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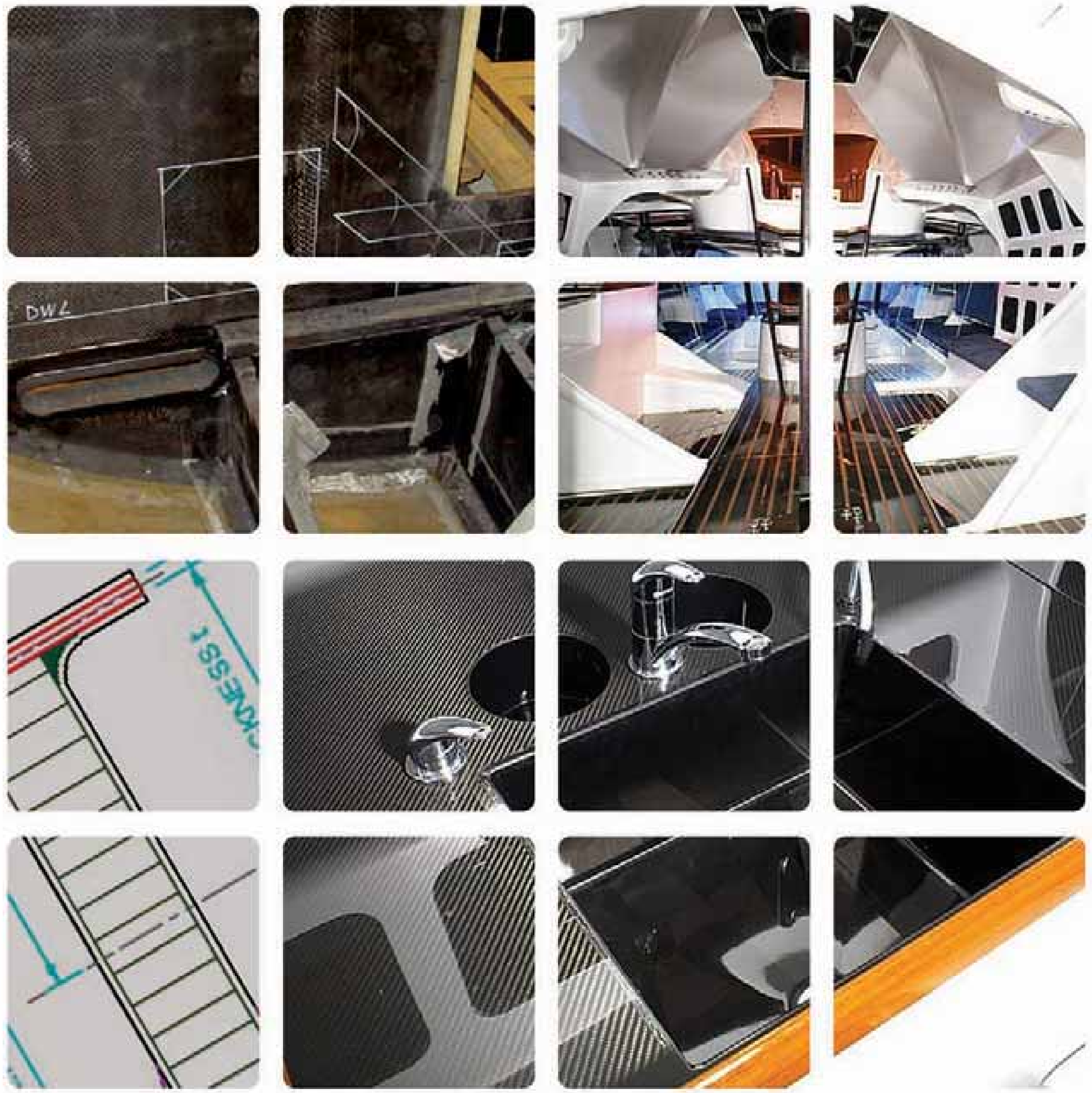
# Superyacht Structure Insights

## The interaction between interior and structure, in planning the layout of a composite superyacht



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# INTRODUCTION

**This booklet is intended for interior designers and naval architects, aiming to help create a simpler structural design at an early stage of a superyacht project.**

**The challenges faced by the structural engineer behind each compromise are highlighted in each section, but the focus is on practical suggestions, rather than technical explanations.**

In today's competitive design environment, is it neither enough to design a racing yacht focused purely on meeting technical efficiency targets, nor to design a cruising boat focused purely on comfort and elegance.
By combining speed, handling, seaworthiness, functionality, comfort and elegance, the steady growth of the superyacht market pushes the boundaries of each of these conflicting requirements.

Producing a yacht inherently leads to clashes between the requirements of each party involved. To satisfy the designer's, builder's and interior designer's wishes, compromises on the structure are made depending on the relative importance between weight, comfort and cost. Whichever compromise is made, a yacht has to be capable of withstanding the loads that she will be subjected to during her lifespan.

These challenges can be overcome by working closely together to understand the objectives that each party wants to achieve.

Comfort is measured via different considerations: feeling of an open space between each bulkhead, light coming through portlights and hatches, headroom, systems on board, flexibility of the interior design…

Designing for each of these considerations has become a requirement, and it is typically leading to challenging compromises…

***Katia Merle*** *Design Engineer*

Other useful references:

***"Comfortable Structure"***, By Rozetta Payne and Nicolas Siohan
***"Challenges associated with design and built of composite sailing superyachts"***,
By Rod Fogg and Marion Meunier

# GENERAL ARRANGEMENT

Taking the structural requirements into account whilst defining the general arrangement can lead to major saving in terms of design time, complexity of build and weight of the structure. A structure-friendly general arrangement is also key to the performance and the general behaviour of the yacht during her lifespan.

