space between decks was minimised, and the high mechanical properties of carbon allowed for smaller beam depths, reducing the overall height of each superstructure deck.

FIGURE 5 – 73M LENGTH LAUREL'S LOW SUPERSTRUCTURE PROFILE

(1) Photo by Benoit Donne

c. Material Supplier, Designer Collaboration

In almost all cases of composite uses in motor yacht design there has been significant collaboration between the material suppliers and the manufacturing shipyard, to ensure that the supplied raw materials are used in a manufacturing process that harnesses the full potential of the raw material ("Collaborating on Composite Craft", Reinforced Plastics, 2012). The higher cost of carbon over glass and the subsequent desire to minimise use of reinforcement makes this increased co-operation beneficial to the designer.

This supplier / manufacturer relation becomes more and more critical as the materials used become high performance. Where a yard chooses carbon fibre reinforcement the material suppliers will almost inevitably conduct a full review of the yards' manufacturing process, and provide advice and technical processes to create a final yacht structure with mechanical properties matching design expectations.

Classification societies will, on similar lines review not only a yachts structural design but also require certification of the yards manufacturing facilities and technique, in an effort to ensure the cured laminates perform as expected.

4. Mechanical Properties Comparison

The most obvious advantages for using Carbon Fibre arise from the improved mechanical properties present when compared to metals and more conventional composite materials. E – Glass, as the primary reinforcement currently used in composite motor yacht construction, provides adequate mechanical properties whilst costing significantly less than in its carbon counterpart.

A comparison based on these mechanical properties was part of the initial investigations for the design of the carbon fibre superstructure conducted with the assistance of the Azimut Benetti group.

a. Simple Beam Theory Investigation

A simple beam theory comparison was conducted in an attempt to quantify the advantages that carbon fibre provides to the design and production of superstructures as a result of the reinforcements improved mechanical properties.

Modelling a composite sandwich beam under a centralised uniform pressure load using simple beam theory calculations completed in Excel allowed for an investigation into the material properties effect on structural performance. Three avenues of investigation were conducted to examine and quantify the strength and weaknesses of a full carbon versus a full E – Glass reinforcement layup. Layups were designed as symmetrical skin – core – skin sandwiches with core thicknesses and beam length arbitrarily chosen for the purpose of the scenario.

A model beam with fixed width of 500mm was loaded with a 250kg mass distributed over a 400mm x 400mm square centred in the middle of the beam. This load was converted to its equivalent distributed line load in order to proceed with simply supported beam calculations. This loading scenario is similar to one used by Azimut yachts to certify deck deflections for aesthetic purposes.

i. Equivalent Stiffness

Panel deflection, as a measurement of panel stiffness, was singled out as a method to compare the possibilities when using carbon fibre compared to the more commonly used E – Glass fibres. Varying both the beam length and core thickness it was possible to observe the varying behaviour of the beams deflection for the two reinforcement materials.

The table below summaries the various layup scenarios and variables examined in an effort to analyse the strongest benefits of a carbon fibre layup in regards to minimising panel deflection. In general it was found that a for a fixed core thickness a 3 – Core – 3 layup with Carbon fibre had similar stiffness to a 6 – Core – 6 layup using E – Glass. Requiring half the laminate layers for equivalent stiffness is a significant saving to manufacturing time, with a resulting link to material cost savings. (See FEA analysis section for a more complete manufacturing cost comparison).

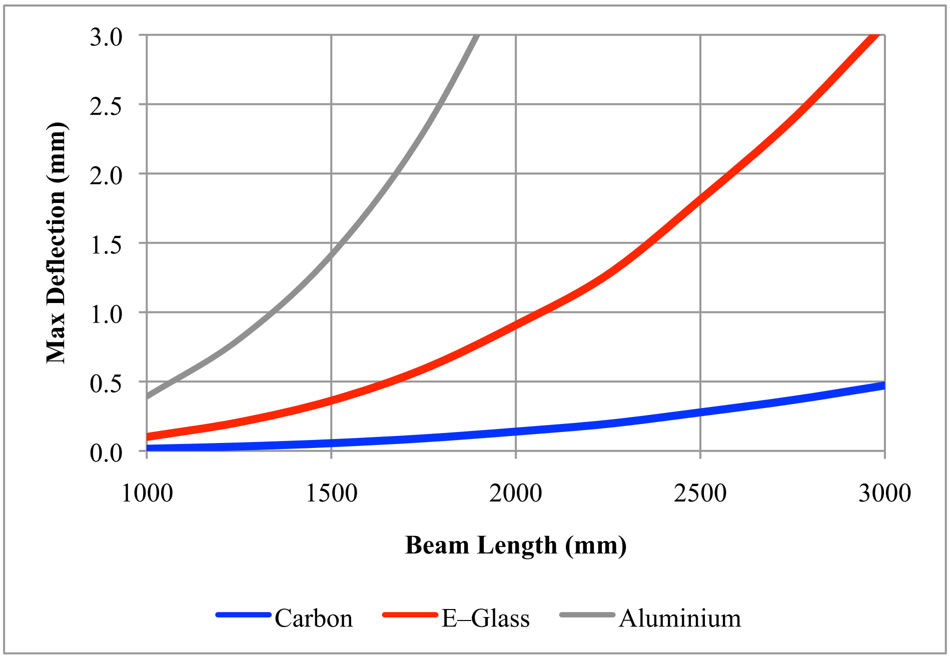
TABLE 3 – PANEL DEFLECTION RESULTS – 50mm CORE THICKNESS

Beam Scenario[1]	Variable Investigated	Carbon	E – Glass
• 500 x 1250 Beam • 50mm Core	Max Deflection (mm)	0.031	0.034
	Bending Stress (MPa)	143	72
• 500 x 2500 Beam • 50mm Core	Max Deflection (mm)	0.273	0.296
	Bending Stress (MPa)	313	158
• 500 x 5000 Beam • 50mm Core	Max Deflection (mm)	2.278	2.476
	Bending Stress (MPa)	654	329
• All Beams	Layup Thickness (mm)	51.28	52.65
	Layup Weight (g/m^2)	1,167	3,303

(1) Carbon 3-Core-3 layup vs. E-Glass 6-Core-6 Sandwich layup

(2) Cured Lamina properties for Gurit Epoxy Prepregs with Bi–Directional fabrics

FIGURE 6 –BEAM DEFLECTIONS FOR VARYING MATERIALS



(1) Both Carbon and E–Glass Sandwich Panels are 6-Core-6 for the purpose of this graph

(2) 30mm Thick Marine Grade Aluminium 5083-H321 beam included for comparison

The above tables show how the increased modulus of carbon laminates allow for a reduction in the number of layers required for an equivalent stiffness and therefore the total weight of the laminate. But as shown in the table on the following page, the reduction in the number of reinforcement layers gives rise to greater stresses carried by each of the carbon reinforcement layers.

Although deflections are similar between the two materials the higher modulus of carbon results in greater stresses, ultimately leading to the carbon layup reaching its tension limit (or class society maximum allowable) first. As such these high stresses place a limit on the geometric reductions available when replacing E – Glass with carbon fibre.

TABLE 4 – PANEL DEFLECTION RESULTS – 35mm CORE THICKNESS

Beam Scenario[1]	Variable Investigated	Carbon	E – Glass
• 500 x 1250 Beam • 35mm Core	Max Deflection (mm)	0.063	0.068
	Bending Stress (MPa)	204	103
• 500 x 2500 Beam • 35mm Core	Max Deflection (mm)	0.554	0.601
	Bending Stress (MPa)	448	225
• 500 x 5000 Beam • 35mm Core	Max Deflection (mm)	4.634	5.020
	Bending Stress (MPa)	**934**[2]	470

(1) Carbon 3-Core-3 layup vs. E-Glass 6-Core-6 Sandwich layup with prepregs

(2) Bending Stress in bold is above ultimate tension stress of cured carbon laminate

The sandwich structures and core thicknesses chosen for the above analysis under the load specified gave shear stresses resulting from the maximum shear force of the order of 0.1 MPa or below. The shear strength of the chosen core material is of an order of 10 greater than this, and so shear in these cases was not a cause for concern. The bending stiffness of the sandwich core was considered negligible compared to the skins and therefore neglected for the bending beam calculations.

On the basis of simple beam theory any variation in shear stress is a result of variation in the cross section geometry and so not effected by the choice of reinforcement material.

The reduction in layup size as a result of using carbon reduces the volume of raw materials required to complete the superstructure, however the raw material cost of carbon is higher than its rival E – Glass, which must be offset by the reduction in reinforcement material used.

TABLE 5 – PANEL LAYUP MATERIAL COSTINGS

Beam Scenario	Variable Investigated	Carbon	E – Glass	% Difference
• 1585 x 1840 Panel[2] • 8mm Core Thickness • Max Deflection Target = 1.273mm [1.215, 1.273][1]	Total Number of Layers in Laminate	6	12	100
	Bending Stress (MPa)	426 SF = 1.7	214 SF = 2.5	-50
	Layup Weight (g/m^2)	1,165	3,301	183
	2003 Reinforcement Costing[3] (€)	128	28	- 78
	2013 Reinforcement Costing[4] (€)	216	288	33

(1) Actual deflection values are included in [] for Carbon and E – Glass results respectively

(2) Panel size is typical maximum in Azimut E – Glass superstructure designs

(3) 2003 Gurit material costs per m^2 £18 for Carbon and £2 for E – Glass (Converted to €)

(4) 2013 Azimut supplier material costs per m^2 taken as €36 for Carbon and €26 for E – Glass

Historically, carbon reinforcement has been unable to provide equivalent stiffness at an equal or reduced cost. However the greater use of carbon as reinforcement in aerospace and automotive products has increased the volume of carbon fibre available to the marine market. This combined with improved manufacturing process costs has driven down total costs, resulting in carbon now being competitive.

The above comparison therefore shows that carbon reinforcement can provide an equal stiffness for a 33% reduction in cost. The high technical complexity of using carbon fibre combined with the variability of pricing seen in the marketplace makes this not always achievable.

ii. Core Thickness

The same beam model was then used to analyse the effect of varying the core thickness on the laminate. Maintaining the same 6-Core-6 layup for both Carbon and E – Glass reinforcement prepregs, an analysis was conducted into the core thicknesses effect on the beam deflection. The beam length was then increased to determine if the length amplified deflection variations between reinforcement scenarios.

All beams were calculated with a 500mm width and loaded with the same 250kg square area loading as used previously.

TABLE 6 –DEFLECTIONS, 1,500mm BEAM LENGTH

Beam Length (mm)	Core Thickness (mm)	Max Deflection (mm)	
		Carbon	E – Glass
1,500	2.5	8.3475	-[1]
	5.0	2.3852	5.2237
	7.5	1.1100	2.4304
	10.0	0.6391	1.3991
	15.0	0.2908	0.6365
	20.0	0.1655	0.3623
	25.0	0.1067	0.2335
	50.0	0.0271	0.0592
	100.0	0.0068	0.0149

(1) Value not required for comparison

TABLE 7 –DEFLECTIONS, 3,000mm BEAM LENGTH

Beam Length (mm)	Core Thickness (mm)	Max Deflection (mm)	
		Carbon	E – Glass
3,000	10.0	5.4258	11.8782
	15.0	2.4688	5.4039
	20.0	1.4052	3.0756
	25.0	0.9058	1.9824
	35.0	0.4659	1.0196
	50.0	0.2297	0.5027
	100.0	0.0578	0.1266

TABLE 8 –DEFLECTIONS, 4,500mm BEAM LENGTH

Beam Length (mm)	Core Thickness (mm)	Max Deflection (mm)	
		Carbon	E – Glass
4,500	15.0	8.4736	-[1]
	20.0	4.8230	10.5563
	25.0	3.1088	6.8040
	30.0	2.1692	4.7474
	35.0	1.5991	3.4997
	40.0	1.2274	2.6862
	50.0	0.7884	1.7253
	60.0	0.5488	1.2010
	75.0	0.3521	0.7705
	100.0	0.1985	0.4344

(1) Value not required for comparison

TABLE 9 – DEFLECTIONS, 6,000mm BEAM LENGTH

Beam Length (mm)	Core Thickness (mm)	Max Deflection (mm)	
		Carbon	E – Glass
6,000	30.0	5.3304	11.6661
	35.0	3.9296	8.6000
	40.0	3.0163	6.6011
	50.0	1.9373	4.2397
	60.0	1.3486	2.9513
	75.0	0.8652	1.8933
	90.0	0.6018	1.3169
	105.0	0.4426	0.9686

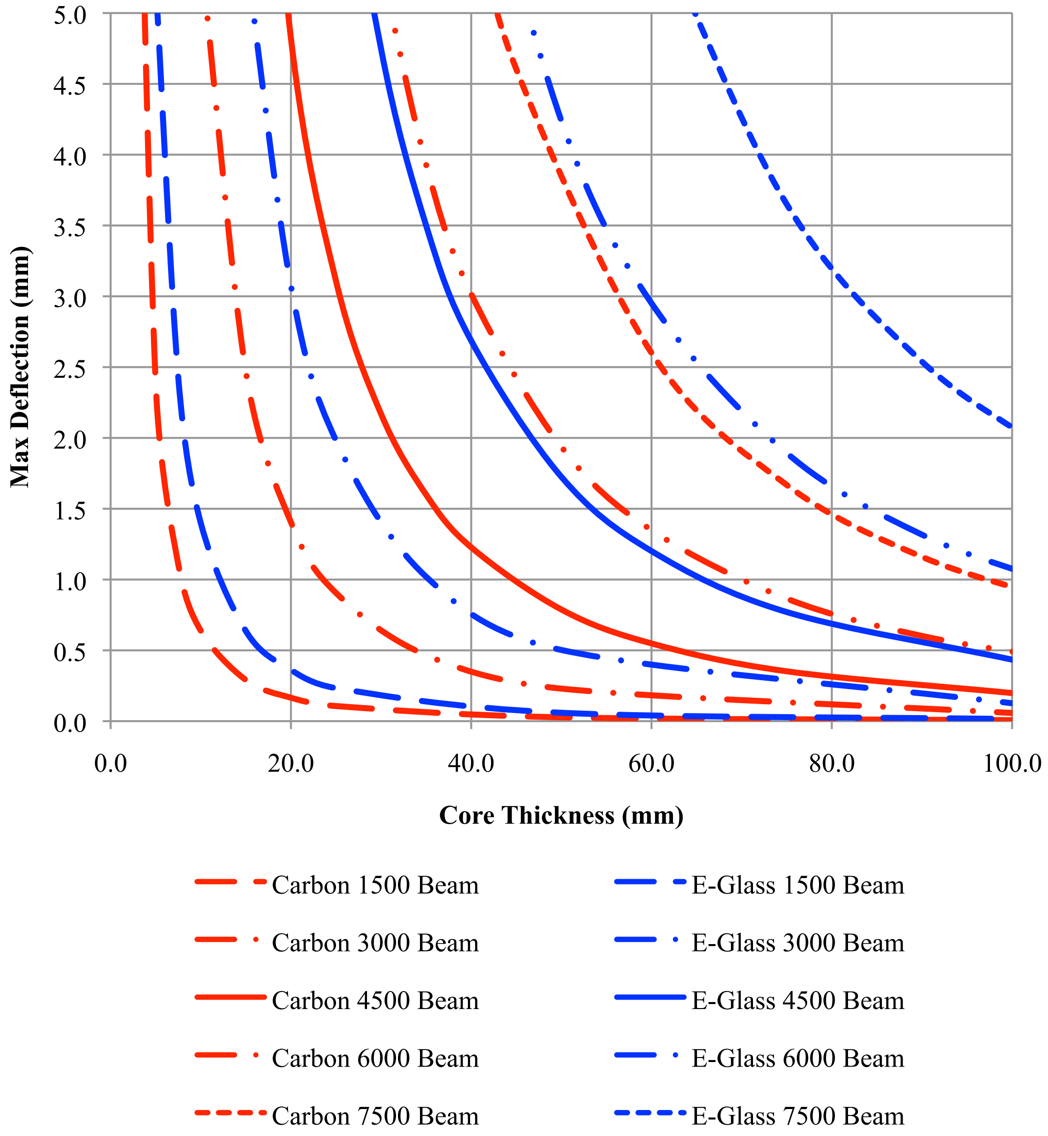
TABLE 10 – DEFLECTIONS, 7,500mm BEAM LENGTH

Beam Length (mm)	Core Thickness (mm)	Max Deflection (mm)	
		Carbon	E – Glass
7,500	40.0	5.8153	-[1]
	45.0	4.6039	-[1]
	60.0	2.6000	5.6900
	75.0	1.6680	3.6502
	90.0	1.1602	2.5389
	105.0	0.8533	1.8674

(1) Value not required for comparison

The results are best represented in graph form, with similar line styles representing equal beam lengths and different material by alternate colours.

FIGURE 7 – MAX DEFLECTION FOR ALTERNATE CORE THICKNESS



The chart above displays the curvature of the maximum deflection as the core thickness is varied. In both directions all the curves are moving towards asymptotes. Where the core decreases, the deflection increases as the beam stiffness decreases and vice versa. This corresponds to what is expected under beam theory.

The graph also shows that the variation in material becomes more and more prominent as the beam length increases. Comparing the gap between the deflection curves at 1,500mm and at the extreme 7,500mm the deflection variation between the Carbon and E – Glass beams it can been seen that the effects of carbon on beam stiffness results in a significant difference in beam performance. These higher core thicknesses are not practical for plate thicknesses, but are however more appropriate for deck stiffeners, where extra core materials will push the total core to thicknesses between 40 and 150mm.

The lower deflections when using carbon for long beams allows the designer to increase the distance between frames / stiffeners. Where the higher stiffness is matched by the higher the yield strength of the carbon laminates the stiffener spacing can be increased. The reduction in the number of frames would result in a lighter and cheaper superstructure, showing carbon as a more cost effective solution for the build. The following table compares directly the core thickness for 6 – Core – 6 layups with either material. The higher modulus of carbon allows for approximately half the core thickness to provide equivalent stiffness to the beam. Percentage differences between the two material beams remains constant for varying beam length.

TABLE 11 – VARYING CORE THICKNESS, EQUAL DEFLECTIONS

Beam Scenario	Variable Investigated	Carbon[1]	E – Glass[1]	% Difference
• 500 x 1250 Beam	Max Deflection (mm)	0.1330		0
	Core Thickness (mm)	16.8	25.0	48.97
	Max Stress (MPa)	213	144	-32.17
• 500 x 1250 Beam	Max Deflection (mm)	0.0151		0
	Core Thickness (mm)	50.6	75.0	48.27
	Max Stress (MPa)	71	48	-32.12
• 500 x 1500 Beam	Max Deflection (mm)	0.0264		0
	Core Thickness (mm)	50.6	75.0	48.27
	Max Stress (MPa)	86	58	-32.12

(1) Layups are 6-Core-6 for both materials

The results show that carbon provides an equivalent stiffness with a core thickness near half that of a similar E – Glass layup. As per the case study of the superyacht *Laurel* previously mentioned, using carbon fibre as the reinforcement allows for a reduction in the sandwich core required, and a subsequent reduction in the between deck space required for structural beams sections.

iii. Fabric Variation

Although not a direct result of the beam theory investigations, it emerged that two suppliers providing similar fabrics could provide final sandwich laminates with notably different properties. Mechanical properties for prepreg layups of roughly equal areal weight (equal amount of reinforcement) from two major international suppliers were compared and the following variation in mechanical properties noted.

TABLE 12 – EFFECT OF SUPPLIER ON CURED PROPERTIES

Material Property		Hexcel[1]	SGL Group[2]	% Difference
Areal (Fabric Area) Weight	g / m^2	600	673	12.2
Tensile Modulus	GPa	65	54	-16.9
Tensile Strength	MPa	900	810	-10.0
Tensile Fibre Volume Fraction	-	0.60	0.50	-16.7
Cured Ply Thickness	mm	0.575	0.460	-20.0

(1) Hexcel M34 Epoxy with High Strength Carbon Bi–Directional Fabric

(2) SGL SR8100 Epoxy with four layer HPT 410 Bi-Directional Stitched Fabric ±45º, similar total areal weight to Hexcel fabric (Vacuum Infusion 0.7bar and 16hr cure at 60ºC)

The two reinforcement fabrics differ in that the Hexcel fabric is a single layer bi-directional weave; where the SGL fabric is a stitched four bi-directional layer fabric, with a similar total areal weight. The stitched fabric from SGL reduces fibre crimp, improving drapeability for layup and fibre alignment under tensional loading.

