COMPOSITE STRUCTURES MANUFACTURED WITHOUT THE WASTE FROM TOOLING USING 3D COMPOSITE KITS

François Geuskens, PhD; Tahira Ahmed, PhD
Curve Works
Curieweg 17A
Alphen aan den Rijn, 2408 BZ The Netherlands

ABSTRACT

Large FRP structures such as ship hulls are manufactured as either a single piece, or as an assembly of a few very large components. This requires the design and fabrication of very large moulds and in many cases large curing ovens. The tooling cost and lead-time of very sizable moulds are the limiting factors leading to the stagnation of widespread composite uptake as large structures are in many cases one-off designs or small series designs.

3D Composite Kits offer a disruptive tool-less method for the manufacturing of large composite structures. A 3D Composite Kit is a set of panels with single- or multi-step overlaps and enable the assembly of a complete composite structure without the waste from tooling. 3D Composite Kits are manufactured using adaptive mould technology and on-the-mould curing equipment. This technology enables a shift from the current state-of-the-art composite building of capital-intensive infrastructure and the wasteful "disposable tooling" mindset to an economically beneficial, faster and more sustainable approach.

1. INTRODUCTION

The objective of this paper is to explain how large one-off and small series composite structures can be economically realised without the waste from tooling. To this end, two key production technologies will be presented of the panel assembly and 3D Composite Kits, and applied to case of a composite ship hull.

1.1 The problem of small series manufacturing of large composite shell structures

The use of composites for large shell structures is still a rarity when it concerns one-offs and small series manufacturing. In particular, the marine market is the biggest market where composites are lagging in their potential. The main reason is that, despite the many benefits of Fibre Reinforced Polymers (FRP), the manufacturing of large composite structures is too costly to compete with conventional building materials such as steel and aluminium.

The main cost drivers that are responsible for this stagnation in growth are:

1) Mould production:

FRP structures are manufactured as either a single piece (Figure 1), or as a panel assembly of a few very large components. This requires the design and fabrication of very large moulds. Considering ship hulls for example, the length of the hull is proportional to the surface area squared, and so the cost of a mould (€ 1.000/m^2) increases exponentially for longer hulls. For each new ship design comes a new mould which must be amortized over the number of vessels produced from it. As large ship hulls are often one-off or small series designs, these costs can increase especially when taking additional costs of mould storage, transport, and eventual disposal into consideration.

Figure 1: Demoulding the hull of the 34M superyacht (MM341) at Baltic Yachts. Courtesy of Baltic Yachts.

2) Curing oven:

In many applications large composite structures are cured in an oven. A typical curing oven for a 40m ship hull costs around €1.000.000. These ovens are used 1 to 4 times a year resulting in very high capital expenditures (CAPEX). Such large curing ovens are a large cost burden when there is no guarantee that they can be amortized on many products.

3) Lead time:

The manufacturing of large FRP structures including fabrication of very sizable moulds is a very time-consuming process. The lead time of a FRP ship is around 25% longer than the lead time of a metal ship. This extra lead time results in additional costs and lower productivity of the shipyard.

The introduction of cost-effective manufacturing methods for large composite structures is necessary since the transport sector requires rapid transformation to meet the 40% greenhouse gas emissions cut, defined in the 2030 EU climate targets. A FRP ship-hull weighs up to 45% less than a metal hull, resulting in a fuel consumption reduction of 25%. The fuel consumption reduction results in both a reduction in emissions and a significant cost-saving. Next to the weight reduction, FRP eliminates the problems of corrosion, which is of critical importance to reduce vessel maintenance costs, while increasing ship stability and diminishing underwater radiated noise (URN).

Having a modular building method for composite ships would likewise reduce the lead-time greatly.