Unlike metal structures, a composite structure does not require a tight grid of transversal and longitudinal stiffeners. The use of composite materials can offer much longer unsupported spans, creating physical space for the interior designer for less cramped accommodation space. However the location of the transverse supports (bulkheads) is critical for the structural design, and the following points should be considered:

**Closing the boat at key locations reduces global deformations and provides sufficient support for the main load paths**.

Reasonably full transverse bulkheads (see section on bulkheads) are required in way of the mast and in way of the keel structure to take the grounding load. Provision should also be made for a supporting bulkhead in way of the inner forestays and mainsheet.

In between these major enclosing partitions, bulkhead spacing will have an effect on the stiffness of the hull panels. Excessive deformation would be visible from the inside through the furniture moving, and or cracking, asides the concern over the structural longevity.

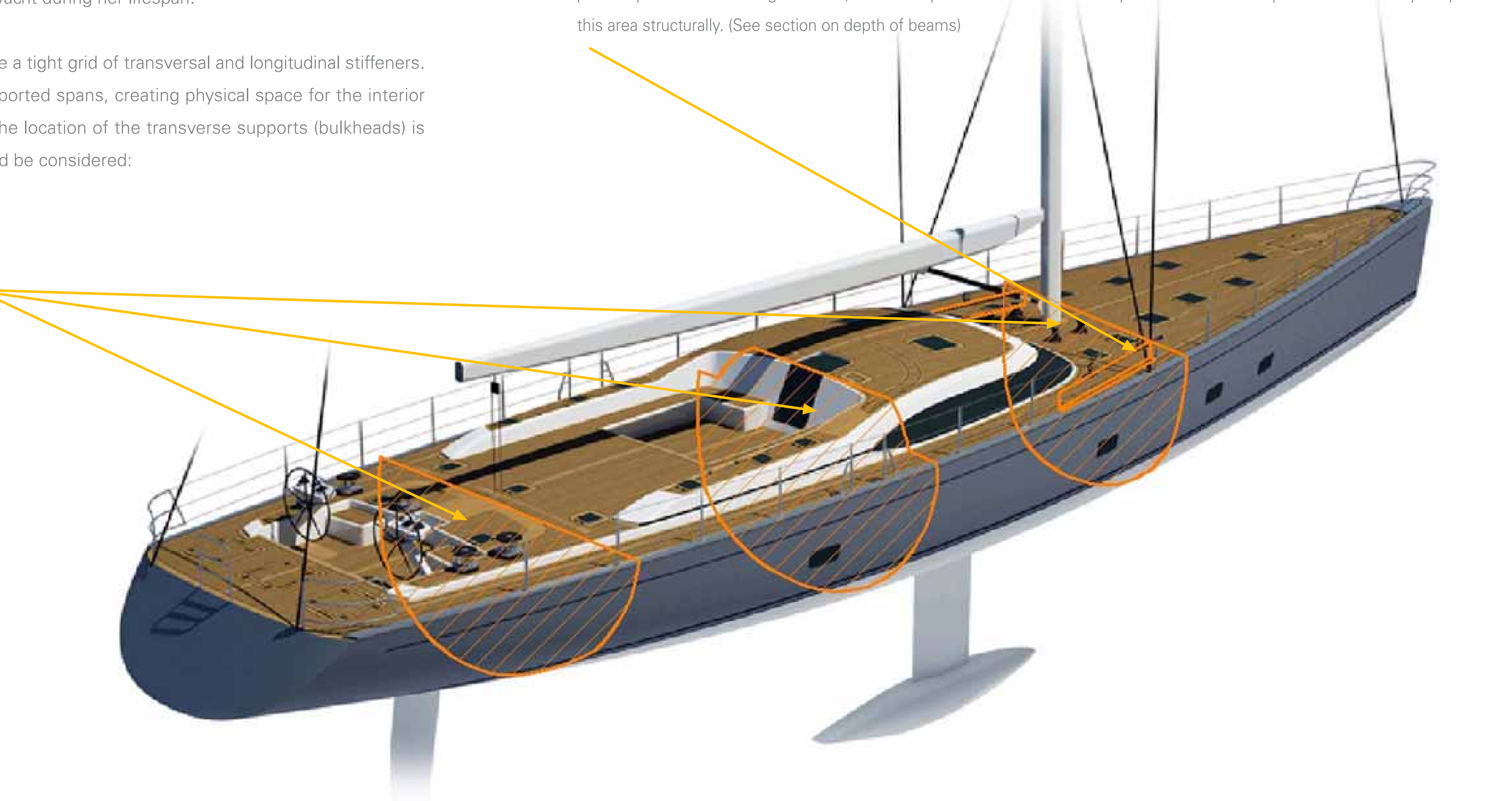
In most cases, the acceptable bulkhead spacing ties in with the volume required for the main accommodation space, but this should be discussed at an early stage to avoid complications.

The mainsheet is often located within key accommodation space, and the need for structure in this area is often left aside until the structural requirements are highlighted.

The mainsheet on a 100' superyacht will typically see around 8 tonnes working load. In order to support this very high load, substantial structure below the mainsheet track is required.

SP's experience is that compromises made against the structural requirements at these locations have rarely paid off. A General Arrangement that provides insufficient support to these highly critical load paths always has a very negative effect either on the structural behaviour or the weight of the structure. In any case it leads to more complex solutions, which are bound to be expensive to design, and complex to build.

In most cases, jib sheet loads are fed into the structure via a support beam below the track. Running the jib track support beam forward and aft to the next substantial bulkhead is usual. The structural efficiency of the support beam is largely related to the proximity of the surrounding bulkhead, and it is important to look at the deck plan and the interior space simultaneously to optimize this area structurally. (See section on depth of beams)



**Longitudinal continuity and transverse symmetry at main load points can help to make a good structure.**

Longitudinal discontinuity can affect the global behaviour of the structure. Where the interior design imposes constraints to the hull and/or deck beams layout, the structural continuity might have to be forced by joining misaligned beams together. This is not an ideal situation: it requires additional work for the builder as well as inducing concentration of load in the structure.