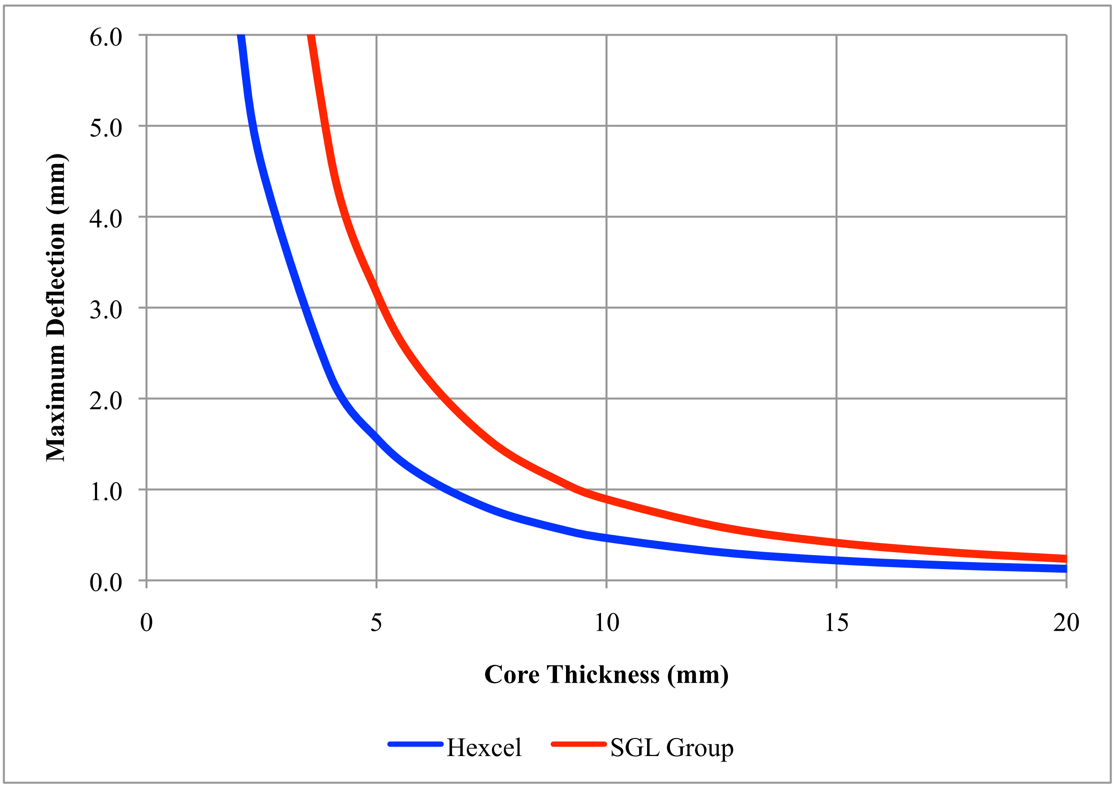
Despite having the higher areal weight and improved fibre alignment the final tensile strength of the SGL stitched fabric is less that that of the Hexcel single layer fabric. As no further information was available regarding the curing process used to provide the Hexcel properties it must be assumed that the variation in properties is the result of curing techniques.

Without knowing the complete story for either set of properties it becomes difficult to quantify the advantages gained from either manufacturer. Knowing the complete laminates story through from the fibre manufacture (surface treatment used), strand size and type (tow / yarn), fabric stitch (limitless options), wetout method and finally the chosen curing process a direct comparison between any two setups can prove extremely difficult. International testing standards for determining mechanical properties also vary in method, providing further variation in the final tabled properties. This demonstrates the reliance on the composite supplier for technical support during design development and manufacturing.

In an attempt to control the number of variables unaccounted for all E – Glass and Carbon comparisons within the simple beam theory section have been limited to epoxy prepregs and bi-directional fabrics under vacuum, curing in temperatures typical of oven setups for large moulds such as ship structures. As a result all tensile strength and modulus figures are the result of physical lab tests and not classical laminate theory. The laboratory results accounting for such variables fibre straightness and fibre matrix adhesion.

The two prepreg manufacturers chosen were then compared in a sandwich construction. The graph below plots the core thickness against the deflections that occur for a 500mm wide beam with 2,000mm length.

FIGURE 8 – MAX DEFLECTION FOR ALTERNATE FABRIC TYPES



As the core pushes the beam second inertia moment value higher, the variation in the material properties becomes less significant. It would seem therefore that minor variations in selection of manufacture are of less importance when using carbon in stiffeners where greater core thicknesses exist. As fabric type is less of a factor for higher inertia values, cost therefore becomes the main driving factor when procuring the reinforcement material.

Deflection delta between the two cases above is consistently ~80%, however in absolute value terms this delta is negligible for the larger core thicknesses, and as such material manufacturer plays minimal choice when using carbon in sandwich laminate construction, where the second moment of inertia is the predominant term in calculations.

5. Structural Design Comparison

a. Sundeck Plate + Stiffeners

Although a simple raw material cost comparison displayed an economic advantage for using carbon fibre a more in depth examination of how material strength effects design was conducted. The higher price and improved manufacturing techniques required for carbon reinforcements requires the designer to ensure its use is economically justified.

This section outlines the structural design work conducted in an effort to see how varying the reinforcement material affects the choices available to the structural designer. The investigation centred on placement of stiffeners for the sundeck of a proposed Azimut Benetti fast displacement motor yacht.

i. FEA Model Setup

Provided with a 3D computer model of the superstructure, a comparison was completed of a superstructure deck built in all carbon, then all E – Glass. Both models used prepregs with identical resin cured at around 85ºC under vacuum bagging. This resin and curing method is one standard practice used for larger motor yacht large mould construction, where the curing oven is build around the hull mould for the duration of the cure.

FIGURE 9 – AZIMUT BENETTI YACHT USED FOR STUDY

(1) Render courtesy Azimut Yachts

The decks outer edges were fixed in the three translations to mimic the existence of the supporting structure along the outer edges (Except the stairwell edges). Although this connection in practice would not be completely stiff, the objective of the model was to investigate the flow of deck loads to the edges, and the stiffeners required to support this load transfer. As such the simple edge fixed displacement was a suitable arrangement for the analysis.

The weight of each load items placed on the deck was applied as a uniform pressure over the area they covered. Where item weights could not be directly determined (Eg. in build deck furniture), an estimate was calculated based on the area footprint and geometry of the fit out object. The pressure loads applied to the deck are listed in the table below.

TABLE 13 – SUNDECK LOADING WEIGHTS

Sundeck Item	Object Weight[1] (kg)	Footprint Area (m^2)	Pressure Loading ($x10^{-3}$ N/mm^2)
Jacuzzi	1,540	3.77	4.013
Fwd L Couches	165	6.20	0.260
Dining Area Couches	165	3.91	0.415
Dining Table Mounting Points	172	0.04	47.865
Bar Area	353	3.32	1.043
Aft Sunbed	110	6.64	0.163

(1) 10% weight margin is included in loads

For this design RINA requirements for design vertical accelerations used during direct calculations were below 1.0g for the full sundeck length, which sits aft of amidships on the waterline length. As such the FEA model was conducted under standard gravity loads. It is possible that this loading is not a practical representation of the service loads, however RINA stipulates permissible laminate stresses significantly lower than the ultimate strength of the laminate, and these were later analysed to confirm acceptable levels of strength.

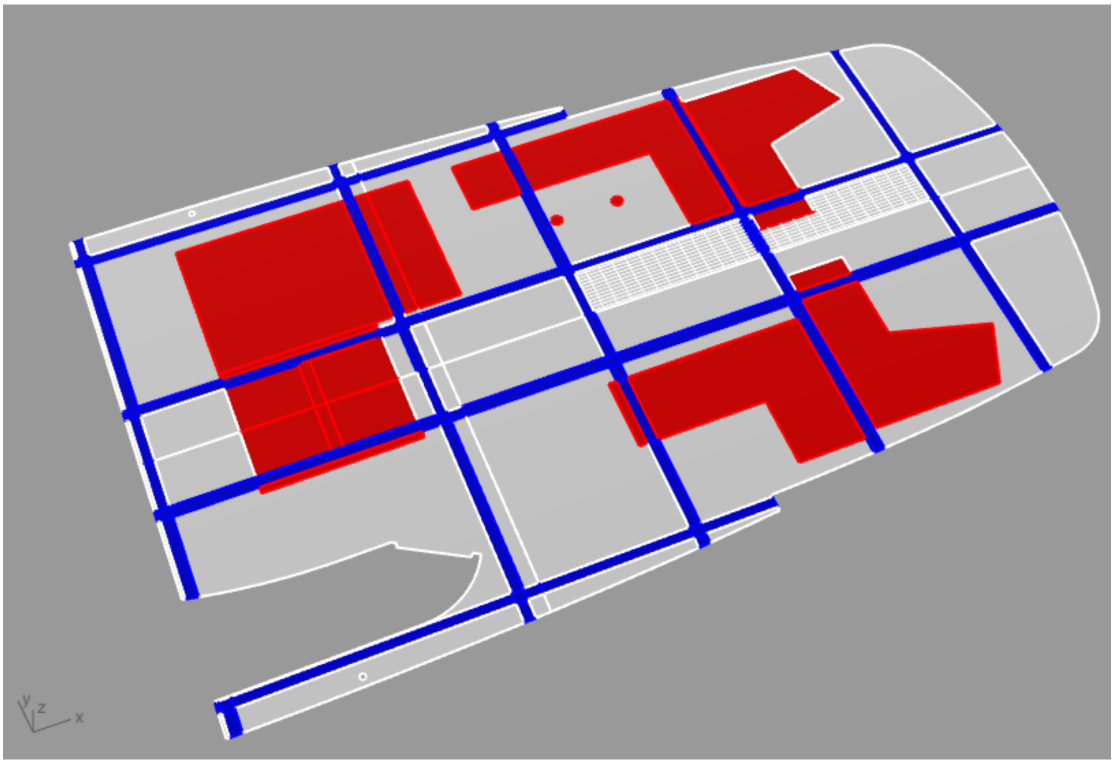
Meshing of the deck geometry was completed using Patrans Hybrid quadrilateral element meshing option with 8-point elements, allowing for curvature in the element sides. A global edge target of 50mm was observed to give results that showed mesh independence. The mesh used for the deck models consisted of approximately 31,300 elements.

TABLE 14 – MESH INDEPENDENCE TESTING

Element Shape, Type	Global Edge Length Target	Total Nodes	Total Elements	Max Deflection (mm)
Tri – 6 Points	100	32,171	15,843	369
Quad – 8 Point	100	24,402	7,992	364
	75	42,775	14,078	364
	50	94,254	31,173	369[1]

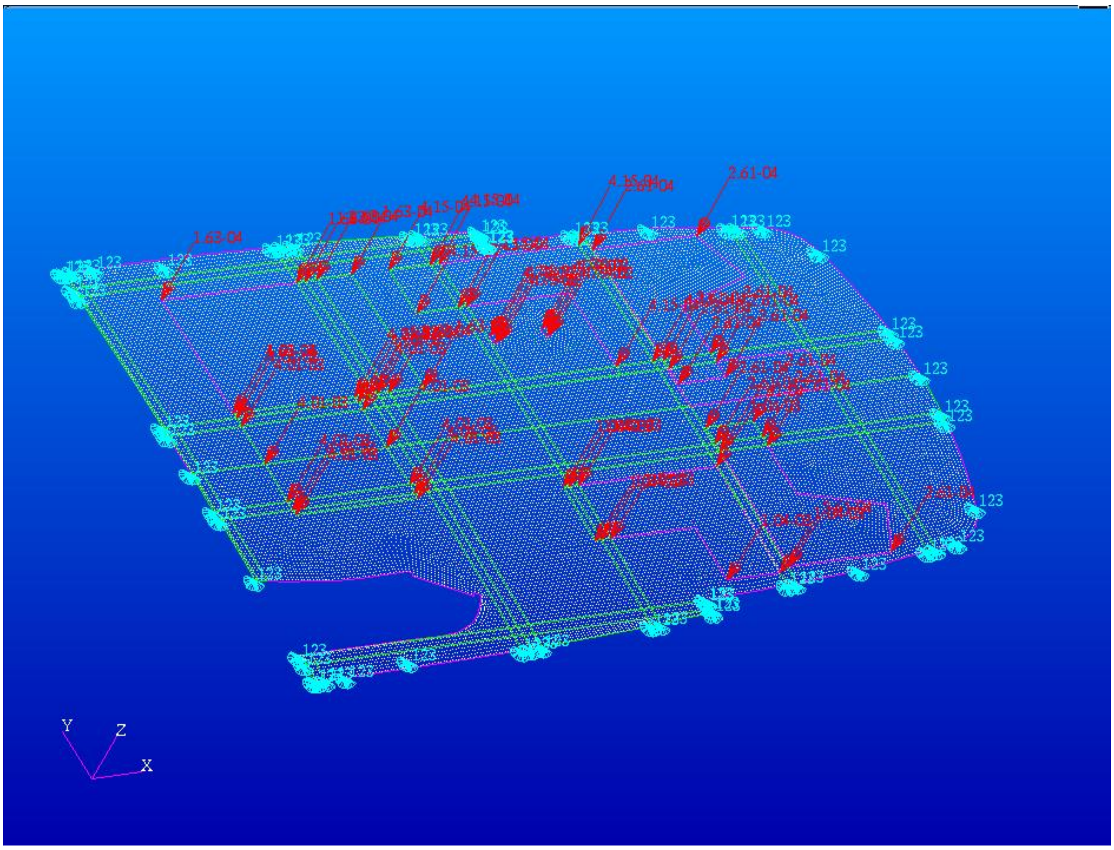
(1) Variation in Max Deflection is under 1.4 %

FIGURE 10 – STIFFNER AND PRESSURE LOAD GEOMETRY



(1) Rhino geometry for IGES export to Patran for pre-processing

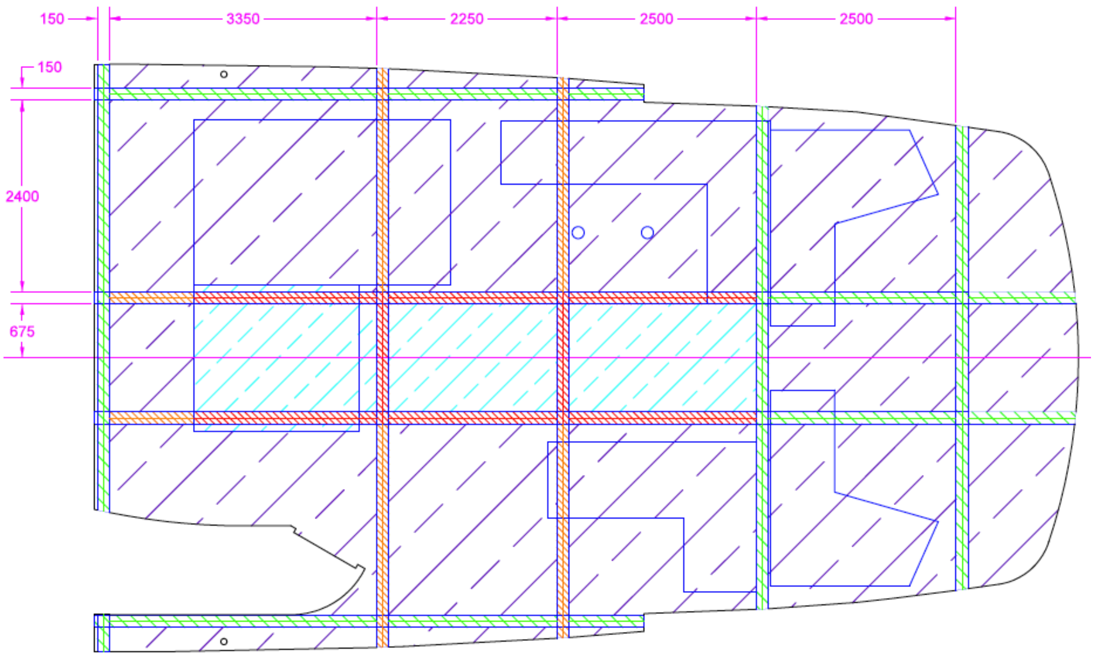
FIGURE 11 – PATRAN LOADS AND BOUNDARY CONDITIONS



ii. *Carbon Sundeck Structure*

Initial design work placed the stiffeners at standard distances forward of the aft stairwell, allowing continuous transversal frames to run across the deck to the supporting side structure. Frame were typically 150mm wide sandwich stiffener strips with all reinforcement properties taken as cured prepregs values for ease of obtaining declared mechanical properties for both 0 / 90º and unidirectional Carbon and E – Glass fabrics.

FIGURE 12 – CARBON STIFFNER LAYOUT AND PLATE LAYUP



(1) Dark Purple plate = PL_01, Green plate = PL_02

(2) Green Stiffener = ST_01, Orange = ST_02, Red = ST_03

The stiffener geometry was imposed onto the deck surface, creating the stiffener strips as separate geometric surfaces. These stiffener-linked surfaces were then given the different layup properties within Patran. This setup does not directly model the transition between the plate and the stiffeners, however the objective of the setup was to examine the effect of carbon fibre on the structural layout options available to the designer. Total length of stiffeners in the deck was roughly 68m.

TABLE 15 – CARBON SUNDECK PLATE SCHEDULES

Layer ID	Plate – PL_01		Plate – PL_02	
	Material	Orientation	Material	Orientation
01	Roving Twill 200g/m^2	0	Roving Twill 200g/m^2	0
02		45		45
03		90		90
04	20mm Core		100mm Core	
05	Roving Twill 200g/m^2	90	Roving Twill 200g/m^2	90
06		45		45
07		0		0
08			UD Tows 476g/m^2	90
09				90

(1) Gurit SE84 LV Prepreg Epoxy Resin

The second plate layup was required specifically to support the water filled Jacuzzi on the aft sundeck. It should be noted that as this load was defined as a uniform pressure loading across the footprint of the Jacuzzi supplying additional stiffness as a uniform thick sandwich plate corresponded to an acceptable design solution. In practical terms the support points may be different to this, and the stiffener design would have to be altered accordingly.

The addition of the two UD fabrics supplied additional transversal support to the plate under and forward of the Jacuzzi, where deformations were found to be the greatest. The additional two layers give transverse stiffness to the plate reducing deflections between the two central longitudinal stiffeners that result from the Jacuzzi load.

TABLE 16 – CARBON SUNDECK STIFFENER SCHEDULES

ID	Stiffener – ST_01		Stiffener – ST_02		Stiffener – ST_03	
	Material	Orientation	Material	Orientation	Material	Orientation
PL	20mm Core Plate				100mm Core Plate	
S_01	100mm Core		160mm Core		80mm Core	
S_02	UD Tows 476g/m^2 (10 Total)	0º	UD Tows 476g/m^2 (10 Total)	0º	UD Tows 476g/m^2 (10 Total)	0º
:						
S_11						

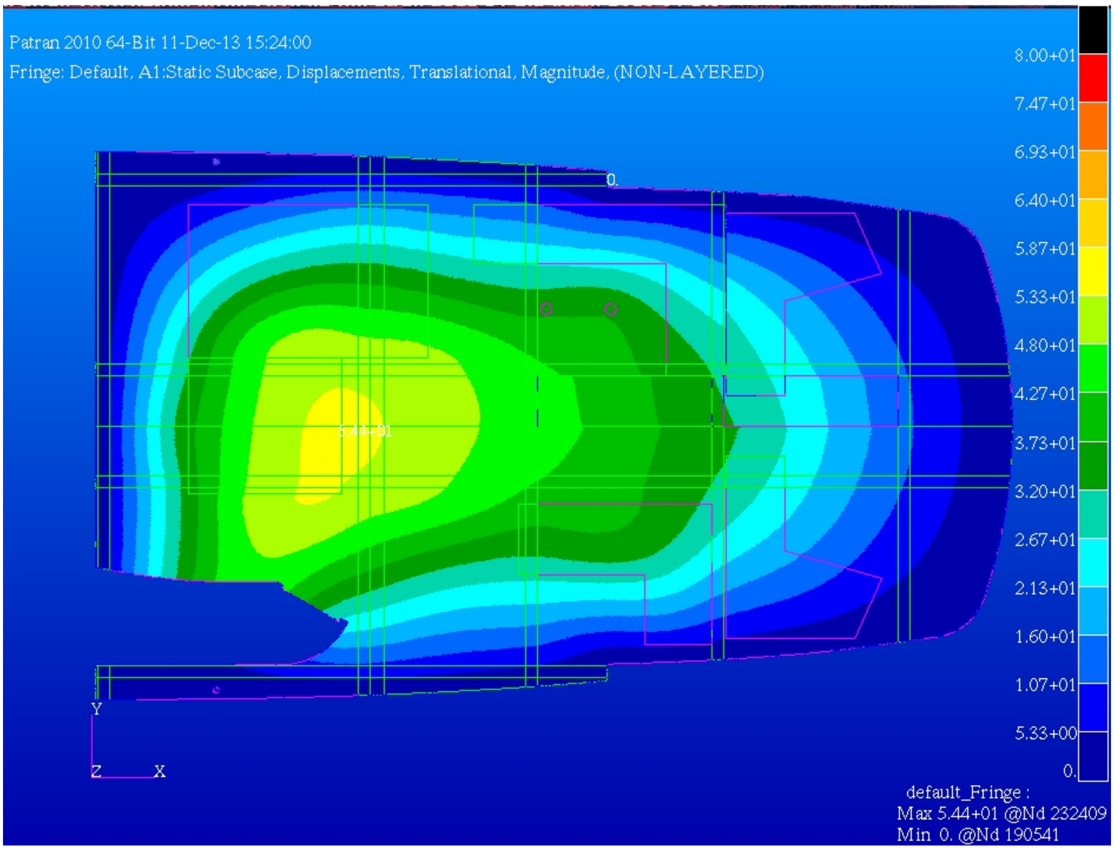
(1) Gurit SE84 LV Prepreg Epoxy Resin

The unidirectional orientations are relative to the layups primary axis, and as such when applied to the Patran geometry, the local material orientation for each transversal or longitudinal was orientated by global vectors to match the stiffener type (Eg. Transverse frame material vector = <0,1,0>).