1.2 The advantage of modular building methods

1.2.1 Metal panel assemblies

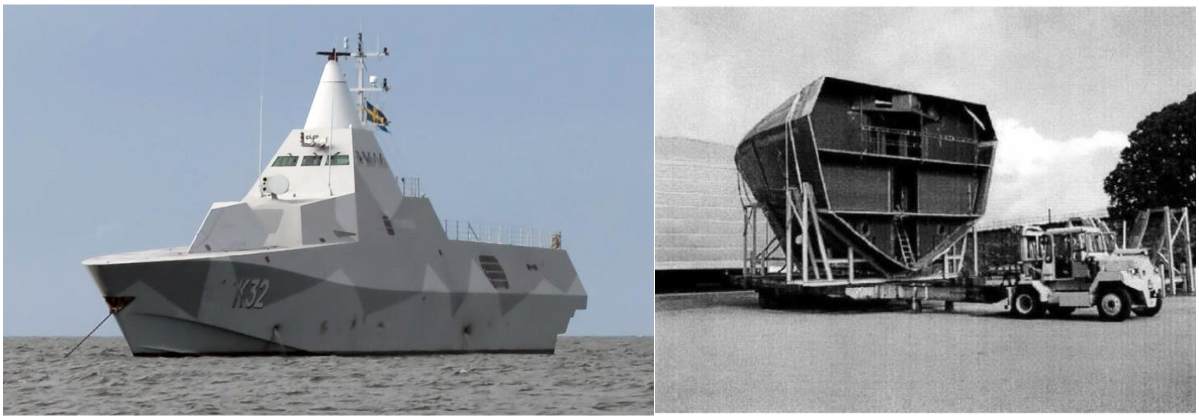
Metal ships are built using the panel-block assembly method as shown in Figure 2. The hull is divided longitudinally into blocks and each block is again divided into assemblies and sub-assemblies. Each block is individually manufactured from its (sub)assemblies, and the blocks are welded and/or fastened together according to the structural drawings prepared by the design department of the shipyard. This modular building method is a lot more flexible and allows for the processes of hull fabrication and outfit installation to run in parallel. This significantly reduces building time and is termed "advanced outfitting".

Figure 2: Illustration of the panel-block-assembly method

1.2.2 Composite panel assemblies for ships

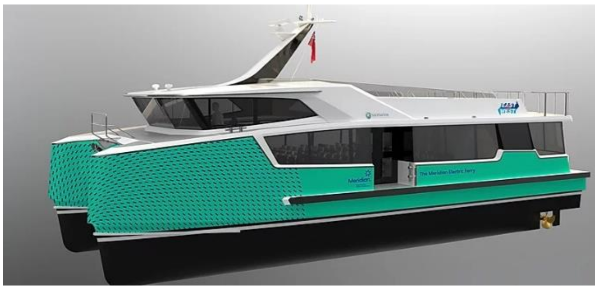
Composite panel assembly structures are already operational. Three examples from 3 applications (*naval, commercial and superyacht*) are shown in

Figure 3(a-c) below. In all these examples composites are required to meet the performance criteria and the composite panel assemblies yielded for these ships the fastest and most efficient, in terms of the infrastructure required, building method.



a. Visby class corvette (5 built and delivered between 2002-2009) [1] and [2

The 72.7m Visby class corvette ships were built as composite panel block assemblies. Flat panels were required for stealth properties.



b. Wellington Electric Boat Building Company *(in-build) [3]*
A fully electric 19m long carbon composite passenger ferry. The weight of the hull is minimised to maximise the range. Below the waterline the hull is made in one-shot in moulds, above the waterline, the structure a composite panel assembly of flat panels.

c. Baltic 146 Custom *(in-build) [4]*
A 45m long hull made in three individual sections on high-quality individual moulds

Figure 3: Examples of composite panel assembled ships in different markets

In general, shaped panels have been manufactured on high-cost tooling when performance is required (eg below the waterline, or in racing vessels) and manufactured of flat panels in less critical areas to compensate for the cost. Even with this compromise, the cost barrier of FRP tooling and infrastructure has prevented the wide uptake of FRP hulls beyond specific applications.

2. COMPOSITE PANEL ASSEMBLIES USING 3D COMPOSITE KITS

3D Composite Kits enables a shift from the current state-of-the-art composite building of capital-intensive infrastructure and the wasteful “disposable tooling” mindset to an economically beneficial, faster and more sustainable approach. An explanation of how 3D Composite Kits are made and its structural concept in the panel assembly is provided in this section.

2.1 Adaptive moulds for the manufacturing of curved panels

Various forms of reconfigurable tooling has been researched and developed extensively as a solution to reducing the manufacturing costs of composite parts eg [4,5]. One of the small handful of commercially available reconfigurable tools is the adaptive mould from the Danish company Adapa. The adaptive mould is a pin-bed of individually controlled actuators, a membrane support system and a rubber membrane surface.

The mould forms into smooth single or double curved shapes within minutes directly from the 3D CAD software (Figure 4). A laser projector that is part of the system projects all edges, features and references onto the 3D surface.