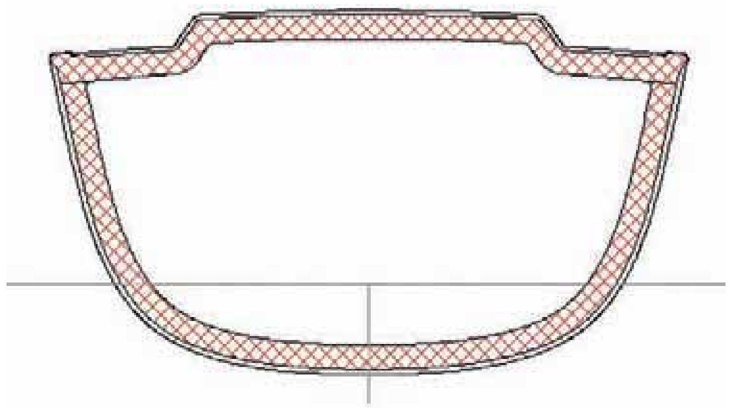
Each component of the general arrangement provides an opportunity for the load to dissipate, whether it is intentional or not. Therefore the asymmetry of the arrangement often leads to the asymmetry of the structural behavior, which has to be avoided on the primary structure. (See section on non structural panels)

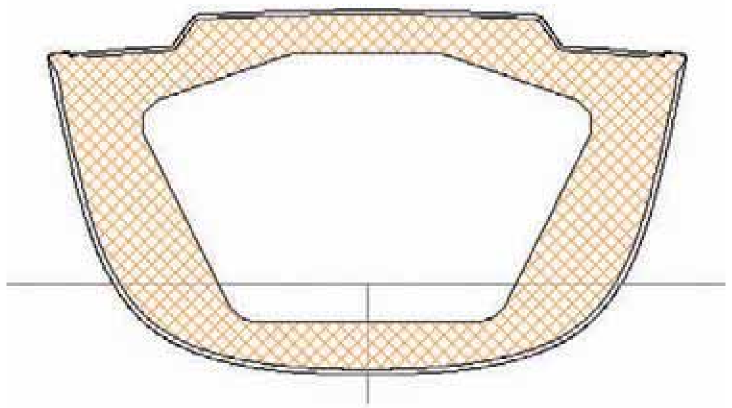
# BULKHEAD SHAPES

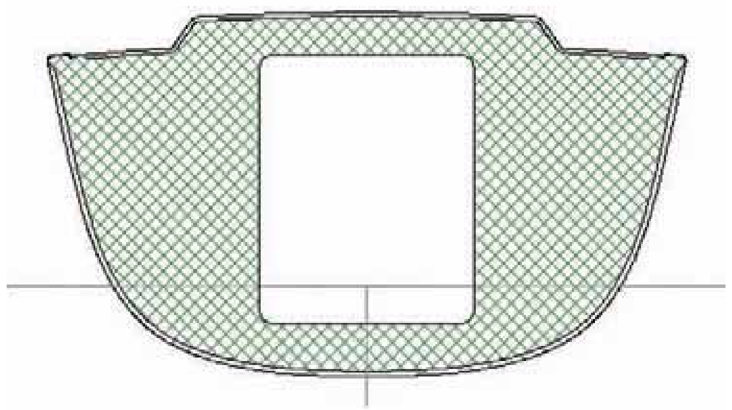
Provides limited support to the structure, only acting as hull and deck beams. Can lead to excessive deformations and weight/cost penalty

Provides enough support for highly loaded areas of the structure, but the geometry is critical and has to be discussed and defined at an early stage

Provides full support to any area of the structure







Ring frames provide adequate support to the hull and deck shells in areas that are not highly loaded by the rig.

However they provide limited support to the overall distortion of the boat: the bulkheads directly forward and aft will need to be substantially fuller to avoid global deformation. Using this type of arrangement is less efficient and requires more engineering effort.

**Ringframe depth is a key parameter for their structural efficiency, very shallow ring frames will induce a weight penalty, and require a more detailed analysis** (see section on beam depth).

The geometry of a central opening often can be modified to suit the internal space required and provide an efficient structural load path.

Bulkheads highly loaded by rig and keel loads are often located in areas of the boat where the interior wants to be as open as possible. The compromise illustrated above is a common solution, where only the portion of the bulkhead that is structurally useful is kept.

**Support relies on the geometry of the central cut-out and this should be defined as early as possible.**
The location of additional cut-outs should also be defined at an early stage as most parts of the bulkhead are likely to be highly loaded and in this case particularly the lower outboard corner.

A full bulkhead with a central opening that provides a reasonable depth at hull and deck offers the most complete structural support to the boat. It provides hull and deck shell support as well as providing means of dissipating the load more evenly.

However, aside the key areas highlighted in the general arrangement section, there is not a requirement for all bulkheads to provide this level of support.

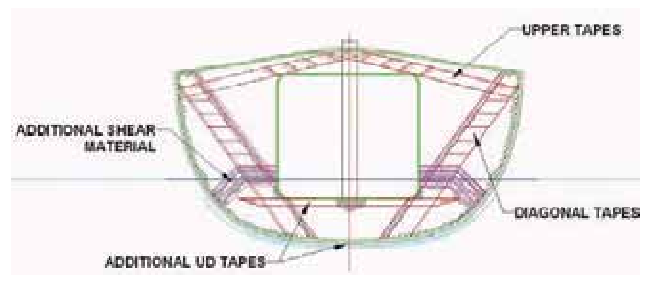
**Having anticipated the need for running systems or any other factors affecting the geometry of the bulkhead, it is often preferable to make it as open as it will need to be, as early as possible in the design.**

# AN IDEAL MAST BULKHEAD

The main purpose of a mast bulkhead is to transfer the mast compression load towards the rest of the structure generally via the topsides.