Under static 1.0g loading from all the major weights on the sundeck the deflection results were compared with Azimut criteria and the stresses against the allowables imposed by RINA class. A maximum deflection of 54mm occurs on the centreline immediately forward of the Jacuzzi with maximum stress shown in the model as 117 MPa, where the RINA allowable stress for deck structure must be below 0.4 σ_{Yield} for the laminate.

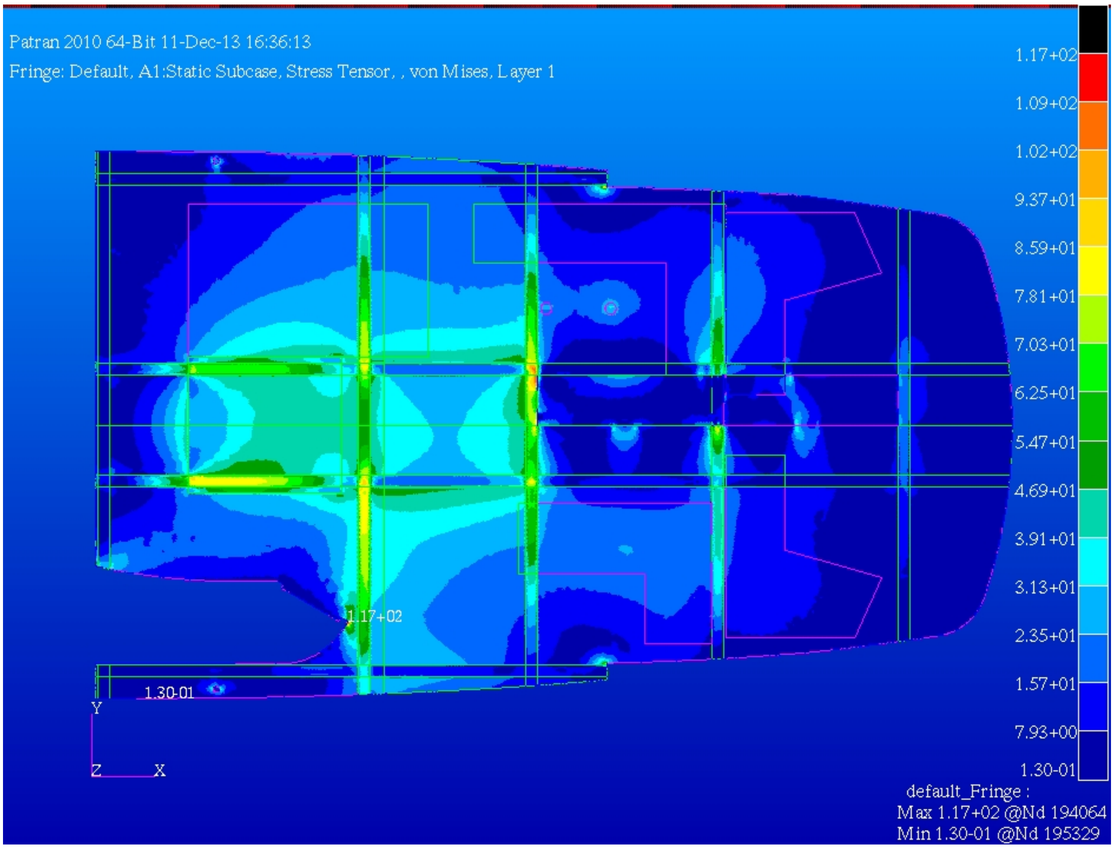
The RINA maximum allowable stress for the prepreg chosen is 304 MPa. The Azimut Benetti panel deflection requirements allows for a maximum 3mm deflection under the loading condition specified by the criteria, where the actual plate layup deflects 1.5mm under the Azimut Benetti specified load.

FIGURE 13 – ABSOLUTE DEFLECTIONS: CARBON FIBRE DECK



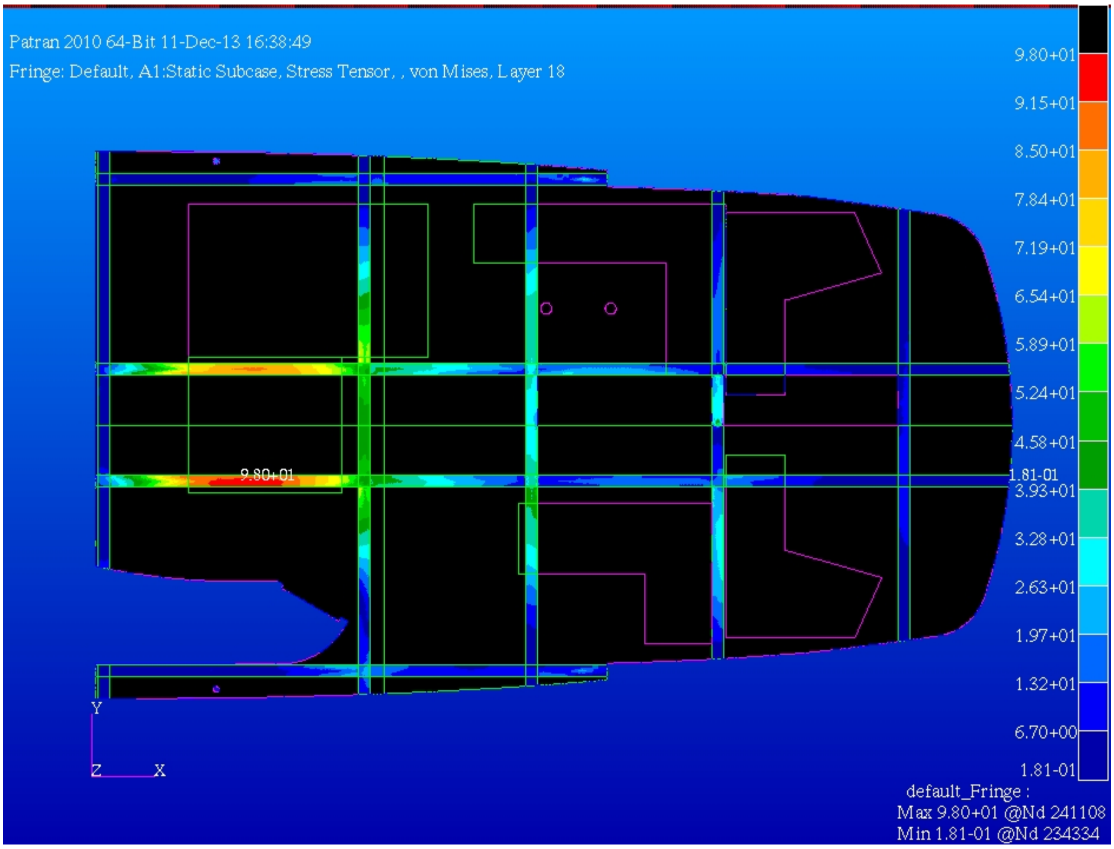
(1) Maximum deflection under load = 54.4mm

FIGURE 14 – VM STRESS DECK LAYER: CARBON FIBRE DECK



(1) Maximum stress = 117 MPa is a mesh geometry extreme (Stairwell corner), stress distribution remains indicative of that expected

FIGURE 15 – VM STRESS STIFFENER EXTREME: CARBON FIBRE DECK



(1) Maximum stress = 98 MPa is a maximum bending value

These results for an all carbon sundeck structure formed the basis for the comparison with E – Glass reinforcement setups. In an attempt to observe the gains from switching to a carbon fibre reinforcement design, several alternative E – Glass designs were created with the objective of equalling the deflection stiffness.

TABLE 17 – QUANTITIES USED IN CARBON DECK LAYUP

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	6	0	346	0	0.02
Plate_02	6	2	57	19	0.10
Stiffener_01	6	10	35	57	0.12
Stiffener_02	6	10	12	20	0.18
Stiffener_03	6	10	15	25	0.18
		TOTALS (m^2) =	465	121	

iii. E-Glass Sundeck Structure

From the acceptable carbon deck design several additional models were created to compare what is required for a successful design using E – Glass as the reinforcement. From the original carbon design the following variations in design were investigated as methods of countering the weaker mechanical properties of E – Glass.

1. Identical Layup Schedule

A first comparison of the deflections and stresses encountered between identical laminate schedules varying only the reinforcement material was conducted in an attempt to quantify the difference in deflections experienced by the two materials. It was expected that the difference would correspond to similar differences seen during the simple beam theory work.

TABLE 18 – E – GLASS CONTROL STRUCTURE PLATE SCHEDULES

Layer ID	Plate – PL_01		Plate – PL_02	
	Material	Orientation	Material	Orientation
01	Roving Twill 600g/m^2	0	Roving Twill 600g/m^2	0
02		45		45
03		90		90
04	20mm Core		100mm Core	
05	Roving Twill 600g/m^2	90	Roving Twill 600g/m^2	90
06		45		45
07		0		0
08			UD Yarn 600g/m^2	90
09				90

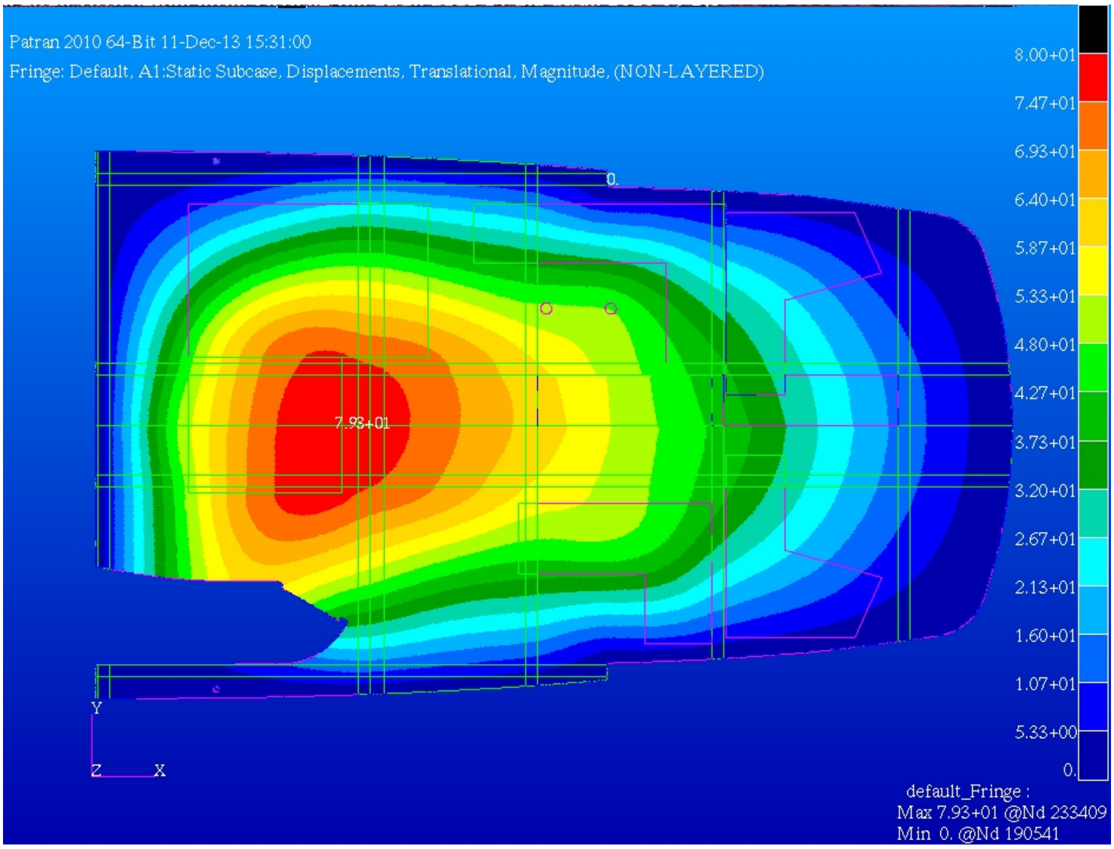
(1) Hexcel M34 Prepreg Epoxy Resin

TABLE 19 – E – GLASS CONTROL STIFFENER SCHEDULES

ID	Stiffener – ST_01		Stiffener – ST_02		Stiffener – ST_03	
	Material	Orientation	Material	Orientation	Material	Orientation
PL	20mm Core Plate				100mm Core Plate	
S_01	100mm Core		160mm Core		80mm Core	
S_02	UD Yarn 600g/m^2 (10 Total)	0º	UD Yarn 600g/m^2 (10 Total)	0º	UD Yarn 600g/m^2 (10 Total)	0º
:						
S_11						

(1) Hexcel M34 Prepreg Epoxy Resin

FIGURE 16 – ABSOLUTE DEFLECTIONS: E – GLASS FIBRE CONTROL



(1) Maximum deflection under load = 79.8mm

The lower modulus of E – Glass results in a larger maximum deflection but also lower stresses through the deck. Although the tensile strength of E – Glass is lower than that of carbon, the safety factor (SF) to the RINA allowable stress for the glass fibre layup is 1.6 times greater than that of the carbon layup (Carbon SF = 2.59 vs. E – Glass 4.36).

Purely on tensile modulus, the carbon prepreg used for the FEA trumps E – Glass by 64%, however this figure does not translate directly to the deflections in the models.

The E – Glass prepreg fabrics used for the finite element properties had areal weights near double that of the carbon fabrics used, however both the Carbon and E – Glass cured laminates achieved similar cured fibre volume fractions (FVF), and any additional areal weight is therefore countered by a thicker cured ply thickness. The relation between FVF and ply thickness is shown in the formula below.

FIGURE – CURED PLY THICKNESS FROM FVF, DENSITY, AREAL WEIGHT

Parameters :

wf : Fibre areal weight in prepreg (g/m²)

ρf : Fibre density (g/cm³)

Vf : Fibre volume (%)

$$CPT = \frac{wf}{\rho f \times 10 \times Vf}$$

(1) Hexcel Composites Prepreg Brochure

It can be said that as the FVF is similar for both materials the areal weight variation does not affect the cured laminate beyond increasing the lamina thicknesses, which considered next to the core thickness is considered negligible.

The maximum deflection between the two material controls with identical geometry shows a difference of 47%, which is significantly less that the 64% variation in the modulus values of the two bi-axial fabrics (Greater modulus difference exists between UD fabrics for 0º orientation).

The control E – Glass plate layup fails under the Azimut maximum deflection requirements, with a deflection of 3.4mm over the 3.0mm limited by the panel geometry.

2. Increased Core Thickness

Previous results from the simple beam theory work had shown that the sandwich characteristic of the laminate was the most significant variable available to create a stiffer beam or panel layup. The first alteration from the original carbon setup was to increase the core thicknesses involved until an equivalent level of maximum deflection to the carbon model could be obtained.

TABLE 20 – E – GLASS CORE INCREASE PLATE SCHEDULES

<table>
<tr><th rowspan="2">Layer ID</th><th colspan="2">Plate – PL_01</th><th colspan="2">Plate – PL_02</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>01</td><td rowspan="3">Roving Twill 600g/m^2</td><td>0</td><td rowspan="3">Roving Twill 600g/m^2</td><td>0</td></tr>
<tr><td>02</td><td>45</td><td>45</td></tr>
<tr><td>03</td><td>90</td><td>90</td></tr>
<tr><td>04</td><td colspan="2">27mm Core</td><td colspan="2">135mm Core</td></tr>
<tr><td>05</td><td rowspan="3">Roving Twill 600g/m^2</td><td>90</td><td rowspan="3">Roving Twill 600g/m^2</td><td>90</td></tr>
<tr><td>06</td><td>45</td><td>45</td></tr>
<tr><td>07</td><td>0</td><td>0</td></tr>
<tr><td>08</td><td colspan="2" rowspan="2"></td><td rowspan="2">UD Yarn 600g/m^2</td><td>90</td></tr>
<tr><td>09</td><td>90</td></tr>
</table>

(1) Hexcel M34 Prepreg Epoxy Resin

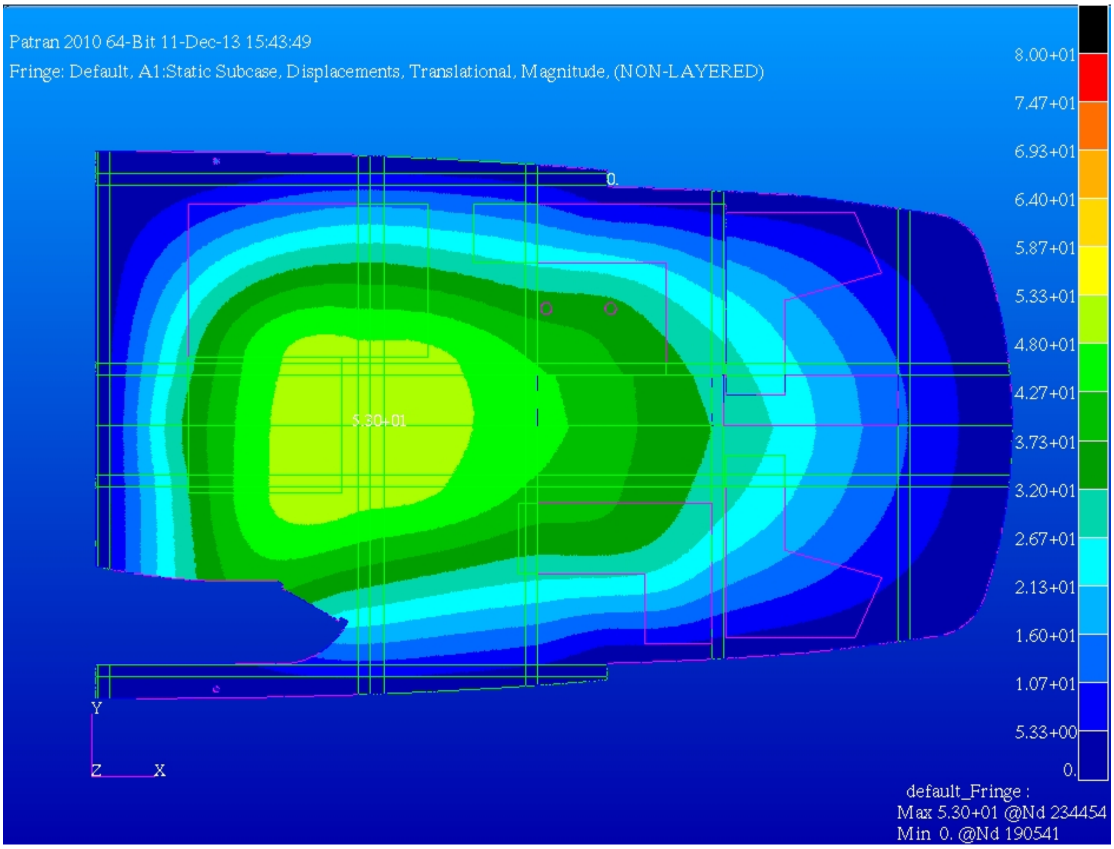
TABLE 21 – E – GLASS CORE INCREASE STIFFENER SCHEDULES

<table>
<tr><th rowspan="2">ID</th><th colspan="2">Stiffener – ST_01</th><th colspan="2">Stiffener – ST_02</th><th colspan="2">Stiffener – ST_03</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>PL</td><td colspan="4">27mm Core Plate</td><td colspan="2">135mm Core Plate</td></tr>
<tr><td>S_01</td><td colspan="2">135mm Core</td><td colspan="2">216mm Core</td><td colspan="2">108mm Core</td></tr>
<tr><td>S_02</td><td rowspan="3">UD Yarn 600g/m^2 (10 Total)</td><td rowspan="3">0º</td><td rowspan="3">UD Yarn 600g/m^2 (10 Total)</td><td rowspan="3">0º</td><td rowspan="3">UD Yarn 600g/m^2 (10 Total)</td><td rowspan="3">0º</td></tr>
<tr><td>:</td></tr>
<tr><td>S_11</td></tr>
</table>

(1) Hexcel M34 Prepreg Epoxy Resin

Both the plate and stiffener core thicknesses were increased uniformly by a given percentage until a similar maximum deflection profile was obtained. Through optimisation techniques a 35% increase in the E – Glass core thicknesses provided deflections of similar magnitude and profile to the carbon fibre control.

FIGURE 17 – DEFLECTIONS: E – GLASS FIBRE WITH CORE INCREASE



(1) Maximum deflection under load = 53.0mm (Carbon deflection = 54.4mm, Δ = 2.6%)

The core thickness increase results in a larger structural depth. In absolute terms where the carbon deck maximum depth is limited to 180mm, the equivalent E – Glass structure requires 245mm of depth to reach the same stiffness. Stresses in the E – Glass layup are also reduced; with a maximum Von Mises stress of 47 MPa reached compared to the carbon schedules 117 MPa.

TABLE 22 – QUANTITIES FOR INCREASED CORE THICKNESS MODEL

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	6	0	346	0	0.03
Plate_02	6	2	57	19	0.14
Stiffener_01	6	10	35	57	0.16
Stiffener_02	6	10	12	20	0.24
Stiffener_03	6	10	15	25	0.24
		TOTALS (m^2) =	465	121	

3. Additional Reinforcement Layers

Additional layers of E – Glass reinforcement were added to the schedule in an attempt to create match the stiffness of the carbon control design. Layers were added uniformly across the deck members in order to ensure comparable final structure weight and material costings.