Diagonal tapes are often used to transfer the load from the mast step towards the topside, and upper tapes are required to prevent the section from closing under the mast compression.

See below for typical additional reinforcement for a mast bulkhead.




To assess the impact of the opening size on the cost and weight of the bulkhead, three different designs of mast bulkhead are shown, with varying opening size.

The first design, from an engineering perspective, is ideal. For bulkhead n°2 and n°3, additional shear material and unidirectional tapes are required in the bottom part of the bulkhead.

| | BULKHEAD n°1 "TRIANGULAR" OPENING | BULKHEAD n°2 "MEDIUM" OPENING | BULKHEAD n°3 "MAXIMISE" OPENING |
|---|---|---|---|
| WEIGHT (kg) | 172 | 222 (+30%) | 305 (+77%) |
| MATERIAL COST (AUD$) | 9364 | 11994 (+28%) | 15826 (+70%) |
| LABOUR COST (AUD$) | 6300 | 8460 (+34%) | 9360 (+48%) |
| GLOBAL COST (AUD$) | 15664 | 20454 (+30%) | 25186 (+60%) |

Find more about this study in *"Comfortable Structure"*

# DECK HATCHES AND HULL PORTLIGHTS

**Can interfere with some of the most important load path of the structure, and add complexity to the analysis and build of the boat**

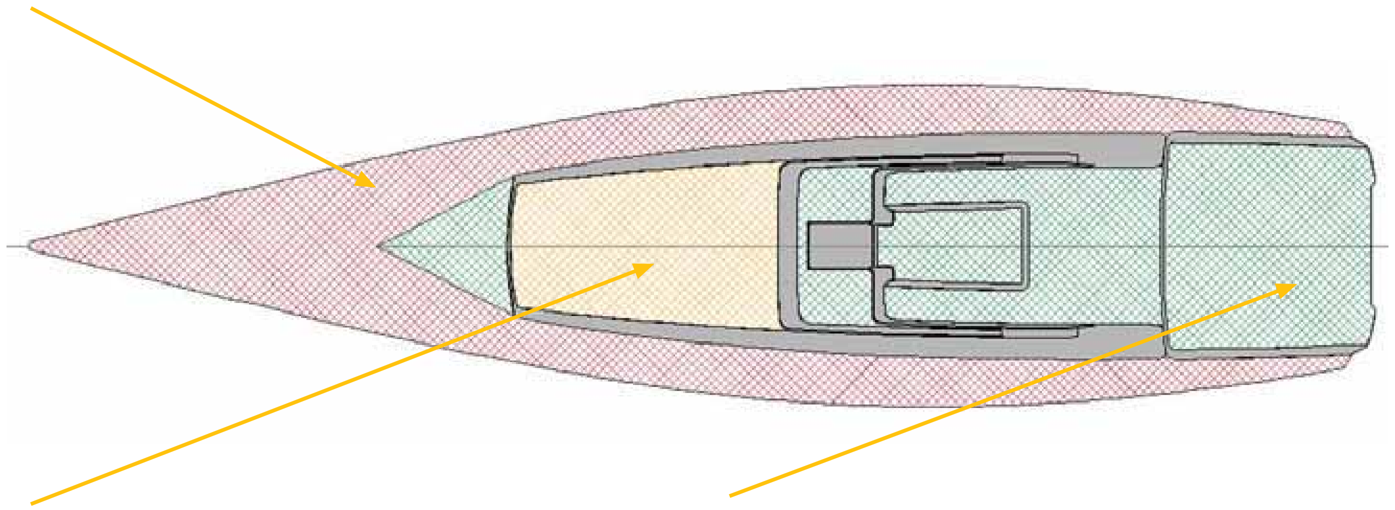
**Requires specific local considerations but does not interfere with the overall behaviour of the structure**

**Do not interfere with the overall behaviour of the structure, local reinforcement is typical**

The flat deck offers a natural load path for the longitudinal bending of the boat, which is a crucial performance driver. Deck hatches in this area will interrupt or limit the fore and aft load path, and create high stress concentrations.

The use of full width deck tapes to stiffen the hull girder is a viable solution for boats up to 22m to 25m. It presents many advantages, one being its simplicity in terms of design, built, and minimum interaction with styling and interior design.

Other solutions, such as solid planks of unidirectional fibres, have to be considered as boat length increases, but in any case **there is a requirement for all parties in the design team to discuss the requirements in way of the side deck at an early stage of the design and determine acceptable compromises, as this can affect placement of deck hardware.**
Read a detailed study in "*Challenges associated with design and built of composite sailing superyachts*"

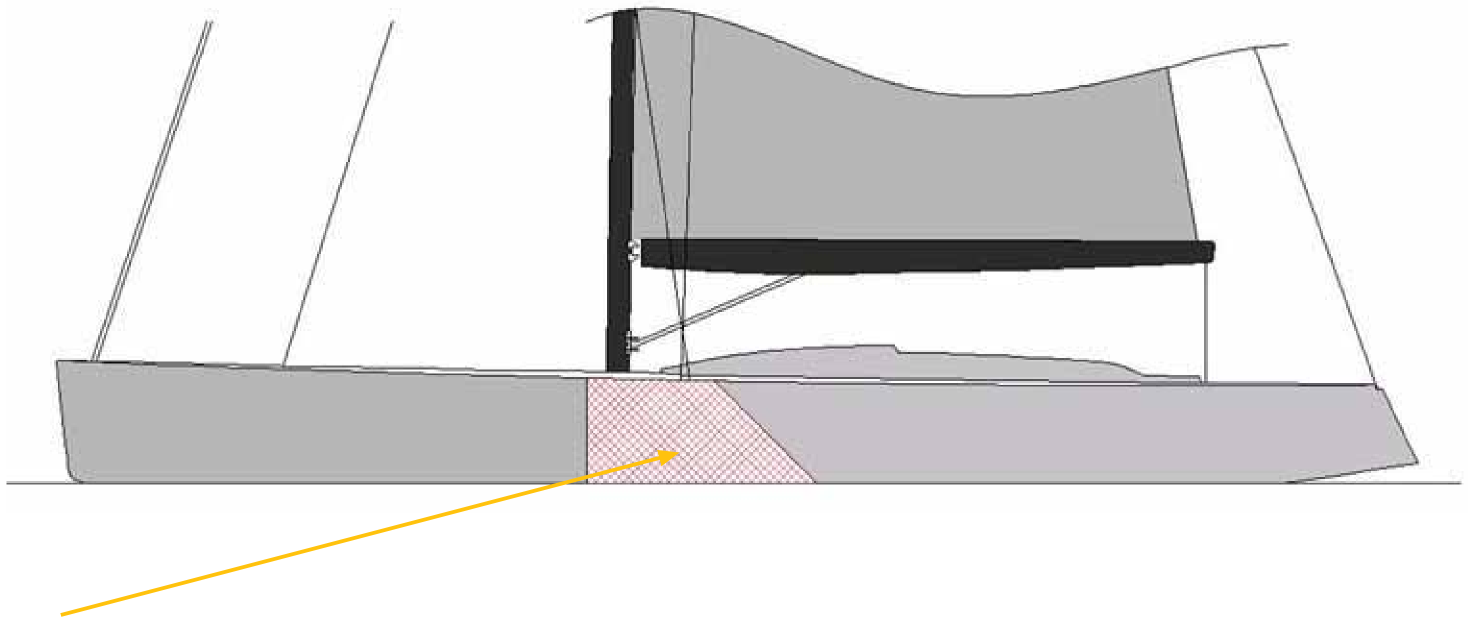


The equilibrium between shroud tension and mast compression creates a highly loaded load path through the strip of coachroof that links the mast to the shrouds. Avoiding deck hatches in way of this load transfer can significantly reduce the amount of reinforcement required locally.

The central part of the deck, due to its geometrical discontinuity, is not naturally providing a load path for the longitudinal bending. Deck hatches in this area are not critical to the overall longitudinal bending and, providing they have reasonable dimensions, they can often be locally reinforced without major consequences.

**However large openings affect the torsional rigidity. This global loading of the boat is more difficult to measure, and compensating for the loss of torsional rigidity is harder than for the longitudinal bending. Large openings can lead to complications in the design, serious weight penalty, and unexpected deformations.**

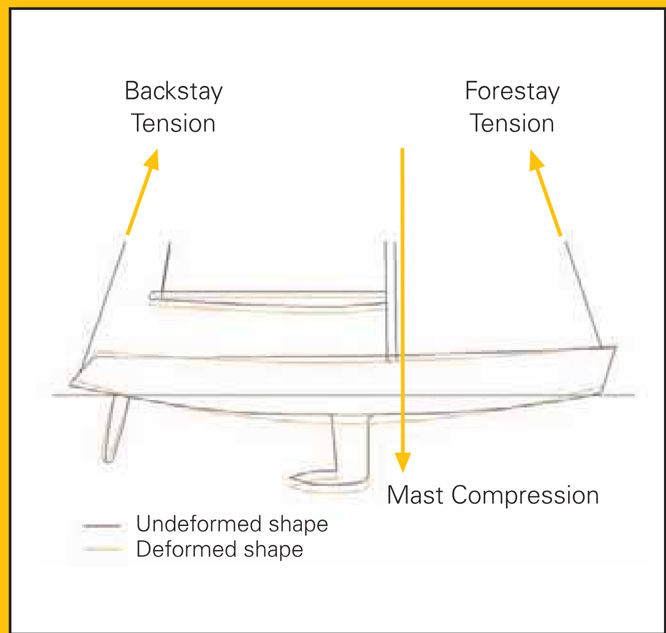




Shroud tension is transmitted from the fitting to the hull topside, often through a structural panel bonded to the hull topside. The hull experiences very high loads locally and **portlights should never be located directly below the shrouds**. As a guideline, they should be avoided in an area defined by a 45° line each side of the shroud support.

The proximity of the mast and its supporting bulkhead creates a much stiffer load path forward of the shroud panel than aft of it, therefore portlights should also be avoided in way of the critical load path between the shrouds and the mast.

# THE LONGITUDINAL BENDING




One of the main global loadings to consider when designing larger sailing yachts is the longitudinal bending moment induced by rigging loads. This loading is caused by the tensile loads in the forestay and backstay pulling upwards on the bow and the stern, whilst the mast compression opposes with a downward action. The deck is subjected to compressive load, the hull bottom to tensile load and the hull topside to shear force.

Larger boats tend to have taller rigs and higher righting moment; it has been shown that the maximum working forestay load increases exponentially with boat length.

As boats get bigger, they also tend to get sleeker, i.e. the length increases more than the depth.

This is why it becomes more and more challenging to meet the required longitudinal stiffness with increasing boat length.