Maintaining a symmetrical deck sandwich layup a global maximum deflection of 52.2mm was obtained with a plate layup consisting of 5 – Core – 5 configuration, an additional three transversal UD layers in the vicinity of the Jacuzzi and stiffeners with 13 UD lamina layers in the flange. Core material was fixed to that of the original control structural designs.

TABLE 23 – E – GLASS ADDED REINFORCEMENT STIFFENER SCHEDULES

Layer ID	Plate – PL_01		Plate – PL_02	
	Material	Orientation	Material	Orientation
01	Roving Twill 600g/m^2	0	Roving Twill 600g/m^2	0
02		45		45
03		90		90
04		45		45
05		0		0
06	20mm Core		100mm Core	
07	Roving Twill 600g/m^2	0	Roving Twill 600g/m^2	0
08		45		45
09		90		90
10		45		45
11		0		0
12			UD Yarn 600g/m^2	90
13				90
14				90

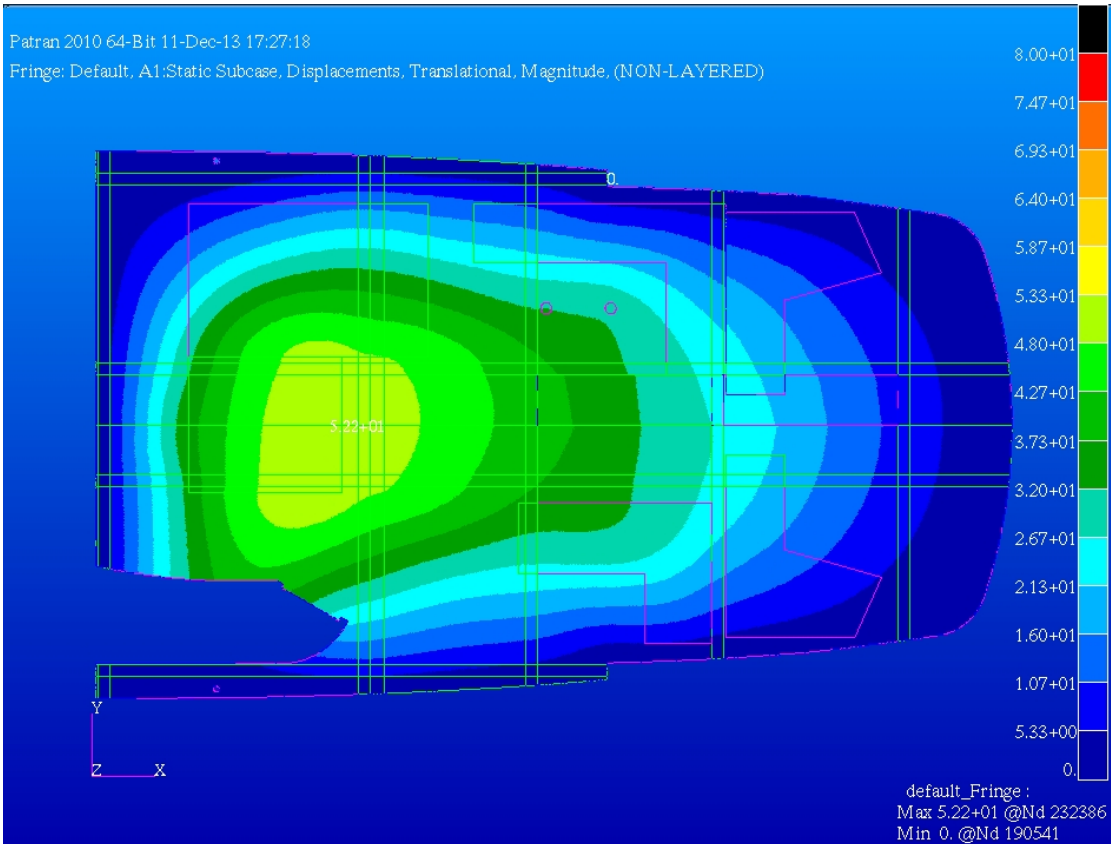
(1) Hexcel M34 Prepreg Epoxy Resin

TABLE 24 – E – GLASS ADDED REINFORCEMENT STIFFENER SCHEDULES

ID	Stiffener – ST_01		Stiffener – ST_02		Stiffener – ST_03	
	Material	Orientation	Material	Orientation	Material	Orientation
PL	20mm Core Plate				100mm Core Plate	
S_01	100mm Core		160mm Core		80mm Core	
S_02 : S_14	UD Yarn 600g/m^2 (13 Total)	0°	UD Yarn 600g/m^2 (13 Total)	0°	UD Yarn 600g/m^2 (13 Total)	0°

(1) Hexcel M34 Prepreg Epoxy Resin

FIGURE 18 –DEFLECTIONS: E – GLASS WITH ADDITIONAL LAYERING



(1) Maximum deflection under load = 52.2mm (Carbon deflection = 54.4mm, Δ = 4.0%)

The table below shows the summation of the fabric area used for the additional reinforcement layers design. In general the increase in the number of layers is 42% for each layup designation. Numerous variations between the fabrics in and around this 42% general increase were checked to determine the layup schedule that resulted in the most similar maximum deflection value

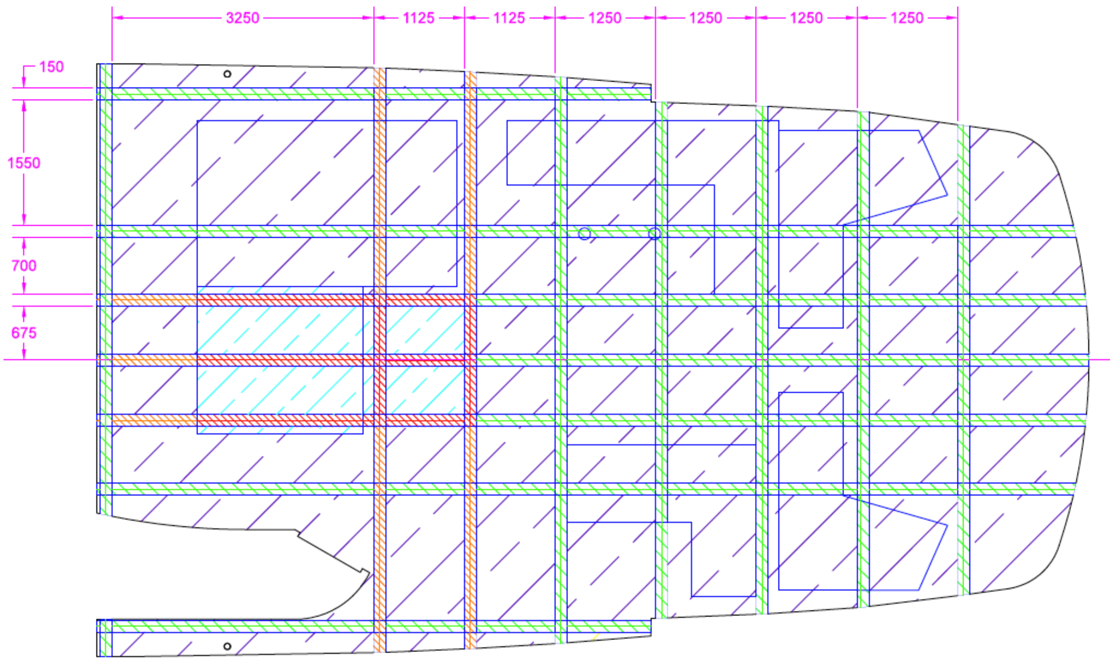
TABLE 25 – FABRIC QUANTITIES FOR ADDED REINFORCEMENT LAYERS

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	10	0	577	0	0.02
Plate_02	10	3	95	28	0.10
Stiffener_01	10	13	57	75	0.12
Stiffener_02	10	13	20	25	0.18
Stiffener_03	10	13	25	33	0.18
		TOTALS (m^2) =	775	161	

4. *Stiffener Spacing Reduction*

In similar vain to the core thickness investigation the spacing between stiffeners was reduced in an attempt to increase the moment of inertia associated with increased material in a given section of the deck structure. The layup scheduling was kept as for the E – Glass control design, and the geometry altered to provide in general stiffener spacing half that of the control design.

FIGURE 19 – HALVED STIFFNER SPACING LAYOUT

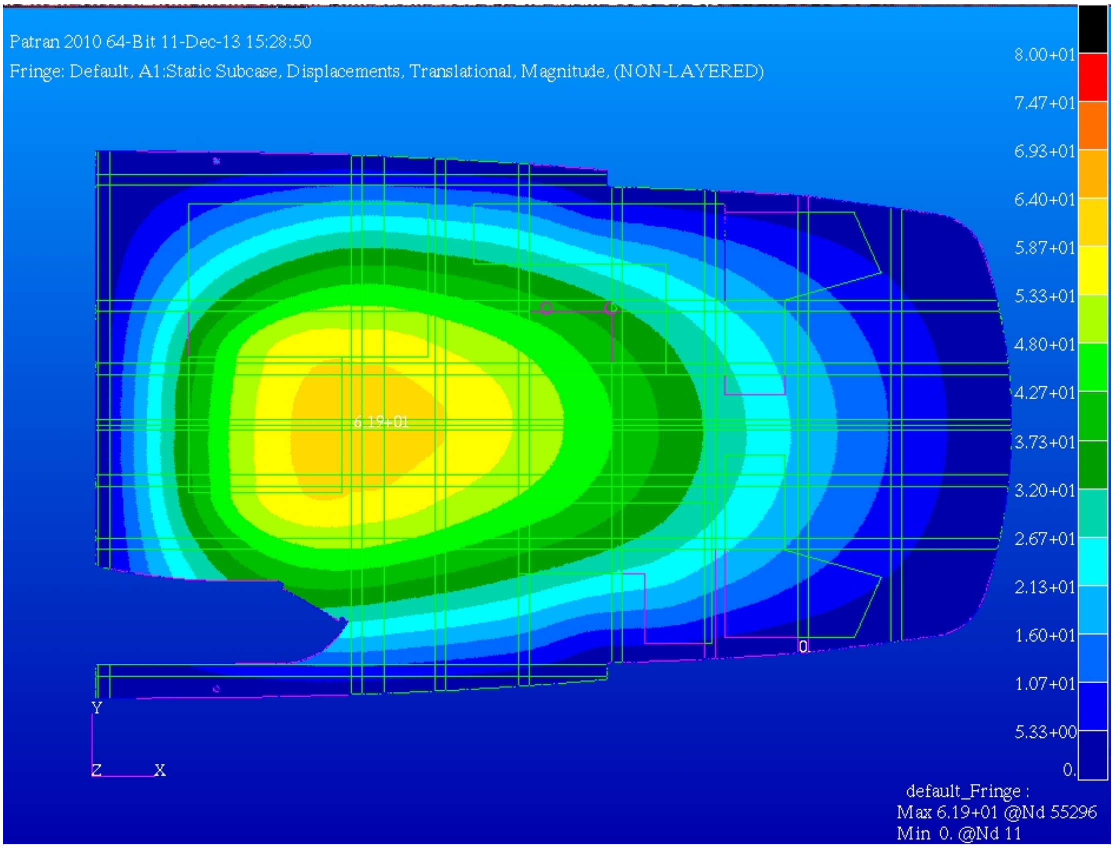


(1) Dark Purple plate = PL_01, Green plate = PL_02

(2) Green Stiffener = ST_01, Orange = ST_02, Red = ST_03

Halving the stiffener spacing previously used for the carbon structure it was not possible to obtain an equivalent maximum deflection value. Maximum deflection with the E – Glass double stiffener model was 62mm, compared the carbon control deflection of 54mm and the E – Glass control 80mm. These amount to percentage differences of 22% between the two E – Glass designs (A result of a 50% drop in stiffener spacing) and 14% difference between the carbon control and the halved stiffener geometry fibreglass layout.

FIGURE 20 – DEFLECTIONS FOR HALVED STIFFENER SPACING



(1) Maximum deflection 61.9mm (Carbon deflection = 54.4mm, Δ = 13.8%)

This deflection result shows that for a 50% reduction in stiffener spacing, the target 31% reduction in the E – Glass deck deflection cannot be obtained. The reduction in stiffener spacing does not therefore seem a feasible method of reaching an equivalent stiffness to the carbon structure design.

Conversely it is possible to conclude that carbon fibre reinforcement provides a significant advantage over E – Glass by allowing for disproportionally larger stiffener spacing, reducing structure weight and layup complexity. The length of stiffeners in the deck resulting from the reduced spacing totalled 119m, a 75% increase over the geometry of the carbon deck, and a 53% increase in unidirectional fabric used.

TABLE 26 – FABRIC QUANTITIES E – GLASS -50% STIFFENER SPACING

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	6	0	333	0	0.02
Plate_02	6	2	25	8	0.10
Stiffener_01	6	10	82	137	0.12
Stiffener_02	6	10	13	22	0.18
Stiffener_03	6	10	12	19	0.18
		TOTALS (m^2) =	465	186	

iv. Hybrid Carbon & E-Glass Sundeck

The deflections observed in the deck structure were predominately global in nature, that is, sustained by the transversal stiffeners, as opposed to a local between stiffener bending. As such a hybrid glass deck plate and carbon stiffener arrangement was investigated to observe how limiting the use of carbon to only the stiffeners improves the cost of the structure and the corresponding stiffness loss and weight increase.

A similar study to that of the all E – Glass structure was conducted, beginning with a control layup schedule identical to the all carbon, and equivalent stiffness structures with a single variable altered to obtain a stiffness matching the carbon control.

1. Identical Layup Schedule

Initially a control hybrid layup with identical stiffener geometry, core thickness and reinforcement layer numbers to the carbon control was analysed to determine the maximum deflection value, placing the hybrid structure between the all carbon and all E – Glass layups.

TABLE 27 – HYBRID MATERIAL CONTROL PLATE SCHEDULES

<table>
<tr><th rowspan="2">Layer ID</th><th colspan="2">Plate – PL_01</th><th colspan="2">Plate – PL_02</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>01</td><td rowspan="3">E – Glass Roving Twill 600g/m^2</td><td>0</td><td rowspan="3">E – Glass Roving Twill 600g/m^2</td><td>0</td></tr>
<tr><td>02</td><td>45</td><td>45</td></tr>
<tr><td>03</td><td>90</td><td>90</td></tr>
<tr><td>04</td><td colspan="2">20mm Core</td><td colspan="2">100mm Core</td></tr>
<tr><td>05</td><td rowspan="3">E – Glass Roving Twill 600g/m^2</td><td>90</td><td rowspan="3">E – Glass Roving Twill 600g/m^2</td><td>90</td></tr>
<tr><td>06</td><td>45</td><td>45</td></tr>
<tr><td>07</td><td>0</td><td>0</td></tr>
<tr><td>08</td><td colspan="2" rowspan="2"></td><td rowspan="2">E – Glass UD Yarn 600g/m^2</td><td>90</td></tr>
<tr><td>09</td><td>90</td></tr>
</table>

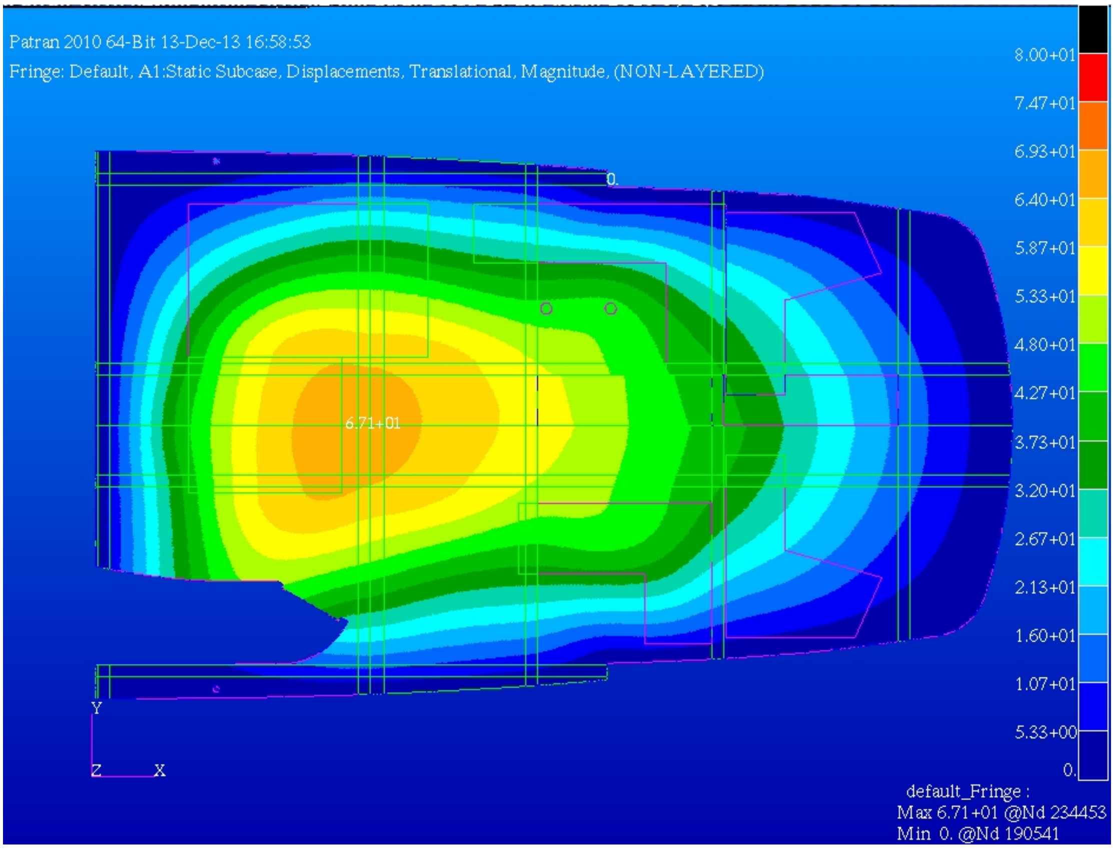
(1) Hexcel M34 Prepreg Epoxy Resin

TABLE 28 – HYBRID MATERIAL CONTROL STIFFENER SCHEDULES

<table>
<tr><th rowspan="2">ID</th><th colspan="2">Stiffener – ST_01</th><th colspan="2">Stiffener – ST_02</th><th colspan="2">Stiffener – ST_03</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>PL</td><td colspan="4">20mm Core Plate</td><td colspan="2">100mm Core Plate</td></tr>
<tr><td>S_01</td><td colspan="2">100mm Core</td><td colspan="2">160mm Core</td><td colspan="2">80mm Core</td></tr>
<tr><td>S_02</td><td rowspan="4">Carbon UD Tows 476g/m^2 (10 Total)</td><td rowspan="4">0º</td><td rowspan="4">Carbon UD Tows 476g/m^2 (10 Total)</td><td rowspan="4">0º</td><td rowspan="4">Carbon UD Tows 476g/m^2 (10 Total)</td><td rowspan="4">0º</td></tr>
<tr><td>:</td></tr>
<tr><td>:</td></tr>
<tr><td>S_11</td></tr>
</table>

(1) Gurit SE84 LV Prepreg Epoxy Resin

FIGURE 21 – ABSOLUTE DEFLECTIONS: HYBRID CONTROL DESIGN



(1) Maximum deflection under load = 67.1mm

TABLE 29 – FABRIC QUANTITIES HYBRID CONTROL DESIGN

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	6	0	333	0	0.02
Plate_02	6	2	25	19	0.10
Stiffener_01	6	10	82	57	0.12
Stiffener_02	6	10	13	20	0.18
Stiffener_03	6	10	12	25	0.18
		TOTALS (m^2) =	465	121	

2. *Increased Core Thickness*

As previously conducted with the all E – Glass structure, the sandwich and stiffener core thicknesses were increased uniformly across the deck structure arrangement until a stiffness similar to the all carbon setup was obtained.