# DEPTH OF HULL AND DECK BEAMS

**Highly stiffness driven or locally highly loaded beams require increased beam depth**

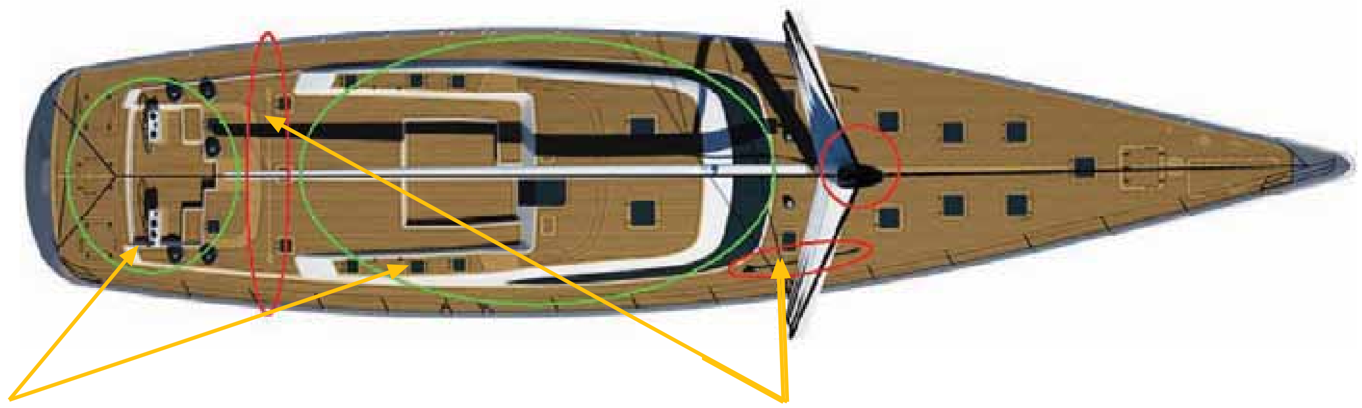
**Potentially more lightly loaded beams can be reasonably shallow**

**Typically the fewer the number of beams, the more highly loaded they are. A very open interior design, or a large unsupported panel in one specific area, will require deeper beams.**

The general arrangement provides support to the hull and deck shells, whose laminates are defined to provide enough strength and stiffness to panels up to a certain size. In addition to the main bulkheads and partitions, hull and deck beams are added to divide the panels further where required.

Hull and deck laminates can be made stronger and stiffer to accommodate a very open interior design with larger unsupported panel sizes, but this implies that each dividing beam or bulkhead will have to support higher loads.

**In addition to this, some areas of the boat require specific support from hull and deck beams. Providing enough depth below deck or below the sole level allows significant savings, and it can become essential in some areas.**



The depth required for deck beams in these areas is mainly dependent on the size of deck panel supported. Assuming numerous beams can be accommodated, the cockpit and coachroof areas are not subjected to specifically high loads.

Jib track support beam and mainsheet support tend to be highly stiffness driven. Allowing for deep beams below deck can lead to major savings, and greatly help reducing the deflections. As a 10% increase in beam depth gives around 20% increase in stiffness, important gains can be made by accommodating deep beams at these locations.

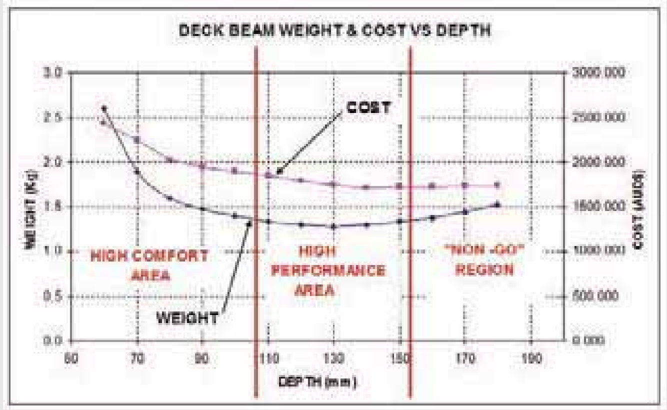
Hull pressures are lower towards the stern, which makes hull beams lightly loaded in this area

Rudder bearing support requires significant depth above the hull level

Keel loads are obviously very demanding for the structure; even a fixed keel arrangement will require deep beams between the mast and keel bulkheads.



## THE WEIGHT AND COST OF DECK BEAMS

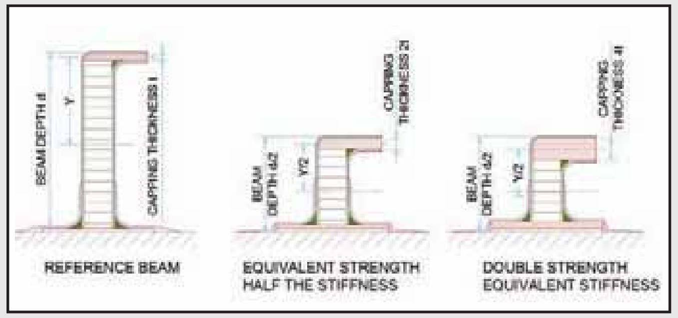



The case study above deals with longitudinal L-flange carbon deck beams located under the side deck of a 65' racing yacht. It illustrates a general behaviour, and similar results will be obtained by looking at most beams of a larger superyacht.

The results show that weight and cost are highly sensitive to the geometry of the beam, with both decreasing as the beam depth increases until they reach their respective minimum. Past this minimum, weight tends to increase again, whereas the cost stays constant.

By splitting the analysis domain in three regions, it can be seen that comfort comes at the expense of cost and weight. The results also show that selecting a beam deeper than the optimal depth is to be avoided as there is no benefit in term of cost, weight or comfort. As the load increases, more depth will be required, even when the compromise goes in the direction of the high comfort area.

Find more about this study in *"Comfortable Structure"*




Halving the depth of a beam will require twice the amount of laminate to regain the equivalent strength. This might be an acceptable compromise in certain circumstances, to accomodate internal space.

However, in order to regain the full stiffness, the laminate has to increase by a factor of 4, which represents a large loss of efficiency of the beam.