TABLE 30 – INCREASED CORE THICKNESS HYBRID PLATE SCHEDULES

Layer ID	Plate – PL_01		Plate – PL_02	
	Material	Orientation	Material	Orientation
01	E – Glass Roving Twill $600g/m^2$	0	E – Glass Roving Twill $600g/m^2$	0
02		45		45
03		90		90
04	23mm Core		116mm Core	
05	E – Glass Roving Twill $600g/m^2$	90	E – Glass Roving Twill $600g/m^2$	90
06		45		45
07		0		0
08			E – Glass UD Yarn $600g/m^2$	90
09				90

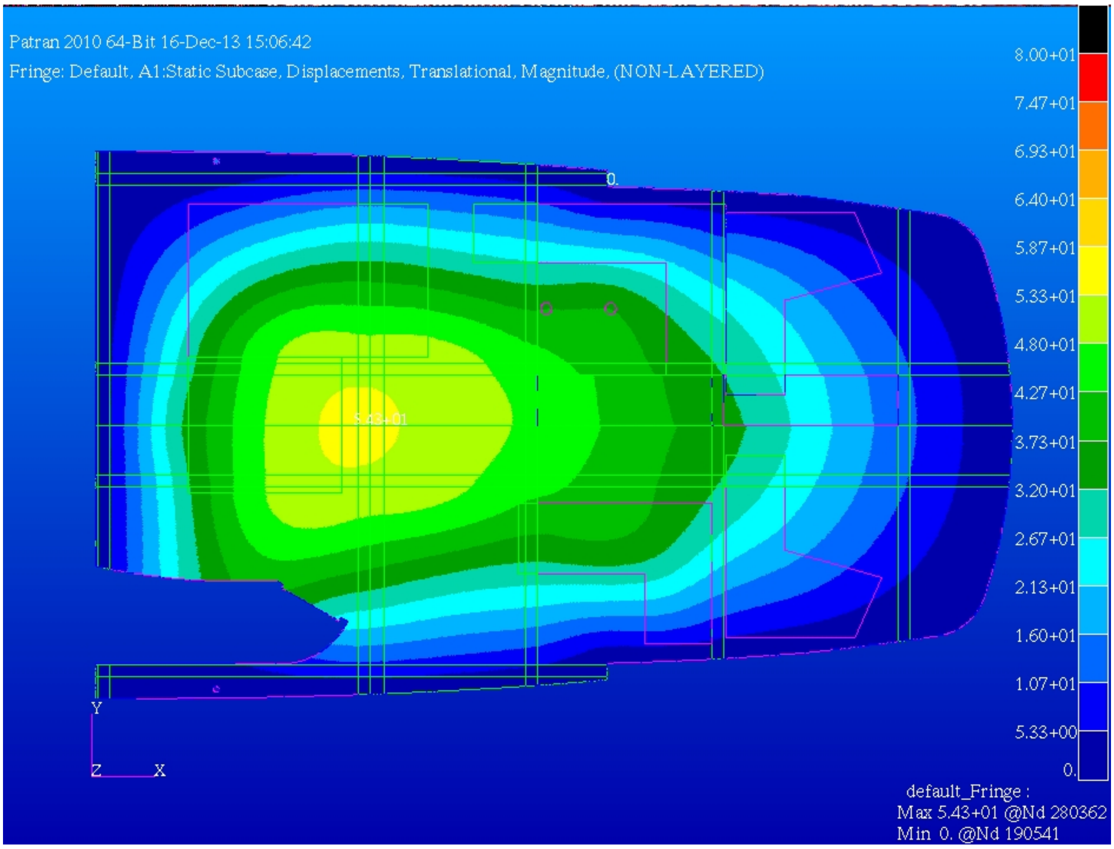
(1) Hexcel M34 Prepreg Epoxy Resin

TABLE 31 – INCREASED CORE HYBRID STIFFENER SCHEDULES

ID	Stiffener – ST_01		Stiffener – ST_02		Stiffener – ST_03	
	Material	Orientation	Material	Orientation	Material	Orientation
PL	23mm Core Plate				116mm Core Plate	
S_01	116mm Core		186mm Core		93mm Core	
S_02	Carbon UD Tows $476g/m^2$ (10 Total)	0º	Carbon UD Tows $476g/m^2$ (10 Total)	0º	Carbon UD Tows $476g/m^2$ (10 Total)	0º
:						
:						
S_11						

(1) Gurit SE84 LV Prepreg Epoxy Resin

FIGURE 22 – DEFLECTIONS: HYBRID WITH INCREASED CORE THICKNESS



(1) Maximum deflection under load = 54.3mm (Carbon deflection = 54.4mm, Δ = 0.2%)

TABLE 32 – FABRIC QUANTITIES HYBRID INCREASED CORE THICKNESS

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	6	0	333	0	0.02
Plate_02	6	2	25	19	0.12
Stiffener_01	6	10	82	57	0.14
Stiffener_02	6	10	13	20	0.21
Stiffener_03	6	10	12	25	0.21
		TOTALS (m^2) =	465	121	

3. *Additional Reinforcement Layers*

As per the all E – Glass deck investigation, the stiffness of the hybrid control setup was brought to a stiffness equivalent to that of the all carbon design by means of additional reinforcement layers. The increase was uniformly applied across both the plate and stiffener structural members.

TABLE 33 – ADDITIONAL LAYERING HYBRID PLATE SCHEDULES

<table>
<tr><th rowspan="2">Layer ID</th><th colspan="2">Plate – PL_01</th><th colspan="2">Plate – PL_02</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>01</td><td rowspan="4">E – Glass Roving Twill 600g/m^2</td><td>0</td><td rowspan="4">E – Glass Roving Twill 600g/m^2</td><td>0</td></tr>
<tr><td>02</td><td>45</td><td>45</td></tr>
<tr><td>03</td><td>90</td><td>90</td></tr>
<tr><td>04</td><td>45</td><td>45</td></tr>
<tr><td>05</td><td colspan="2">20mm Core</td><td colspan="2">100mm Core</td></tr>
<tr><td>06</td><td rowspan="4">E – Glass Roving Twill 600g/m^2</td><td>45</td><td rowspan="4">E – Glass Roving Twill 600g/m^2</td><td>45</td></tr>
<tr><td>07</td><td>90</td><td>90</td></tr>
<tr><td>08</td><td>45</td><td>45</td></tr>
<tr><td>09</td><td>0</td><td>0</td></tr>
<tr><td>10</td><td colspan="2" rowspan="3"></td><td rowspan="3">E – Glass UD Yarn 600g/m^2</td><td>90</td></tr>
<tr><td>11</td><td>90</td></tr>
<tr><td>12</td><td>90</td></tr>
</table>

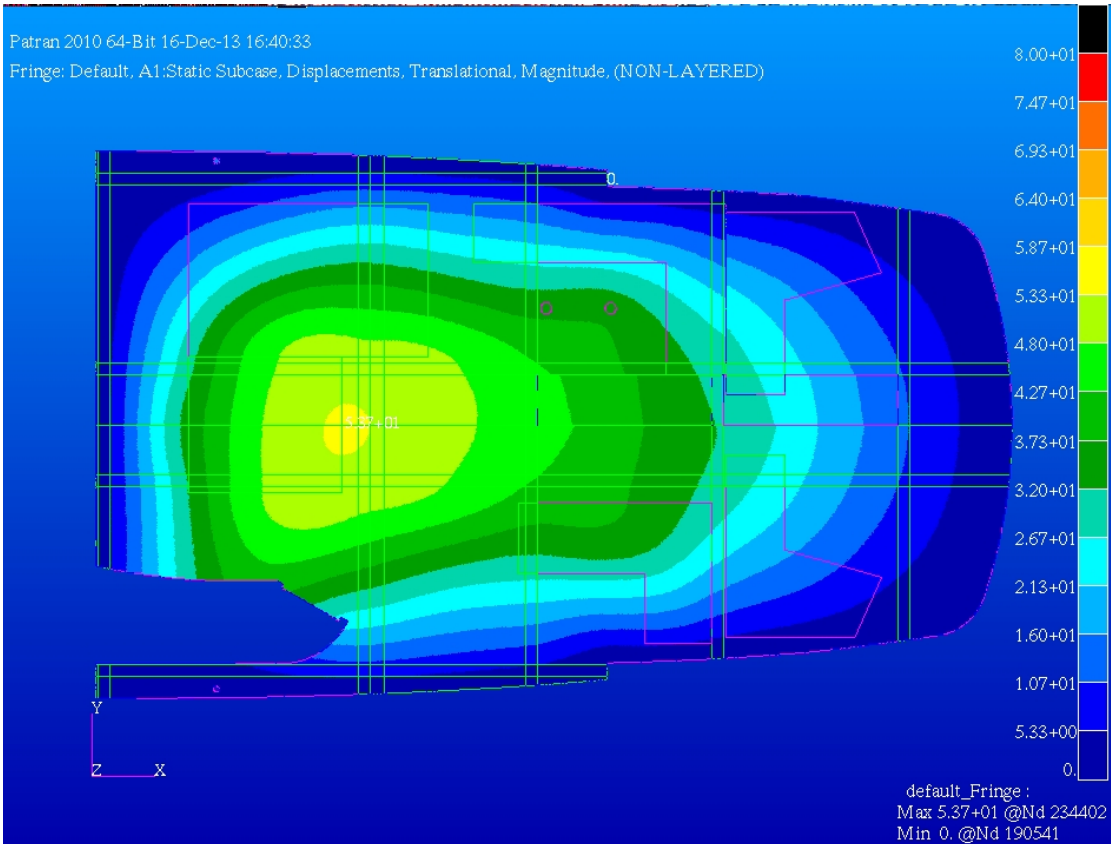
(1) Hexcel M34 Prepreg Epoxy Resin

TABLE 34 – ADDITONAL LAYERING HYBRID STIFFENER SCHEDULES

<table>
<tr><th rowspan="2">ID</th><th colspan="2">Stiffener – ST_01</th><th colspan="2">Stiffener – ST_02</th><th colspan="2">Stiffener – ST_03</th></tr>
<tr><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th><th>Material</th><th>Orientation</th></tr>
<tr><td>PL</td><td colspan="4">20mm Core Plate</td><td colspan="2">100mm Core Plate</td></tr>
<tr><td>S_01</td><td colspan="2">100mm Core</td><td colspan="2">160mm Core</td><td colspan="2">80mm Core</td></tr>
<tr><td>S_02</td><td rowspan="4">Carbon UD Tows 476g/m^2 (12 Total)</td><td rowspan="4">0º</td><td rowspan="4">Carbon UD Tows 476g/m^2 (12 Total)</td><td rowspan="4">0º</td><td rowspan="4">Carbon UD Tows 476g/m^2 (12 Total)</td><td rowspan="4">0º</td></tr>
<tr><td>:</td></tr>
<tr><td>:</td></tr>
<tr><td>S_13</td></tr>
</table>

(1) Gurit SE84 LV Prepreg Epoxy Resin

FIGURE 23 – DEFLECTIONS: HYBRID WITH ADDITIONAL LAYERING



(1) Maximum deflection under load = 53.7mm (Carbon deflection = 54.4mm, Δ = 1.3%)

TABLE 35 – FABRIC QUANTITIES HYBRID ADDITIONAL LAYERS

Layup Designation	No. of Reinforcement Layers		Total Fabric Used (m^2)		Total Core Thickness (m)
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	
Plate_01	8	0	462	0	0.02
Plate_02	8	3	76	28	0.10
Stiffener_01	8	12	46	69	0.12
Stiffener_02	8	12	16	24	0.18
Stiffener_03	8	12	20	30	0.18
		TOTALS (m^2) =	620	151	

v. Design Comparisons

The eight designs tabled above were then compared in terms of total reinforcement weight and fabric cost based on the prepreg areal weights and costing provided by Azimut for similar areal weight fabrics available to them at commercial price.

1. Structural Weight

Tabling together the layup schedules and the fabric weights the structural weight of each deck and stiffener design above was calculated for comparison. It should be noted that the bi – directional and unidirectional carbon epoxy prepregs reinforcement areal weights were 334 and 476 g/m^2 respectively and both fibreglass fabric types were 600 g/m^2. Density of the sandwich foam core for all layups was taken as 108 kg/m^3.

TABLE 36 – CARBON DECK LAYUP WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi– Directional	Uni – Directional	Bi– Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	346	0	116	0	1.16	124
Plate_02	57	19	19	9	0.95	102
Stiffener_01	35	57	12	27	0.69	74
Stiffener_02	12	20	4	9	0.35	38
Stiffener_03	15	25	5	12	0.45	49
Section Weights (kg) =			155	58	-	387
WEIGHT OF CARBON CONTROL DECK (kg) =						**600**

TABLE 37 – E – GLASS CONTROL DECK LAYUP WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi– Directional	Uni – Directional	Bi– Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	346	0	208	0	1.16	124
Plate_02	57	19	34	11	0.95	102
Stiffener_01	35	57	21	34	0.69	74
Stiffener_02	12	20	7	12	0.35	38
Stiffener_03	15	25	9	15	0.45	49
Section Weights (kg) =			279	73	-	387
WEIGHT OF E – GLASS CONTROL DECK (kg) =						**738**

TABLE 38 – E – GLASS ADDED GEOMETRY LAYUP WEIGHT

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	333	0	200	0	1.11	119
Plate_02	25	8	15	5	0.42	45
Stiffener_01	82	137	49	82	1.65	177
Stiffener_02	13	22	8	13	0.39	42
Stiffener_03	12	19	7	12	0.35	37
Section Weights (kg) =			279	112	3.91	420
WEIGHT OF E – GLASS ADDED STIFFENERS DECK (kg) =						**811**

TABLE 39 – E – GLASS ADDED CORE THICKNESS WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	346	0	208	0	1.56	168
Plate_02	57	19	34	11	1.28	137
Stiffener_01	35	57	21	34	0.93	100
Stiffener_02	12	20	7	12	0.48	51
Stiffener_03	15	25	9	15	0.61	66
Section Weights (kg) =			279	73	4.86	522
WEIGHT OF E – GLASS ADDED CORE THICKNESS DECK (kg) =						**874**

TABLE 40 – E – GLASS ADDED REINFORCEMENT WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	578	0	347	0	1.16	124
Plate_02	95	28	57	17	0.95	102
Stiffener_01	57	75	34	45	0.69	74
Stiffener_02	20	25	12	15	0.35	38
Stiffener_03	25	33	15	20	0.45	49
Section Weights (kg) =			465	97	-	387
WEIGHT OF E – GLASS ADDED REINFORCEMENT DECK (kg) =						**948**

TABLE 41 – HYBRID DECK LAYUP WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	346	0	208	0	1.16	124
Plate_02	57	19	34	11	0.95	102
Stiffener_01	35	57	21	27	0.69	74
Stiffener_02	12	20	7	9	0.35	38
Stiffener_03	15	25	9	12	0.45	49
Section Weights (kg) =			279	60	-	387
WEIGHT OF HYBRID CONTROL DECK (kg) =						**726**

TABLE 42 – HYBRID DECK ADDED CORE WEIGHT CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	346	0	208	0	1.34	144
Plate_02	57	19	34	11	1.10	118
Stiffener_01	35	57	21	27	0.80	86
Stiffener_02	12	20	7	9	0.41	44
Stiffener_03	15	25	9	12	0.53	57
Section Weights (kg) =			279	60	-	449
WEIGHT OF HYBRID ADDED CORE DECK (kg) =						**787**

TABLE 43 – HYBRID DECK ADDED REINFORCEMENT WEIGHT

Layup Designation	Total Fabric Used (m^2)		Fabric Weight (kg)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Weight (kg)
Plate_01	462	0	277	0	1.34	144
Plate_02	76	28	45	17	1.10	118
Stiffener_01	46	69	28	33	0.80	86
Stiffener_02	16	24	9	11	0.41	44
Stiffener_03	20	30	12	14	0.53	57
Section Weights (kg) =			372	75	-	449
WEIGHT OF HYBRID ADDED REINFORCEMENT DECK (kg) =						**834**

The higher modulus of the carbon fibre fabric (67%) enables the structure to create a structure of stiffness that is lighter than all the equivalent stiffness E – glass designs.

The lightest of the viable alternatives, the extra core design, is 274kg (45%) heavier than the carbon control structure.

Carbon reinforcement therefore allows for a significant decrease in structural weight, in both hull and superstructure applications, based on the reduction in structural volume required in order to achieve the required strength.

The following table summarises each of the model setups maximum deflection, total weight and variation from the control model setups in an attempt to match the maximum deflection of the carbon structure.

TABLE 44 – SUMMARY OF DEFLECTON AND STRUCTURE WEIGHT

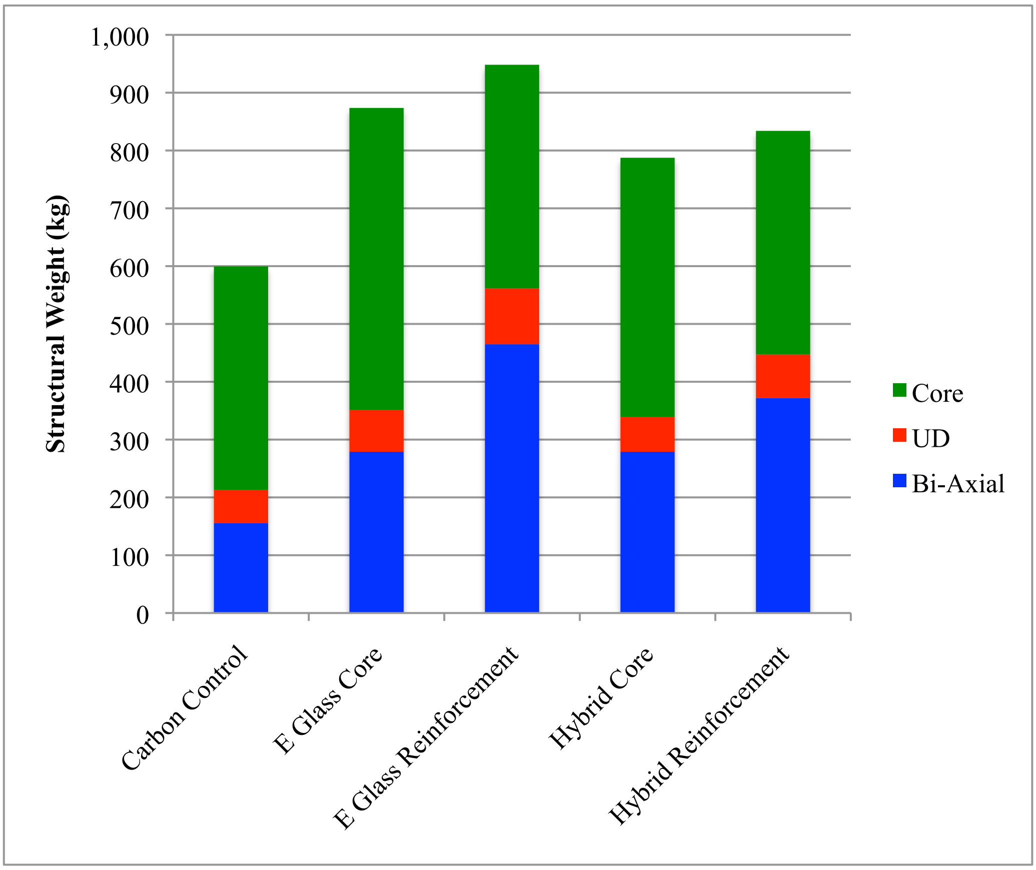
Reinforcement Material	Model Setup Details	Maximum Deflection (mm)	Structural Weight (kg)
All Carbon	180mm Max Depth, RINA Reqs (Control)	54.4[1]	600
All E – Glass	180mm Max Depth (Control)	79.8[2]	738
	-50% Stiffener Spacing	61.9[2]	811[2]
	+35% Core Thickness (Depth = 243mm)	53.0	874
	+42% Total Reinforcement Layers	52.2	948
E – Glass Plate, Carbon Stiffeners	180mm Max Depth (Control)	67.1[2]	726[2]
	+16% Core Thickness (Depth = 209mm)	54.3	800
	+25% Total Reinforcement Layers	53.7	849

(1) Carbon Max Deflection used as target for E – Glass structure variations

(2) Does not obtain equivalent stiffness

The chart below shows the weight breakdown for the four structural setups that obtain equivalent stiffness to the carbon fibre design. It should be noted that each of the equivalent designs has a penalty resulting from the move away from carbon fibre. For the core thickness increased models, there is an increase in the structural depth, and the additional reinforcement setups are significantly heavier than the all carbon setup, as shown in the graph.

FIGURE 24 –WEIGHT BREAKDOWN FOR SUCCESSFUL DESIGNS



2. *Material Costings*

The same designs were then costed based on purchasing prices available to the Azimut shipyard in Viareggio. As per the weight calculation, cost was provided per unit area of fabric (or unit volume for core foam), and tallied for each structural design. Costs used for the calculations are €36 and €32 per m^2 for Bi-Axial and UD carbon fabrics respectively, and €24 and €26 for the Bi and UD E – Glass fabrics. Foam core was taken as €3,280 per m^3 based on € / m^2 pricing of foam sheets of fixed thickness reduced to a unit volume value.

The higher price of the E – Glass UD vs. Bi – Axial fabric is an example of commercial factors affecting price. Where Bi-Axial E – Glass is extremely common fabric, offered by multiple fabric manufacturers and produced in high volumes, fewer boat builders require the axial strength of UD tapes and therefore the less commonly used UD E – Glass fabric is pushed to a higher price, despite the UD fabric being the simpler fabric to manufacture.

TABLE 45 – CARBON DECK LAYUP COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	346	0	12,482	0	1.16	3,542
Plate_02	57	19	2,044	606	0.95	2,900
Stiffener_01	35	57	1,240	1,837	0.69	2,112
Stiffener_02	12	20	424	628	0.35	1,082
Stiffener_03	15	25	544	805	0.45	1,389
Section Costs (€) =			16,734	3,876	-	11,024
COST OF CARBON CONTROL DECK (€) =						**31,634**

TABLE 46 – E – GLASS CONTROL DECK COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	346	0	8,321	0	1.16	3,542
Plate_02	57	19	1,363	492	0.95	2,900
Stiffener_01	35	57	827	1,493	0.69	2,112
Stiffener_02	12	20	282	510	0.35	1,082
Stiffener_03	15	25	362	654	0.45	1,389
Section Costs (€) =			11,156	3,149	-	11,024
COST OF E – GLASS CONTROL DECK (€) =						**25,329**

TABLE 47 – E – GLASS ADDED GEOMETRY COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	333	0	7,999	0	1.11	3,405
Plate_02	25	8	599	216	0.42	1,275
Stiffener_01	82	137	1,978	3,572	1.65	5,053
Stiffener_02	13	22	311	562	0.39	1,192
Stiffener_03	12	19	276	499	0.35	1,059
Section Costs (€) =			11,164	4,849	-	11,983
COST OF E – GLASS ADDED GEOMETRY DECK (€) =						**27,996**

TABLE 48 – E – GLASS ADDED CORE THICKNESS COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	346	0	7,999	0	1.56	4,782
Plate_02	57	19	599	216	1.28	3,915
Stiffener_01	35	57	1,978	3,572	0.93	2,851
Stiffener_02	12	20	311	562	0.48	1,460
Stiffener_03	15	25	276	499	0.61	1,875
Section Costs (€) =			11,164	4,849	-	14,883
COST OF E – GLASS ADDED CORE DECK (€) =						**29,188**

TABLE 49 – E – GLASS ADDED REINFORCEMENT COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	577	0	13,869	0	1.16	3,542
Plate_02	95	28	2,271	738	0.95	2,900
Stiffener_01	57	75	1,378	1,941	0.69	2,112
Stiffener_02	20	25	471	663	0.35	1,082
Stiffener_03	25	33	604	851	0.45	1,389
Section Costs (€) =			18,593	4,192	-	11,024
COST OF E – GLASS ADDED REINFORCEMENT DECK (€) =						**33,810**

TABLE 50 – HYBRID CONTROL DECK COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi–Directional	Uni – Directional	Bi–Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	346	0	8,321	0	1.16	3,542
Plate_02	57	19	1,363	492	0.95	2,900
Stiffener_01	35	57	827	1,837	0.69	2,112
Stiffener_02	12	20	282	628	0.35	1,082
Stiffener_03	15	25	362	805	0.45	1,389
Section Costs (€) =			11,156	3,762	-	11,024
COST OF HYBRID CONTROL DECK (€) =						**25,943**

TABLE 51 – HYBRID EXTRA CORE COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi– Directional	Uni – Directional	Bi– Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	346	0	8,321	0	1.34	4,109
Plate_02	57	19	1,363	492	1.10	3,364
Stiffener_01	35	57	827	1,837	0.80	2,450
Stiffener_02	12	20	282	628	0.41	1,255
Stiffener_03	15	25	362	805	0.53	1,611
Section Costs (€) =			11,156	3,762	-	12,788
COST OF HYBRID EXTRA CORE DECK (€) =						**27,706**

TABLE 52 – HYBRID EXTRA RIEINFORCEMENT COST CALCULATION

Layup Designation	Total Fabric Used (m^2)		Fabric Cost (€)		Sandwich Core	
	Bi– Directional	Uni – Directional	Bi– Directional	Uni – Directional	Total Volume (m^3)	Total Cost (€)
Plate_01	462	0	11,095	0	1.16	3,542
Plate_02	76	28	1,817	738	0.95	2,900
Stiffener_01	46	69	1,102	2,205	0.69	2,112
Stiffener_02	16	24	377	753	0.35	1,082
Stiffener_03	20	30	483	967	0.45	1,389
Section Costs (€) =			14,874	4,663	-	11,024
COST OF HYBRID EXTRA REINFORCEMENT DECK (€) =						**30,561**

The following table summarises the four designs that obtain equivalent stiffness with the carbon control structure, their structural weights and materials cost.

TABLE 53 – SUMMARY OF DEFLECTON AND STRUCTURE COST

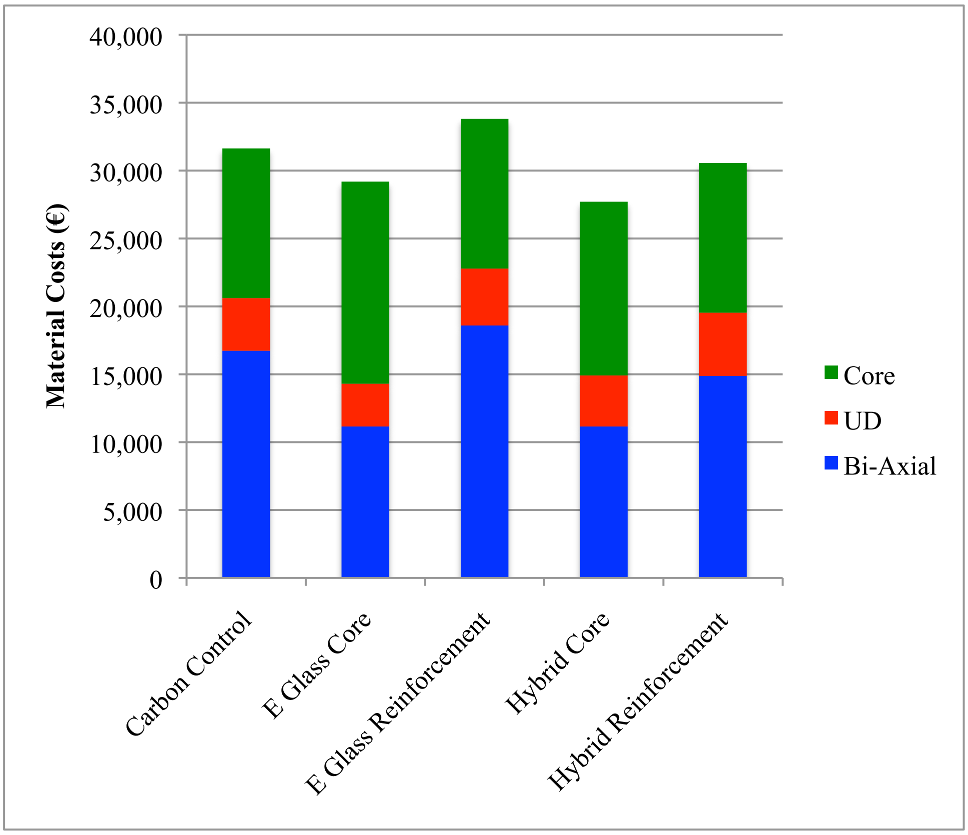
Reinforcement Material	Model Setup Details	Maximum Deflection (mm)	Structural Cost (€)
All Carbon	180mm Max Depth, RINA Reqs (Control)	54.4[1]	31,634[1]
All E – Glass	180mm Max Depth (Control)	79.8[2]	25,329[2]
	-50% Stiffener Spacing	61.9[2]	27,996[2]
	+35% Core Thickness (Depth = 243mm)	53.0	29,188
	+42% Total Reinforcement Layers	52.2	33,810
E – Glass Plate, Carbon Stiffeners	180mm Max Depth (Control)	67.1[2]	25,943[2]
	+16% Core Thickness (Depth = 209mm)	54.3	27,706
	+25% Total Reinforcement Layers	53.7	30,561

(1) Carbon Max Deflection used as target for E – Glass structure variations

(2) Does not obtain equivalent stiffness

The cost comparison, in similar line to the simple beam theory investigation shows that a carbon design can be cheaper than an equivalent stiffness E – Glass based on a reduction in the use of raw materials. Comparing both the all carbon control with the all E – Glass added reinforcement setup (fixed core thickness) the carbon design has a lower overall cost despite being the dearer raw material.

FIGURE 25 – MATERIAL COST BREAKDOWN FOR SUCCESSFUL DESIGNS



In light of structural weight, material cost, and deck structure depth, carbon fibre provides the required minimal deck structure depth for the lightest weight (Minimum number of reinforcement layers), and at a small cost penalty.

If no exact fixed deck structure depth is required, the core thickness can be increased to improve the bending strength of the plate / stiffener element. Taking the two scenarios which hold the number of reinforcement layers fixed we see the structural depth for the all E – Glass and Hybrid setups require an additional 63mm and 29mm respectively. The respective additional weight penalties for both alternatives are 274kg (46%) and 188kg (31%).

The two alternate design options that maintain the minimum structure depth (180mm fixed core thickness) do so with additional reinforcement layers. The all E – Glass additional reinforcement design obtains equivalent stiffness with an additional 349kg of structural weight (58% increase), and for an additional €2,176 over the all carbon setup. The Hybrid additional reinforcement design, while €1,073 cheaper than the all carbon setup, is still 234kg (39%) heavier.

These results exhibit the primary benefit of using all carbon sandwich construction as the reduction in weight, with an option exists for varying materials between the plate and stiffener layups if material cost issues arise. Naturally to obtain the most benefit from using carbon its use can be confined to the stiffener flanges.

TABLE 54 – COST, WEIGHT VARIATION FROM CARBON CONTROL

Material Setup	Total Number of Layers[1]	Web Depth (mm)	Weight Penalty (kg)	Cost Saving (€)
Carbon Control[2]	16	180	(600)	(31,364)
E – Glass Core	16	243	274	2,446
E – Glass Reinforcement	23	180	349	- 2,176
Hybrid Core	16	209	188	3,927
Hybrid Reinforcement	20	180	234	1,073

(1) Total number of layers in stiffeners – Indicative of whole structure

(2) Carbon Figures included as baseline values

Flow on effects from the lighter structure into areas such as powering and available fitout weight have not been investigated but would definitely provide advantages to motor yacht designers. The reduction in required reinforcement layers also reduces manufacture costs, with less man-hours required to complete the simpler layup.

b. Discussion of Design Considerations

The process of designing an acceptable deck structure revealed the significance of ensuring the structure accurately reflects the loading that is expected. As previously mentioned, the high price for carbon fibres requires that its use in vessel structure be minimised. Excess carbon in the superstructure is a costly penalty and the designer must ensure that material is not wasted.

The areas noted below are design avenues that during the design process became areas of interest during the development of the sundeck layout.

i. Load Flow Path

Typically with structural design it is pertinent to examine the structural design in terms of load paths – where the forces on the structure are transferred through the geometry of the model to the fixed boundary conditions. In the case of the above structural model, the largest load was that of the Jacuzzi, placed at the aft end of the sundeck, behind the last full cross deck plating position.

The geometry of the superstructure supports required that this load be transferred to the deck sides, where the deck supports are strongest. As with most motor yachts the requirement that living spaces be uncluttered and free of stanchions means that all the support for the superstructure decks comes from the side walls, which themselves are required to be of minimal geometry allowing the largest glass windows possible to provide the illusion of openness inside.

Thus the principle method of refining the superstructure involves analysing the unique load paths and their various requirements. Such is the custom nature of each composite design that stiffeners are not bound by the dimensions available from the suppliers, as raw materials are only given structural geometric shape after their purchase.

ii. Stiffener Locations

Once a load path has been determined it is possible to provide the structure with additional stiffness as required to transfer the load to the support points – in this case the sundeck edges. The heaviest scantlings must match the position of highest stresses or displacements, and excess stiffness removed to optimise the position of reinforcement throughout the structure. Similarly stiffness can be removed where not required by the load paths, thereby fully optimising the use of the high cost carbon fibre.

iii. Core Thicknesses

As previously shown, increasing the core thickness, while increasing structural stiffness will also result in higher flexural stresses. Providing additional stiffness by increasing the sandwich core thickness is restricted by the requirement of motor yachts to have minimal void between decks. Larger cores result in greater void spaces and lower ceiling heights. Modern yacht builds require minimal between deck space in order to maximise deckhead height.

iv. FEA Model Setup

The use of direct FEA calculations to approve a structural design requires that the model within the computer accurately represents the final product. Assumptions and simplifications used in the model may result in incorrect stress predictions used to justify the design.

Standard risks associated with FEA model still apply (Mesh sizing, correct boundary and load definition etc) in addition to the following issues specific to composite laminate modelling.

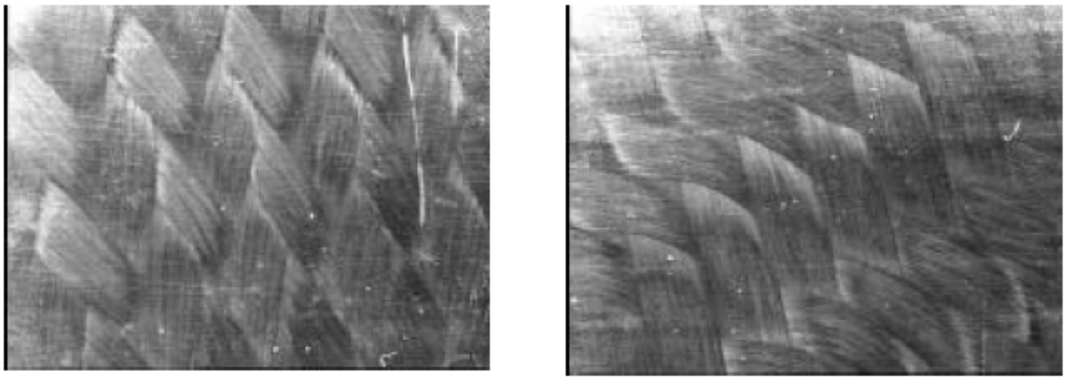
1. Fabric Draping Effects

Modelling fibre orientation that accurately represents what is manufactured becomes extremely difficult as the mould jig surface curvature increases. Most FEA hull and superstructure models define the laminates as 2D orthotropic materials, which is a reasonably acceptable level of detail for bi – directional and unidirectional reinforcement fabrics and tapes.

The orientation of the axes for the fibres are fixed at one node for each element and as long as the mesh sizing captures the full complexity of the geometry curvature then fibre orientations can be reasonably controlled. However where two directions of curvature are present, during placement of the reinforcement fabric must be ‘shaped’ in order to fully match the mould surface. This forced matching can result in fibres being mis-aligned through shear between fibre strands as the fabric deforms through shear to match the mould. Not accounting for this “draping process” in the FEA model can result in a mismatch between the fibre orientations modelled and the final manufactured part.

Few software programs currently provide support for this correction, the Nastran / Patran package being the most significant. Because the shear deformation occurs during the manufacture process, the designer must be able to ‘define’ their manufacturing technique within the FEA program. The infinite number of variables involved in this means that capturing this within an FEA model is extremely difficult.

FIGURE 26 – POST DRAPE FABRIC VARIATION IN TWILL WEAVE FABRIC



(1) "Draping of Woven Composites over irregular surfaces" Sharma, Sutcliffe, Cambridge University

As previously stated, and as is the case for the above deck plate and stiffeners model, simple constant curve geometry is not affected by this issue as the draping process involves minimal fibre disorientation to match the mould. For more complex geometry applications, the draping effect can be accounted for with a correction based on the geometry and a standardised fabric placement manufacturing process.

2. Design Office Processes

The paper presented by Bosauder, Campbell and Jones at the 2006 JEC Conference noted the extensive amount of work required to input a layup for finite element analysis. In order to reduce analysis time for their projects, the design office separated the FEA modelling from the composite engineer, and in doing so split the material definition work between the composite engineer and a supporting FEA technician.

The full composite layup would be defined by an engineer in a simple Excel spreadsheet and converted into an equivalent three layer Skin – Core – Skin that then simplifies the material definition within the FEA modeller. Results showed comparable displacements between this equivalent layup and a laminate fully defined within the Patran / Nastran package.

This simple three-layer laminate method allows for faster material definition as the pre – processing in the FEA program is limited to defining only three layers, regardless of the actual layup at a given position. However it requires that the equivalent properties be obtained. The use of Excel spreadsheets to handle all the material properties also allows for a speedier design iterations where the laminate definition requires additional modification, currently a more time consuming process to complete in Patran than within Excel. The paper also mentioned their custom in house software solution allowing for automatic data transfer between these Excel spreadsheets and the Patran database files, via Patrans Laminate Modeller to correct for draping issues.

Defining a composite structure in FEA can be a long and complex process, design offices must consider the level of FEA detail required to meet the objectives of the analysis. The process used to create the model must take into effect budgetary, timing and accuracy requirements when determining the extent of the FEA modelling to complete.

6. Production Techniques Compared

There are multiple methods available to impregnate the reinforcement fabrics or tapes in their various forms with resin. As the method of production also has a significant effect on the final mechanical properties of the laminate, an analysis of how various techniques effect the final stiffness, strength and cost of the composite was done.

As previously mentioned carbon as a reinforcement material must be supported by an equally high performance matrix, of which the final cured properties are heavily affected by the production method used.

a. Historic (Basic) Lamination Techniques

The two techniques mentioned below form the backbone of composite pleasure craft production. Used with cheap E – Glass reinforcement and Polyester / Vinyl ester resins they provide a high production throughput at low cost.

i. Wet Spray Layup

The simplest and cheapest method for composite hull and superstructure production is conducted with chopped fibres and a spray gun with the resin and reinforcement applied directly to the mould. The resin is sprayed mixed with a catalyst that allows for the full cure to occur at room temperature. The spray gun can be controlled by an experienced operator or mechanically.

The requirement that the fibres are chopped to allow for spray distribution of the fibres and that the laminate must be resin rich to ensure the fibre matrix bond is sound results in a heavy and relatively weak laminate. Additionally, the resin needs to be high in styrene content to reduce it to a sprayable viscosity; styrene is volatile and becomes airborne during the spray up. Environmentally, styrene is highly hazardous and legislation now limits the use of spray layup techniques involving styrenes to highly controlled environments. Where a shipyard now requires an extensive air filtering system it is more feasible to move to an alternate production process and take full advantage of the less hazardous layup and curing conditions available with a new process.

ii. Dry Layup and Manual Wetout

In order for the manufacturer to have greater control over the fibre orientation, the reinforcement can be supplied as a fabric, to be 'draped' over the mould with the fibres orientated as required for the expected loads. Drawing on the vast textile industry these fabrics are produced in an large number of patterns, giving the designer an equal number of possibilities in how he or she develops the structure to meet requirements.

These fibres also have the advantage of being continuous. Where in spray layup the discontinuity of the chopped fibres requires that the resin perform a greater part of the load bearing, the continuous fibres provide a considerable increase in the cured laminate strength and stiffness.

One layer of fabric is draped over the mould and resin is worked through the fabric by hand using rollers and brushes. The amount of resin is measured to ensure that the final laminate contains the correct fibre volume fraction used in the calculations. This ratio is critical to ensure that the composite performs as expected – too much resin and the laminate is excessively thick and costly, too little resin and the continuous fibre orientations within the fabric are not maintained under compression loading, leading to various buckling failure modes in the composite.

While an improvement on spray layup with regards to the reinforcement performance, the manual wet out is still a heavily uncontrolled process. It is necessary to ensure that the resin amount is correct and that this resin is distributed evenly through the reinforcement. The nature of the process gives rise to inconsistency in the laminate properties, both between separate moulds (repeatability) and in different parts of the mould (consistency).

While the process of manual layup does allow for fibre orientation through the use of fabrics, the operation of 'working' the resin through the fabric manually can result in fibre misalignments which affect the final laminate mechanics. This is amplified when using uni-directional fabrics, as there is less cross-stitching holding the fabric fibres in place.

The resin, being free to flow during the curing time can also drain to the base, or bottom of the mould, a problem amplified where vertical mould surfaces exist. Loss of resin in parts of the mould can significantly reduce the compressive properties of the laminate, and so the viscosity of the resin is usually controlled with additives, which further reducing the cured laminate properties.

A wetted out laminate can then be vacuum bagged and cured under atmospheric pressure in order to reduce the resin required for optimum wet out, however, a vacuum bagging after the laminate is wetted out does not guarantee no air remains trapped in the final cured part. If a vacuum bagging process is completed, it is usually in conjunction with an infusion technique (See below).

A significant disadvantage of these wet layup techniques is that the full layup must be completed within a fixed period, defined by the resin curing process. Once the layup process has commenced, it cannot be halted until all layers are completed to ensure strong inter-laminate bonds. This can become a restriction for larger single mould productions.

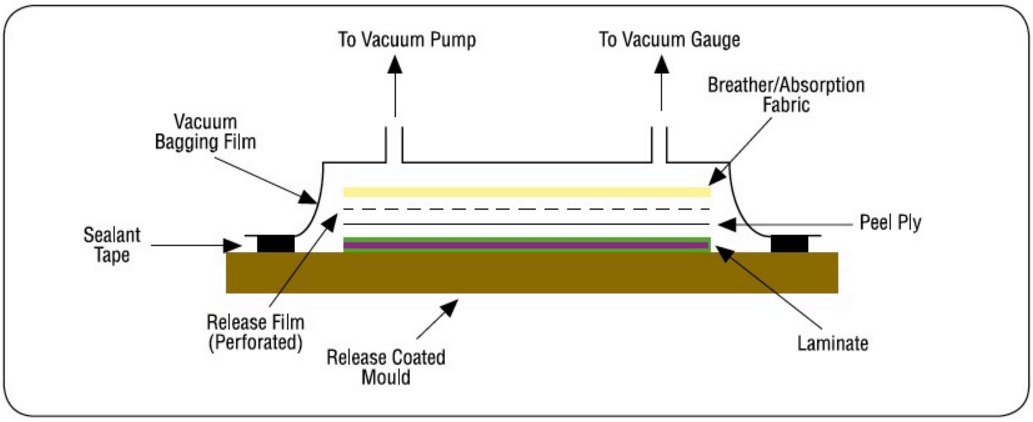
b. Improved Layup Techniques

The above two techniques are used almost solely with the cheaper glass fibres, and in shipyards where speed, cost and repeatability are greater priorities for higher production volumes. The following two methods require a more complex setup for each run, however they are capable of ensuring an improved reinforcement – matrix bond without using excess resin for a safety margin. These methods also allow for the mechanical properties available in the high performance fibre materials, such as carbon, to be fully utilised.

i. Vacuum Bagging / Consolidation

Generally improved mechanical properties can be obtained by applying pressure in various shapes or forms to the laminate as it undergoes the curing process. Once a wetout is completed the mould is covered with an airtight bag and a vacuum drawn, bringing the bag down onto the mould under atmospheric pressure. The uniform force over the laminate improves the final FVF and consequently its stiffness and strength.