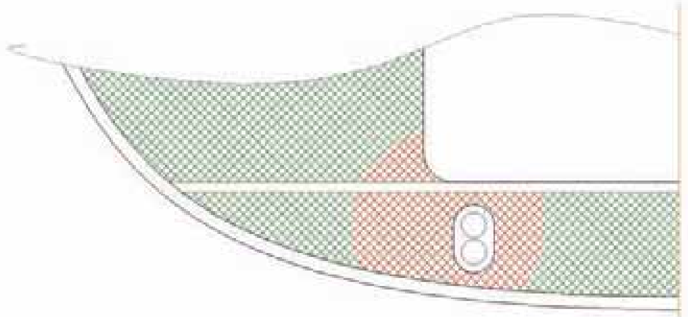
As highlighted on the left, some beams are highly stiffness driven, and providing enough depth in these areas allows significant savings.

# PENETRATIONS

**One fundamental difference between a metal construction and a composite construction is the effect of penetrations on the structure.**

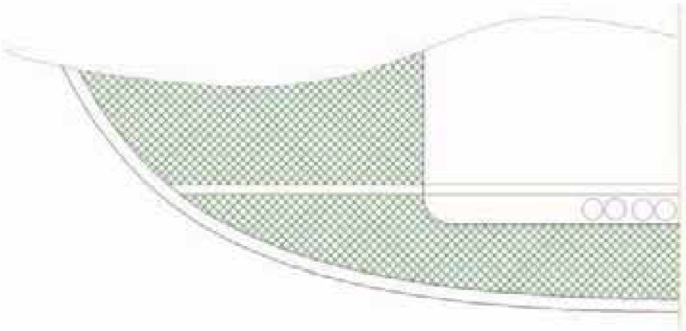
A metal construction will often include a large number of lightening holes, which offer numerous options for running systems along the boat.

A composite structure is tailored to each load path, and the way the load dissipates into the structure implies that every penetration will create a stress concentration, more or less critical depending on which load path it is interrupting. The analysis and the build time required for reinforcing each penetration and ensure the integrity of the composite structure can be greatly reduced with good anticipation. A careful approach to running systems is required, and penetrations need to be considered at a very early stage of the design.



Typically, penetrations will run close to the hull or deck surface and interfere with beams or shallow portions around the perimeter of bulkheads.

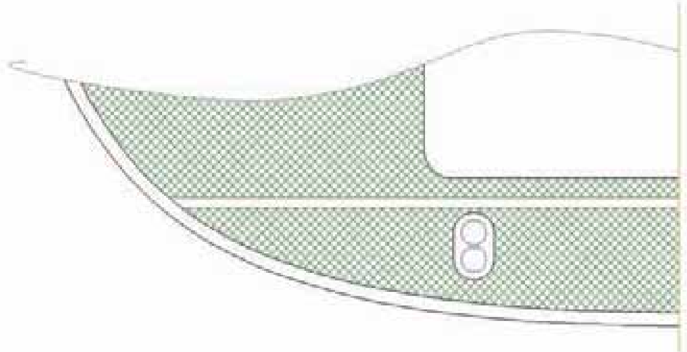
**The penetration will locally reduce the shear depth of the beam, increasing the shear flow above and below the cut out, as well as creating an additional stress concentration at the corners of the cut out.**



One option is to **lower the depth of the beam, and run the systems above the beam**. By doing this, the stress concentration is completely removed.

The weight / cost penalty depends on the depth of the beam and its required stiffness.

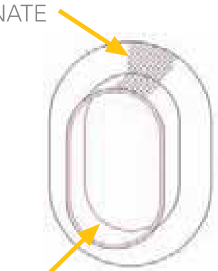
This option is particularly favoured when numerous penetrations are required through the same part.



Another option is to **increase the depth of the beam to accommodate the penetration**. Large penetrations can affect the structure significantly, and generally cut outs less than 1/3 of the beam depth can be accommodated. The lost material can be fairly easily replaced, and this option presents the advantage that a deeper beam will be stiffer (see section on hull and deck beams). However it does not remove the stress concentration created by the cut-out, and peppering beams with cut outs will lead to complications for both the structural engineer and the builder.

**All penetrations should be reinforced locally to cover the stress concentration,** generally with unidirectional tapes around the perimeter and biaxial patches around the edge and lapping on the panel.

Depending on builder's preferences various techniques can provide the required reinforcement (illustrated here is a pre-made composite tube bonded to the panel). The panel itself might also need additional reinforcing around the penetration.

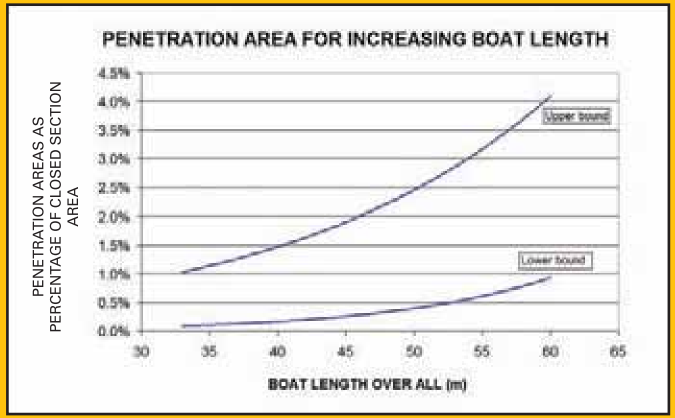


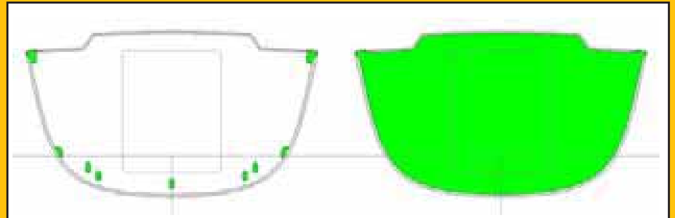

In general it is preferable to reduce the number of penetrations and group several systems into one larger penetration.