FIGURE 27 – VACUUM BAGGING WITH WET LAYUP



(1) Gurit Technical Paper – “Guide to Composites”

However, given the additional advantages which result from an infusion process with minimal additional effort (improved resin quality control, near elimination of harmful airborne emissions from the curing process) vacuum bagging is rarely used in composite motor yacht construction without support from another process.

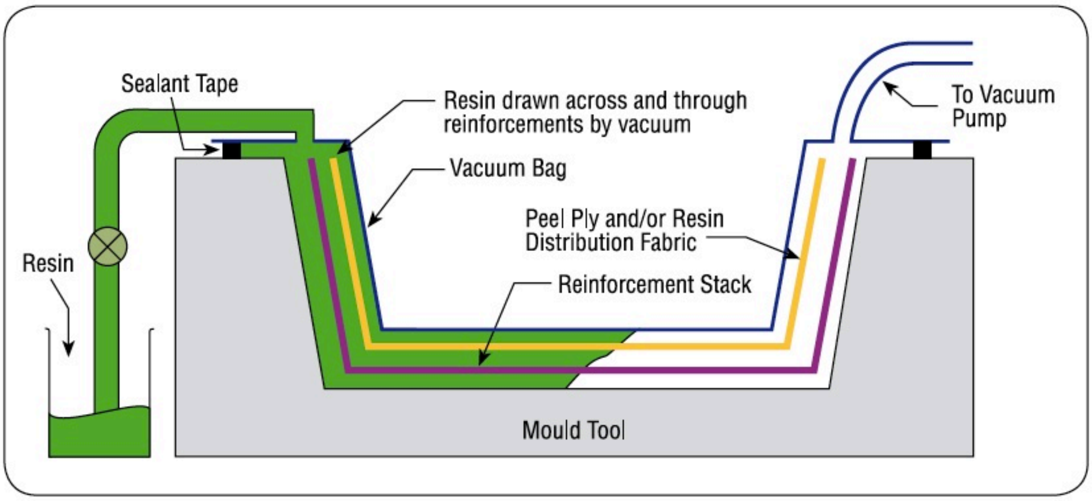
Prior to a resin infusion process it is also possible to place the dry reinforcement fabrics under vacuum pressure in an effort to ensure that the fabrics shape matches that of the mould. In a process called consolidation the laid up fabrics are placed under vacuum and pressed against the mould. The key advantage when using consolidation is the ability to use heavier, stiffer fabrics in the layup that would otherwise be difficult to form to the mould curvature.

Usually two or three fabric layers are placed by hand before a consolidation is applied. However the process can take part at any stage during the layup process. This same process is also used for perform manufacturing processes, which are more common in large throughput production lines such as in the automotive industry.

ii. Dry Layup and Infusion / Resin Transfer

Resin Infusion covers numerous methods that have been patented globally. The common basic principle requires that the reinforcement fabrics are laid up dry as required over the mould and then covered in an airtight bag. The air inside this bag is extracted leaving a vacuum with only the dry reinforcement in place. The resin mixed with the catalyst is then drawn into the vacuum, through the resin fabrics and non – structural layers of fabric designed to aid wet out. When the reinforcement is saturated the mould is left to cure in the vacuum state, with atmospheric pressure pressing down on the laminate as it cures.

FIGURE 28 – VACUUM INFUSION PROCESS



(1) Gurit Technical Paper – "Guide to Composites"

The dry layup means harmful airborne emissions from the resin mixture are controlled to the small period during the physical infusion and ensures the reinforcement fibres are orientated as required by the design. This orientation benefit is vital to ensuring that costs associated with higher performance materials are offset.
An infusion process provides a uniform pressure on the laminate during the cure, so the fibres are not at risk of significant distortion as the resin saturates the fabric(s), maintaining fibre orientation in the cured process.
Various forms of resin impregnation methods are listed below. The key similarity is the use of pressure to drive / draw the resin through a dry layup.

- **Vacuum Infusion:** Resin under atmospheric pressure is pulled through a dry layup under vacuum. Flow paths are provided by an additional loose strand mat, which is removed upon final cure. This step usually requires a release film to aid removal. Processes using Infusion include SCRIMP™ and RIFT™.
- **Resin Transfer Moulding:** Resin is pushed through dry layup by pressurised resin. Again a sacrificial mat, removed upon cure, provides flow paths for the resin. Extremely high pressures involves requires stiff, usually metallic mould. High inlet pressure can be assisted by a vacuum suction (VARTM).

- **DIAB Sandwich Core:** The DIAB company has patented a sandwich core with machined grooves that provide resin flow channels for use with infusion. These resin flow paths remove the need for loose strand mat that is difficult to remove post cure. It is possible with their foam grooves to complete full sandwich layup and provide resin flow through the core layer, producing full sandwich layup in one infusion.

iii. Prepregs (Including Preforming)

Fabrics pre-impregnated with the resin (Prepregs) are the latest solution provided by composite material manufacturers. The reinforcement fabric is provided to the shipyard with a film layer of ready to cure resin coating on top, as a single assembly.
This process has the tightest control on the resin amount, and the uniform distribution of the resin over the fabric ensures that no areas of the mould become resin deficient. It is for this reason that prepregs can obtain higher FVFs than infusion, as complex geometry corners in an infusion will tend to pool resin inefficiently.
Additionally, the low distance that the resin must 'travel' before curing allows the use of higher viscosity resins, which improves cross – linking bonds, resulting in the resin having higher compressive and shear strength.
The higher curing temperatures bring the resin to liquid form, which then flows 'down' through the reinforcement fabric, curing as the combined laminate. Prepregs are considered high performance materials and so are usually combined with a vacuum pressure process to ensure good reinforcement matrix bonding.
Preform fabrics are composite fabrics (usually prepregs) that have been shaped to roughly match the final part, in an effort to ease the compiling of the laminate fabrics in the final layup. Often the fabric has been created from scratch by the material manufacturer with the final cured shape in mind, and as such performs can be customised as required during the original fabric creation.
Used typically for more complex shapes in mass production applications (car body parts etc), preforms are usually supplied as prepregs because of the difficulties resins infusing complexly curved surfaces (Eg Pooling).

c. Production Method Comparison

An investigation was conducted into how varying the production technique alters the final mechanical properties of the laminate. Although not directly targeting the effect of using carbon fibre reinforcement, the method of laminate manufacture will significantly effect final cured properties, particularly as the modulus / strength of the reinforcement becomes more extreme (as is the case with carbon).

i. Production Method & Cured Properties

Final cured properties of the laminate revolve around the fibre volume fraction obtainable without risking poor reinforcement / resin bonding. Improving the wetout technique by minimising air voids and reducing excess resin allows for use of reduced resin amounts, yet maintaining adequate matrix / reinforcement bonding.

Both vinyl ester and epoxy resins were investigated to determine their effect on modulus of the matrix material. As previously mentioned carbon fibre reinforcement is rarely combined with a resin other than epoxy, due to the weak fibre – matrix linking between carbon and vinyl ester or polyester.

The tables below outline the four most common production methods and subsequent cured laminate mechanical properties for both Carbon and E – Glass reinforcement materials. Combinations of resin and production method are limited to those more commonly used marine composite construction. The general trend is to match a higher performance resin with the improved manufacturing technique.

TABLE 55 – BI – DIRECTIONAL CARBON CURED PROPERTY VARIATIONS

Property	Bi – Directional E – Glass Fabric: Production Method					
	Wet Layup, Open Cure	Vacuum Bagging		Resin Infusion		Prepreg
Resin Type	Vinyl Ester	Vinyl Ester	Epoxy	Vinyl Ester	Epoxy	Epoxy
Modulus (GPa)	32.5	41.0	42.1	43.4	48.3	55.9
Areal Weight (g/m^2)	600					334
FWF (%)	0.41	0.45	0.45	0.51	0.51	0.58
FVF (%)	0.30	0.34	0.35	0.39	0.40	0.57
CPT (mm)	1.04	0.99	0.97	0.80	0.80	0.21

TABLE 56 – BI – DIRECTIONAL E – GLASS CURED PROPERTY VARIATIONS

Property	Bi – Directional E – Glass Fabric: Production Method					
	Wet Layup, Open Cure	Vacuum Bagging		Resin Infusion		Prepreg
Resin Type	Vinyl Ester	Vinyl Ester	Epoxy	Vinyl Ester	Epoxy	Epoxy
Modulus (GPa)		13.3	13.7	17.9	18.4	21.9
Areal Weight (g/m^2)	600					581
FWF (%)	0.46	0.50	0.50	0.65	0.65	0.72
FVF (%)	0.27	0.30	0.31	0.45	0.46	0.54
CPT (mm)	0.86	0.77	0.75	0.52	0.51	0.22

With each level of improving production method comes improved FVFs and matching increases in improved mechanical properties, as per classical laminate theory. The FVFs indicated in the above tables are minimums that ensure good bonding between resin and reinforcement, and provided that these maximum FVFs are not exceeded and resin distribution is conducted correctly throughout the mould, the higher performance processes will provide higher final cured mechanical properties.

ii. Labour Time and Skills set

The increased level of manual labour required for any given manufacturing process will affect the level of variation possible between production parts. In the case of laminates this variation may have an ill effect on the cured strength properties of the structure, risking reduced performance of the laminate under loads.

The complexity of the manual tasks will affect the skill level required by the worker. For composites this varies greatly based on the geometry of the mould, the fabric and resin chosen and the curing process used.

TABLE 57 – HOURLY WORKER COST FOR RESIN AND METHOD SETUPS

Resin Type	Wet Layup	Vacuum Bagging	Resin Infusion	Prepreg
Epoxy	€ 28	€ 29	€ 30	€ 40
Vinyl Ester	€ 22	€ 23	€ 24	-[1]

(1) Figure unavailable as Vinyl Ester prepregs are not used in marine construction

Epoxy resin requires an exact resin to hardener ratio to ensure the final laminate has the predicted mechanical stiffness and strength. Workers when using epoxy must ensure that this ratio is obtained correctly, and that the hardener is evenly distributed through the pre cured resin.

The steady increase in labour costs associated with the improved processing method is linked to the increase in steps and process knowledge required for each method. The additional cost with regards to prepreg arises from the need to have workers form the laminate within a limited period of time, as the ready – cure resin in a prepreg will being to cure at room temperature, and the need for cold storage of the prepreg.

1. *Mould Complexities and Draping*

Reinforcement materials, as tapes or fabrics, bi – directional or unidirectional, are considered for design purposes orthotropic. The variation in the cured laminates mechanical properties requires that the fibre orientation within the cured laminate matches that of the theoretical design. The physical hand layup of the fabric or tape must therefore be conducted with this at the forefront of the layup procedure.

The previously mentioned drape effect on bi – axial fibre orientations means that the complex curvature standard in most motor yacht superstructures run the risk of high fibre misalignment when the fabric is shaped to match the mould. Capturing and controlling this deformation requires process matching between the designer tool and the layup worker.

This additional skill set requires unique worker training (Based on design software draping method) for shop floor workers in order to standardise the fabric shear deformations to that predicted in the design calculations. The draping effect is not specific to one material. However the higher performance application typically required when using carbon means that accounting for this effect is more critical.

2. *Mould Shape and Resin Pooling*

Mould complexity can also lead to pooling of resin in corners of the mould. These areas become heavy as the result of excess resin pooling in these areas, and as resin amounts are controlled by FVF under the assumption that distribution is uniform, resin heavy areas are also matched by areas where the resin content is below that required for good adhesion.

Both wet layup and resin infusion methods require a low viscosity resin mixture to ensure adequate workability and flow rates can be achieved during wetout. However the lower viscosity allows the resin to move freely under gravitational forces during the wetout and curing time. Using prepregs or other resin films reduces the resin flow path required between wetout and cure, allowing for the use of higher viscosity resins that do not flow as freely prior to cure. As outlined below higher viscosity resins are also chemically more capable of creating stronger cross linkages, resulting in an improved final laminate strength.

3. Resin Chemistry

The resin chemical type chosen for use in the mould will cure based on standard chemical reactions, dependent on ratios of molecules present in the fluid inserted into the laminate. Cross – linking between resin polymer chains provides the final matrix its strength, and so the chemical reaction must proceed correctly to ensure the highest possible strength from the matrix.

For Polyester and Vinyl – Ester resins, the cross linking chemically occurs using a catalyst which remains chemically passive during the curing. Therefore excess or insufficient catalyst does not affect the amount of cross – linking in the final matrix, only the speed of the cure. In contrast Epoxy is cured with a hardener, which takes part in the curing reaction. It is therefore vital that workers mix the correct amount of hardener is added and mixed well as the absence of hardener in any part of that prevents the epoxy cross – linking. The correct ratio and diffusion of the hardener through the epoxy resin is a critical worker skill required for epoxy resin use.

iii. Curing Process

The chemical process occurring during curing determines the final mechanical properties of the laminate, and ensuring that the required reaction takes place cleanly and in a controlled environment improves the predictability of the final laminates stiffness and strength. Emissions from the process can be harmful and so must be considered when choosing the resin.

1. Health, Safety and Environment

Improved FVF are typically the result of a more complex resin wetout method. Where prepregs provide the most controlled resin distribution method, the cost associated with prepregs extends beyond the costlier material prices to the requirement for cold storage in order to prevent the impregnated resin from beginning the curing process.

For the simpler resin infusion and vacuum bagging processes, dry fabric and resin are purchased separately and combined on the mould.

Composite resins cured under atmospheric conditions require no additional manual labour once the wetout is completed. Under the heating required by the resin the laminate is left to cure open to the atmosphere. While the simplest of methods available, the curing process can create additional harmful airborne emissions.

Polyester and Vinyl Ester resins pre cure are mixtures of the respective resins and a monomer, usually styrene that allows viscosity control for ease of use and the final curing cross-links. Styrene is hazardous to human health under concentrated or prolonged exposure, therefore open moulding processes require strict air quality control and monitoring systems to control worker exposure. Maximum exposure standards vary from country to country, however all national authorities require stringent monitoring and air recycling systems that are capable of protecting workers from dangerous exposure.

TABLE 58 – INTERNATIONAL EXPOSURE LIMITS FOR STYRENE

Country	National Exposure Limits[1]		
	8hr (ppm)	Short Term (ppm)	Short Term (mins)
Australia	50	100	15
Belgium	50	100	15
France	50	-	-
Germany	20	40	30
Italy	50	100	15
Poland	24	72	-
Romania	12	35	-
Netherlands	25	50	15
Spain	50	100	15
UK[2]	100	250	10

(1) Plastics Europe Technical Bulletin “Occupational Exposure to Styrene”

(2) Manufacturer has “Obligation” to reduce emissions to a minimum

As legal styrene levels are reduced across the international manufacturing industry there is a shift towards closed moulding techniques in order to minimise worker exposure to styrene. Vacuum bagging alone prevents emissions during cure, however the wetout process is still open to the atmosphere and invalidates the complex task of sealing and creating the vacuum pressure in the limited available resin gel time.

Combine the vacuum bag technique with resin infusion and emissions of styrene are reduced to nearly zero. The viscosity of a vinyl ester or polyester resin – typically controlled by styrene content – can be varied as required by the infusion setup without significantly altering the workers exposure to styrene emissions. For this reason, many shipyards in Europe are transferring from open mould wetout to resin infusion techniques in order to meet new health, safety and environmental required stipulated by EU or national regulations. Improvements in achievable FVF is an additional bonus.

2. Curing Requirements

The oven curing temperature and time for each resin is unique, and linked to the declared cured mechanical properties from the supplier. When comparing resin types the significant difference between the two higher performance resins (Vinyl Ester and Epoxy) is the tolerance to curing conditions outside of the prescribed range.

Both Vinyl Ester and Epoxy resins have a variety of curing conditions, which are specific to the resins unique chemical arrangement. Post cure is common for both resins to provide the highest final mechanical property values. Temperatures involved generally range from room temperature through to oven cured maximums of 85ºC, with higher temperatures normally combined with lower curing times. Given that both resins cure exothermically (Heat is released), external heating of the mould must take into account the internal reaction taking place, with the temperature must be kept below that at which the sandwich core foam may begin to chemically decompose and loose strength.

Infusion manufacture techniques also require lower resin viscosities to ensure the mould is fully wetted out before excessive levels of curing have occurred, which would prevent consistency of strength in the final structure. For Vinyl esters, the viscosity of the resin is controlled by the addition of styrene to the mixture, whereas the viscosity of an epoxy is shaped from the initial base monomer viscosity, something that is set during manufacture. Varying the viscosity to suit any given mould scenario is therefore a more complex task for epoxy, as the chemical alteration can only be completed during manufacture of the resin. In short, there is less control of the resins properties on the factory floor when using epoxy than for vinyl esters, and so the moulding process requires a greater level of pre mould analysis.

d. Impact of Future Technical Developments

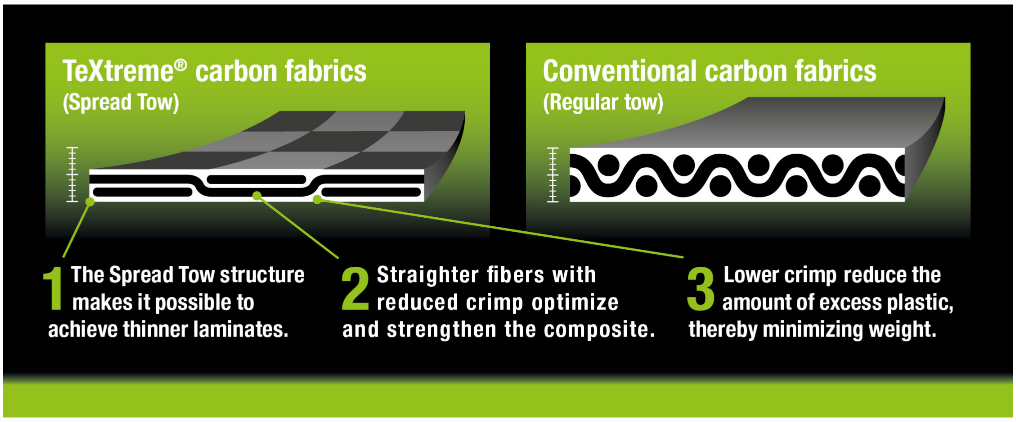
In an attempt to examine possible future paths for composite motor yacht construction, a brief investigation was conducted into current state of the art lamination methods used in aerospace. Where these technologies appeared feasible for motor yacht structure production, a summary of the method and the setbacks that currently prevent its use.

i. Fabric Improvements

In a perfect world, fibres in reinforcement fabrics are continuous and straight allowing them to perform at the maximum material property limits. However, the complexity of laying fibre strands in a single direction presents complexities on the production side.

Single strands of carbon fibre are typically presented in ‘tows’ – bundles of continuous fibres with cylindrical shape (As an aside E – glass fibres are usually sold as ‘yarn’, with torsional twisting of the fibres into the strand). Stacking cylindrical cross sections results in large voidspaces between fibre tows. These voids are filled with heavy and relatively weak matrix.

FIGURE 29 – SPREAD TOW AND REGULAR TOW FABRICS



(1) TeXtreme Spread Tow Fabrics Information Brochure

Flat or spread tow fabrics provide the carbon tows in square geometric shapes, allowing for improved tow stacking in the fabric, and thus greater fibre density per m^2 of fabric. This recent innovation in reinforcement fibres was used in the Americas Cup AC72s, providing improved performance on regular carbon tow fabrics. The thinner fabric also reduces the cured play thickness, and provides a smoother surface finish.

ii. Nano Materials in Resins

The inability of current epoxy resins to provide a matching compressive strength to the tensile improvements provided by carbon places a limit on the performance abilities of carbon laminates. By mixing carbon nanotubes with the resin prior to cure, it is possible to enhance the modulus and strength of the resin further.