The large cut-out can then be reinforced as required, and this reduces the stress concentration.

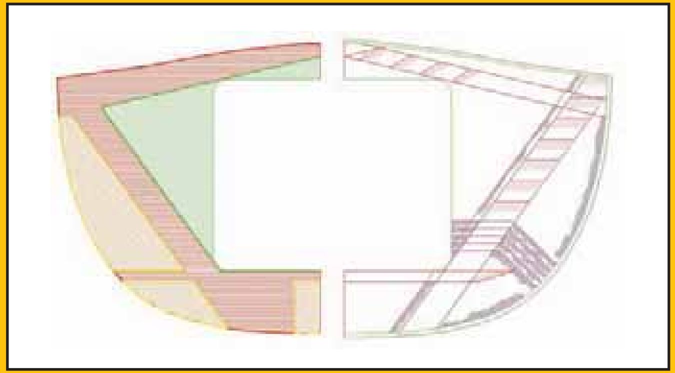
If penetrations cannot be grouped, sufficient spacing must be left between them.

## EXAMPLES OF AN INCREASING CHALLENGE




As illustrated above, the percentage of area taken by penetrations increases dramatically with boat length. With increasing comfort on board, the large amount of systems running through superyachts leads to new challenges for the composite structure.



As illustrated above, the location of cut-outs in relation to the structural laminate of highly loaded panels is crucial.

**As a golden rule, no penetration should go through reinforcing tapes (red area)**.

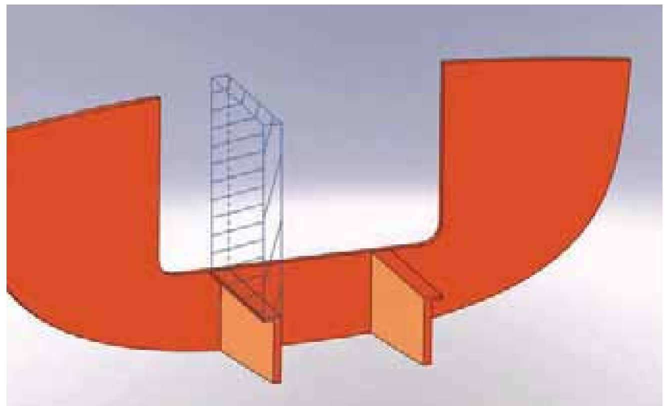
Depending on the load path, moving a penetration from one side of a capping plank to the other can have a great impact on the structure (green to orange areas). Very often the approximate load path can be established early in the design, and potential cut-outs should be discussed at that stage to define acceptable approximate location.

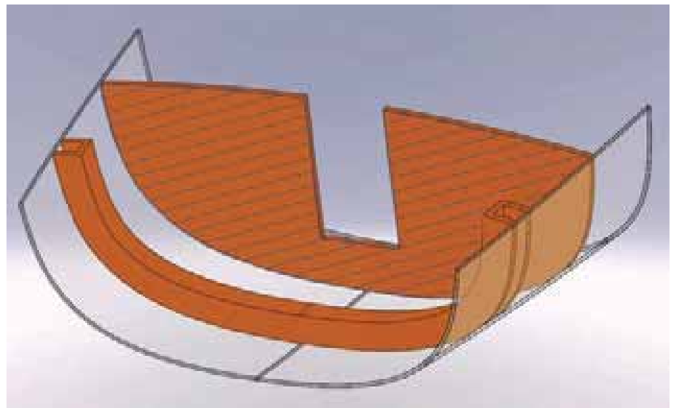
# NON STRUCTURAL PANELS

One aspect of the design philosophy that greatly affects the interaction between interior design and structural design is the decision to integrate all interior panels to the structure, or to separate them out.

The first option will naturally lead to a lighter, more efficient design, as it reduces redundant panels and makes structural use of every part of the interior. However, when this philosophy is adopted, a very efficient communication line is required between each parties involved. If badly managed, this interaction can lead to delays in the project, as well as cost and weight penalty because of the complications it can bring for both the interior and the structural designers.

Making the decision to separate from the structure most panels required for interior accommodation can represent more freedom. It provides more flexibility, and various interior options can be looked at without this delaying the structural analysis and the built of the main components. However, large non structural panels will naturally pick-up some load, and it is crucial to adopt a global approach to both the interior and the structural layout.





In the example illustrated above, a non structural internal partition is added on the top of a longitudinal hull beam.

The difference in stiffness between port and starboard resulting from the addition of this panel can be very large.

Especially in the case of these beams being highly loaded (for example the keel longitudinal beams), the asymmetrical load path created can have dramatic effects on the behaviour of the structure. This can lead to unexpected deformations and even early failure of the laminate if the load path is forced too far away from what has been assumed originally.

**One solution for adding non structural partition on the top of existing structure is to disconnect them completely from the structure, this requires ensuring they are truly floating and no load transfer can exist between the structural and the non-structural panel.**

In order to keep the freedom of adjusting the interior panels, or to provide a choice of different internal arrangements based on the same structural layout, it is not uncommon to specify ring frames to support the hull in non-highly loaded areas.

In the example illustrated above, a non structural internal partition is added very close to a structural ring frame.

Due to its geometry, and even if it is made of a material with lower mechanical properties (typically plywood), this large panel will represent a much stiffer load path than the shallow ring frame.

**Even if the non structural panel is not intended to pick up any load, there is a strong possibility that it will pick up most of the load (here the hull pressures), and it might be better to treat it as a structural member and omit the ringframe.**