TABLE 59 – NANOTUBE RESIN MECHANICAL PROPERTIES

Mechanical Property	Units	Unidirectional High Strength Carbon Fibre	
		Regular Epoxy[1]	Nanotube Epoxy[1]
Fibre Weight	g / cm^2	300	
Tensile Strength	MPa	2,844	2,220
Tensile Modulus	GPa	129	129
Tensile FVF	-	0.598	0.570
Compressive Strength	MPa	**1,187**	**1,640**
Compressive FVF	-	0.575	0.610
Cured Ply Thickness	mm	0.281	0.210
ILSS	MPa	79	75

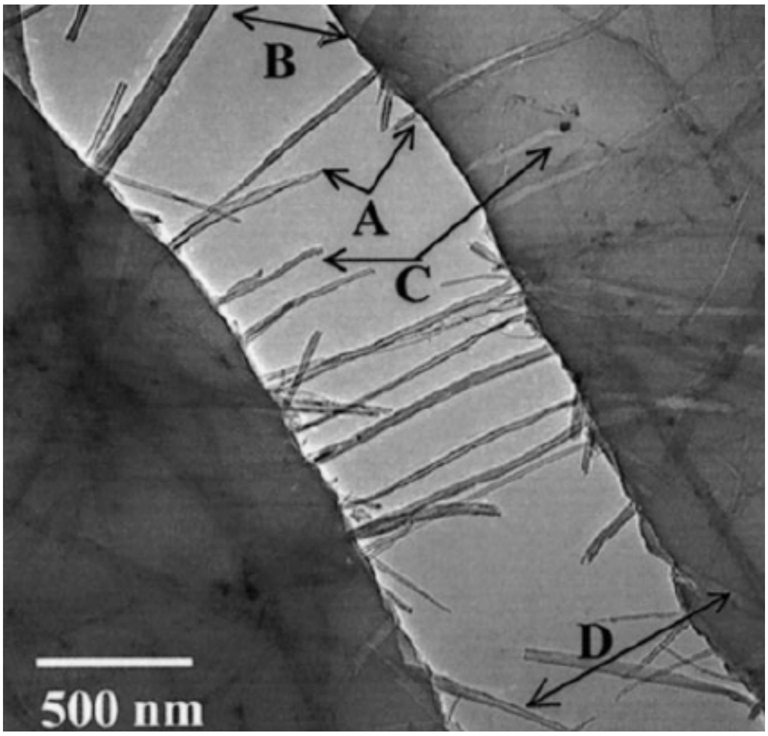
(1) Gurit, SE84LV and SE84 Nano Epoxy Prepreg with near matching cure process

(2) The Nano particles in this case are nano-silica spheres

Under compressive loading the nanotubes provide additional stiffness to the resin, raising the modulus of the matrix. The increased stiffness of the matrix raises the loading required to force fibre – matrix separation, a key component in the progression towards compression failure.

Where such cracks exist, either prior to or are created during loading carbon nanotubes will ‘bridge’ the crack, providing material support across the fracture, hindering propagation of the failure through the material. In this sense the nanotubes provide a significant boost preventing laminate failure through matrix / reinforcement separation.

FIGURE 30 – CARBON NANOTUBES BRIDGING MATRIX FAILURE



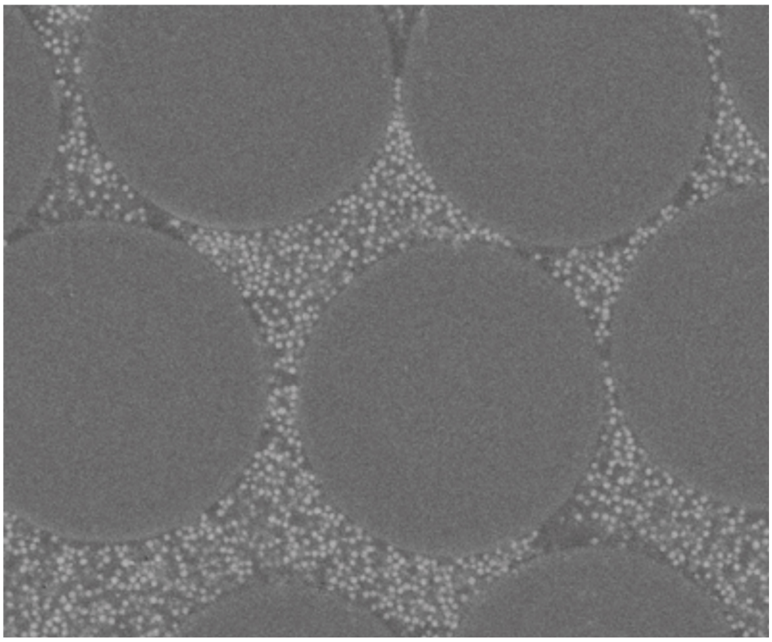
(1) “Load Transfer and deformation mechanisms in carbon nanotube-polystyrene composites” Qian, Dickey, Andrews, Rantell, University of Kentucky

The above image shows several nanotubes bridging a crack gap, providing strength normal to the crack direction, providing resistance to any further widening in the local area. Markers A through D show tubes that have fractured or slipped against the matrix, however numerous other nanotubes successfully cross the gap. The high modulus of the nanotubes themselves (270 – 950 GPa) provides very high stiffness in the crack normal direction.

The primary setback with nanotubes is the extreme difficulty ensuring a uniform distribution of the nanotubes throughout the resin. The nanotubes have a tendency to coagulate, given their long cylindrical shape. The large moulds produced with motor yacht construction mean the probability of coagulation of the nanotubes anywhere in the mould is unacceptable high. As such nanotubes are limited to prepregs with the significantly reduced resin flow path.

Alternate nanotechnology options are available in the market currently, all with the common goal of improving the resins compressive strength through the addition of stiffer material in a form that does not impede the curing process. The aforementioned Gurit nano epoxy resin makes used of nano sized glass beads, which with the help of specific surface treatment is capable of maintaining a uniform distribution throughout the resin when used in an infusion process.

FIGURE 31 – NANO SILICA BEADS BETWEEN CARBON FIBRES



(1) Gurit SP – High Modulus magazine "Advantage" 2011/2012 issue

Nano technology is still a new technology and is under heavy scrutiny, in terms of mechanical property improvements, material and manufacturing process reliabilities, and health concerns as nano particles are small enough to pass directly through cell membranes, and carbon in particular due to its importance in living cells.

iii. Reinforcement Layup Robotics

Currently all production methods used in composite motor yacht construction require the reinforcement – in tape or fabric form – to be laid up by hand. As with all human manufacturing operations in order to provide consistent layups between moulds a high level of skill is required from the worker. Robotics are used in numerous industrial processes globally to provide the consistency required for a certain worker task.

Developments in the aerospace industry composite structures include automated fibre placement (AFP) and tape laying (ATP) machines capable of placing reinforcement tows as required in a 'paintbrush' method across a mould of the final shape. AFP technology uses independent prepreg tows stored either within the machine head or nearby, which are heated immediately prior to placement on the mould, whereas ATP machines place an already fabricated tape of reinforcement tows as one fabric.

Positioning of the tow or tape spools is critical to the machines productivity, as spools placed in the machine head result in a bulky, obstructive and heavy placement head, where spools placed away from the head result in long, often complex thread paths for the tow to reach the placement head.

The relative movement freedom of the placement head confines each machine available to certain level of geometric complexity. As motor yacht surfaces can contain highly complex curvature AFP / ATP machines require a high number of DOFs to ensure that the machine can adapt to the more complex surface curvatures present in yachts.

FIGURE 32 – 6 DOF AFP MACHINE ON A COMPLEX MOULD

(1) Electroimpact Automation High Rail Gantry AFP machine

The development of high degree of freedom machines similar to the above figure allow for greater complexity in the moulds geometry. However currently discontinuities in the mould surface (Steps etc) can only be performed perpendicular to a head ‘run’, and so some limitations exist on the application of this technology to boat structures.

Currently this technology is being assessed for its commercial viability within the aerospace and automotive industries, with aerospace applications interested in improving strength / weight ratios of structures used and automotive industries interested in the repeatability of the process. Based on historical technology trends in composite maritime structures is feasible that this technology will be used in future motor yacht construction.

As all AFP research and design work is currently done with carbon reinforcements it seems logical that future commercial use of the machines will involve the higher performance carbon fibres. It is not expected to be commercially viable for motor yacht construction within the foreseeable future, as capital investment costs are excessive and the requirements for high performance materials / repeatability not as critical as for aerospace / automotive designs.

iv. Carbon Fibre Surface Treatments

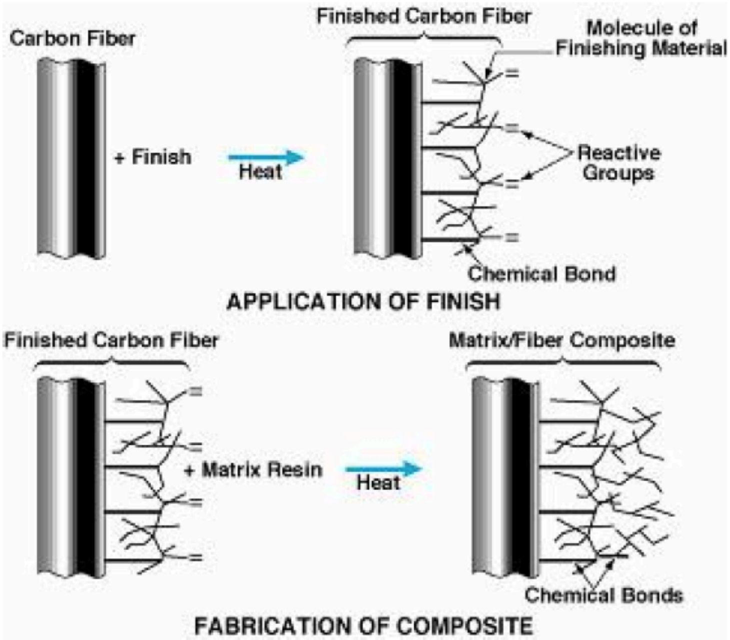
The cured properties of the laminate, in both tension and compression, are a function of the bond that exists between the reinforcement fibres and the resin. In the case of carbon the manufacturing process leaves a smooth finish to the fibres, making good resin – fibre bonding relatively difficult compared to the rougher finished E – glass.

Typically a final surface treatment of the fibres takes place before they are ready for compiling in tows for tapes and fabrics. This process is an extremely tight trade secret area, deep within the realms of material science and surface chemistry. The treatment process must be tailored to suit the tow sizing being treated.

It is industry knowledge that most surface treatments involve electrolysis, albeit with varying parameters, which are set for certain end results or tow sizings. There has been minimal incentive for manufacturers to alter from this tried and true method as most alternative methods present little to no improvement in performance. Thus the carbon fibre surface treatments have remained relatively static for several years.

Specific research is also underway into providing fibre surface treatments that encourage improved bonding between vinyl ester resins and carbon fibres. Improving the carbon fibre to vinyl ester interface would open up more resin infusion friendly vinyl ester resins to use with carbon fibre with minimal reduction in mechanical properties compared to a carbon epoxy layup.

FIGURE 33 – CARBON FIBRE SURFACE / MATRIX INTERFACE



(1) "Reactive Finishes for Improving Interfacial Properties in Carbon / Vinyl Ester Laminates" Allred, Wesson, Hoyt - Haight, Rantell, Adherent Technologies, New Mexico and Whitehead, Northrop Grumman Shipyard Systems, Minnesota

TABLE 60 – UD FABRIC 90º MECHANICALS & SURFACE TREATMENTS

Laminate Sizing Technique	Tensile Strength (MPa)	Modulus (GPa)	Elongation at Failure (%)
Unfinished Carbon Vinyl Ester	23.2	6.03	12.1
Hexcel Vinyl Ester GP Sizing	21.8	4.25	14.2
ATI Vinyl Ester Finish	43.2	5.64	20.3

(1) "Reactive Finishes for Improving Interfacial Properties in Carbon / Vinyl Ester Laminates" Allred, Wesson, Hoyt - Haight, Rantell, Adherent Technologies, New Mexico and Whitehead, Northrop Grumman Shipyard Systems, Minnesota
(2) Unidirectional Strength at 90º is predominately a function of fibre / matrix interface, failure mode being separation of matrix from fibre surface

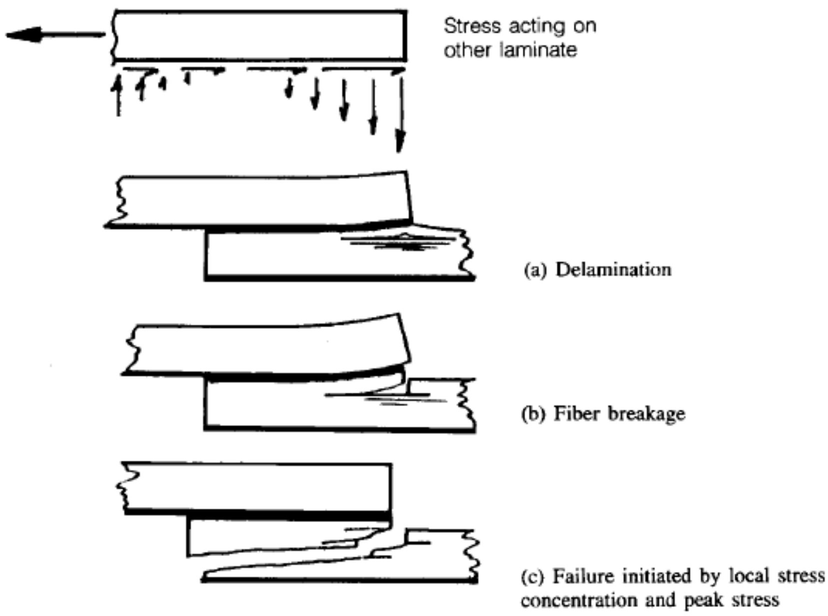
Significant safety, work skill and environmental advantages arise from using vinyl ester resin instead of the more difficult to handle epoxy. Therefore any innovations that provide improvements in carbon fibre / vinyl ester matrix adhesion would provide an improved mechanical properties, such that a vinyl ester cured matrix could provide near equivalent performance to epoxy at a significantly reduced overall manufacture cost.

v. Adhesive Bonding

Multiple composite laminates can be joined into one assembly in a variety of ways. Standard mechanical fastenings are the most reliable of options available to designers, as the technology is developed and failure modes known. However the method requires specific structural reinforcement at fastening points, additional geometry that complicates the moulding process (Particularly with infusion methods). Additionally the high stiffness of carbon laminates required that grouped fasters be fitted with a high degree of accuracy to minimise stresses caused by fastening tolerances. Where in metallic structures material strain around the boltholes encourages distribution of the load to account for dimensional variation the stiffness of carbon does not allow for such a load distribution.

Adhesive bonding simplifies the structure required to provide the fastening point(s) between the parts to a series of flat planes, relying on a curing adhesive to chemically bond the two parts together. As the load is transferred through shear stresses, failure modes occur both within the adhesive bonding material and within the laminates. For thick, sandwich layups this shear is a critical issue.

FIGURE 34 – LAMINATE FAILURE MODES IN BONDED COMPOSITE JOINTS



(1) "Composite Airframe Structures" Michael Niu, Conmilit Press Ltd 1992

Ensuring the adhesives shear strength is not exceeded, the process of adhesive bonding composite parts simplifies part geometry and remove any risk of material failure due to fastener loading imbalances. For this reason adhesive bonding is a focus for the marine industry as motor yacht structures are not completed to the tolerances seen in the aerospace industry, thus mechanical fasteners are less favoured.

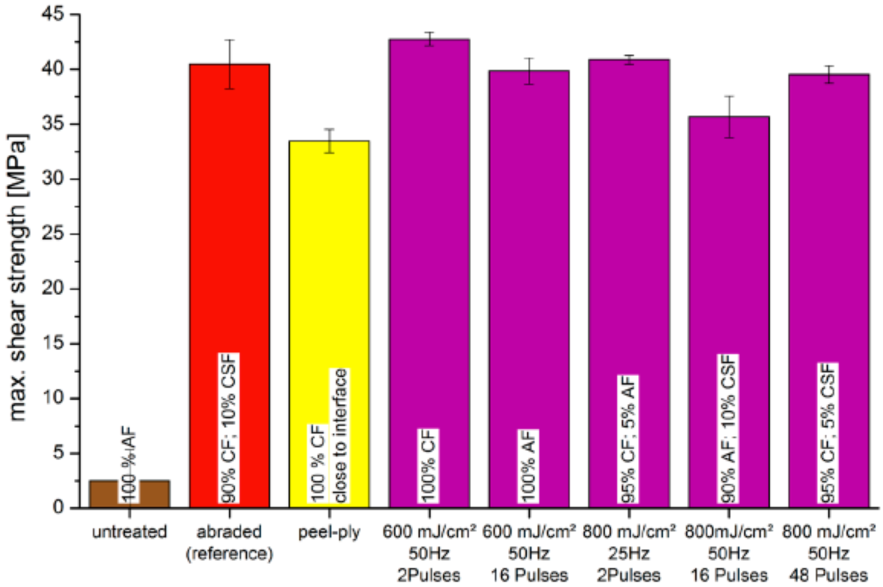
Research is continuing into both adhesives and connection point design, with flow down of technology from the aerospace industry where adhesive bonding is typically used in conjunction with mechanical fasteners to provide surety to critical aircraft joints.

Additional work is being conducted into surface preparation methods that minimise stress concentrations and surface contaminates present on the bonding surfaces. Surface cleaning by mechanical means runs the risk of damaging the reinforcement fibres, and chemical cleaning of the surface may result in a weakening of the matrix in proximity to the bonded surface.

The use of peel plies provides a controlled process of creating a suitable ‘roughness’ on the bonding surface. After placement on the surface during the curing process they are removed prior to adhesive bonding, creating a clean, corrugated surface to improve the adhesion between the parts. Although an acceptable solution for most composite part bonding it cannot guarantee all impurities are removed from the surface. Peel plies also become cumbersome for larger adhesion areas, as in some marine structure joints.

Laser based surface cleaning allows for the removal of impurities from the bonding surface by vaporisation and is a controllable, repeatable process. However the laser type and strength must be closely controlled to ensure the high heat conducted through the carbon fibres does not significantly damage the matrix. Too low laser intensity and the surface impurities are not all removed, too high an intensity and the matrix and fibres may be damaged.

FIGURE 35 – LASER SURFACE TREATED ADHESION SHEAR STRESS



(1) "Using Excimer lasers to clean CFRP prior to Adhesive Bonding" Reinforced Plastic Article September / October 2013

Research and feasibility studies are ongoing, targeting use in aerospace structures. Initial results have shown improved shear strength compared to peel plies. However marine applications of the process is also feasible noting the greater cost effectiveness demand for motor yacht production.

vi. Laminate Behaviour Investigation

The exact nature of inter layer behaviour is still a subject of heavy research. Determining the strains within each individual layer independently has proven difficult to physically measure without the instruments affecting the results. Standard strain gauges require physical cabling out from the laminate, and the small ply thicknesses involved mean that the installed gauge will effect fibre alignment to the load.

Advantages in alternate methods based on optical measurements has allowed for the installation of methods that minimise the fibre misalignments induced by the measuring instruments Fibre optic strands can be placed within the laminate at the point of manufacturing, the strain being measured as variation in the light travel time and reflectivity.

FIGURE 36 – FIBRE BRAGG GRATING SENSORS USED IN ALLINGHI 5

(1) Photo from Alinghi Syndicate Website

Fibre Bragg sensors have been used in advanced marine composite applications previously, with Americas Cup challenger Allinghi installing fibre optic strands in their hull and rigging during construction, which were able to provide in-race strain and stress at key structural points throughout the yacht.

7. Conclusion

The chief drawback in choosing carbon as the reinforcement material for a sandwich composite design has always been the higher material costs. This has been the major reason why carbon has not become the reinforcement of choice within the motor yacht industry as reinforcement of choice.

However, this thesis has shown that carbon can be a feasible reinforcement material option in either all-carbon or hybrid setup designs. The yachts *Ermis*^{2} and *Laurel* are testament to the full carbon and hybrid design setups respectively.

Carbon however only provides strength in tension, and so the resin must be selected and cured in such a way such that the tensile strength of the carbon is not annulled by weak compressive strength of the resin. When combined with high performance resins (epoxy), and the more tightly controlled production techniques (eg resin infusion), the carbon fibres are capable of performing to their full with matching compressive strength from the cured resin.

The simple beam theory investigation showed carbon fibre delivers greater stiffness for a given core thickness, which becomes beneficial as beam length (or stiffener spacing) increases. The improvement from the use of a stiffer material is only of significant benefit in medium to large motor yachts.

The FEA analysis results show that carbon provides measurable benefits with minimal increase in material costs. When the objectives of a motor yacht structure are to be unobtrusive, lightweight and cost effective carbon provides the best overall result for the yacht. The full flow through effect of carbon has not been analysed in this thesis but it can be expected to be of additional benefit (eg. Reduced resistance due to lighter hull displacement).

TABLE 61 – COST, WEIGHT VARIATION FROM CARBON CONTROL

Material Setup	Total Number of Layers[1]	Web Depth (mm)	Weight Penalty (kg)	Cost Saving (€)
Carbon Control[2]	16	180	(600)	(31,364)
E – Glass Core	16	243	274	2,446
E – Glass Reinforcement	23	180	349	- 2,176
Hybrid Core	16	209	188	3,927
Hybrid Reinforcement	20	180	234	1,073

(1) Total number of layers in stiffeners – Indicative of whole structure

(2) Carbon Figures included as baseline values

For the new fast displacement Azimut Benetti yacht used as the case study in this thesis, an all carbon structure makes sense for the benefits associated with a shallow depth, lightweight superstructure deck. The slightly higher material cost being offset by the lower hull weight, and improved efficiency. The additional option remains for a hybrid setup, placing the carbon in the stiffener flanges with deck plating completed with E – Glass to reduce costs. Both design choices display large advantages over the more standard all glass structure.

Additionally, as environmental regulations begin to restrict the use of open wet out processes, shipyards are being forced to adopt closed moulding techniques. As these techniques improve the quality of the final laminate, it becomes more beneficial and viable to improve your resin and reinforcement materials, from say polyester to epoxy and E – glass to carbon.

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