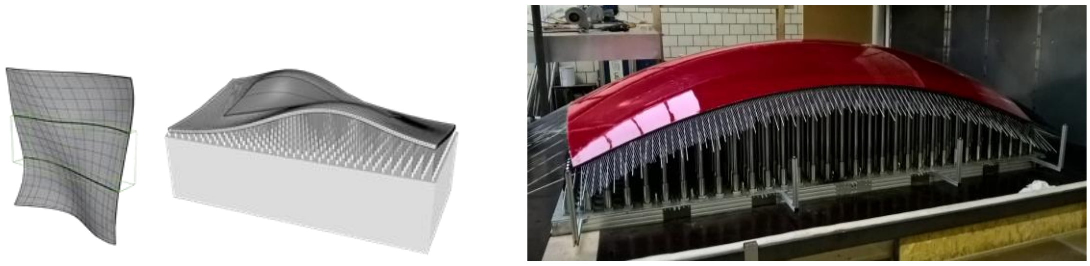


Figure 4: Software converts drawing to control program for the adaptive mould (left) and adaptive mould at Curve Works (right)

Curve Works has developed new membrane technology with integrated heating in order to reduce the on-the-mould curing time for both vacuum infusion and prepregging processes. This new heating technology also eliminates the need of an oven. The membrane with integrated heating has been developed on a small test mould (Figure 5) and the technology will be upscaled for the production adaptive mould in the first quarter of 2021.

Figure 5: Functionality test of a membrane with integrated heating for a small adaptive mould showing uniform heat-distribution.

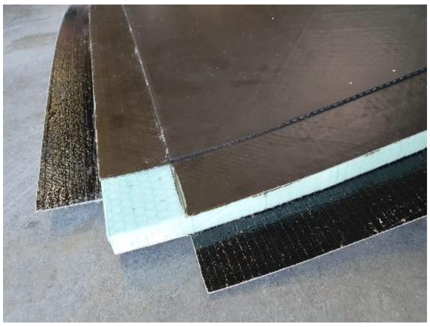
2.2 3D Composite Kits

2.2.1 Explanation of the Kit

3D Composite Kits are a set of pre-manufactured sandwich panels that are assembled together to create a large curved composite surface or shell. The panels have structural single-or multi-step overlaps that are joined with their neighbouring panels for load transfer.

Details of two panels of a 3D Composite Kit are found in Figure 6. The panels shown are both doubly curved with overlapping joints (Figure 6b) and can be joined both along their long (Figure 6c) and short edges (Figure 6d). All neighbouring edges align perfectly demonstrating the accuracy of this technology. Curve Works has applied 3D Composite Kits in architectural projects and for the manufacturing of moulds that are larger than the adaptive mould. The next step is proving the technology for highly structurally loaded applications.

a: Preparation of the vacuum infusion of two sandwich panels on the adaptive mould



b: Panels are manufactured with edge details

c: Mould-side surface quality of panels

d: Alignment of two curved panels along the short sides

Figure 6 3D Composite Kit details

2.2.2 Panel connections using FlexSkin

The edge details shown in Figure 6b and schematically in Figure 7 is a special form of connection developed by Curve Works and termed the “FlexSkin” connection. The FlexSkin connection has the following features:

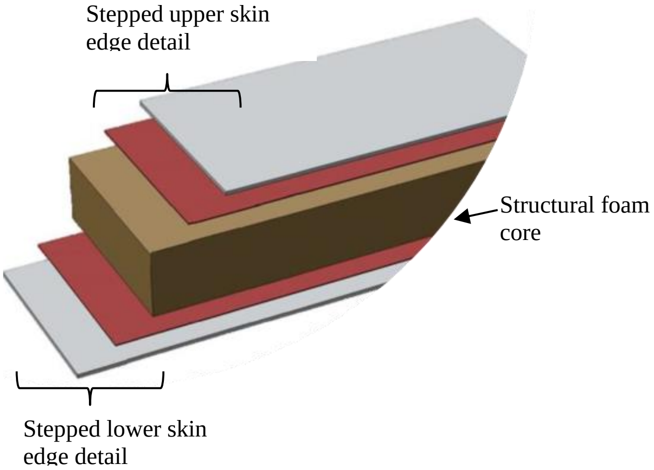


Figure 7: Illustration of the FlexSkin connection

1) Matching **negative** tolerances.

It is important that each panel of the 3D Composite Kit, with its individual tolerances, enables the assembly of a complete shell structure that is compliant with the required dimensions and overall tolerances. The in-plane dimensions are therefore always manufactured slightly smaller than their theoretical CAD-model and overlaps are slightly shorter than their corresponding recesses. The assessment of the negative tolerances depends on the accuracy of the adaptive mould set-up and the tolerances of the manufacturing and assembly procedure. All tolerances can be accommodated by selecting appropriate dimensions for the overlapping connections.

2) Compliant integration at the panel edges.

All panels deviate from their theoretical CAD-model within a certain tolerance range. The deviations depend on the specifications of the adaptive mould and the complexity of the shape. The tolerance deviations need to be captured and compensated at the edges to ensure a compliant integration. This can be achieved in 2 ways:

- by allowing deeper recesses and out-of-plane deviations are compensated through varying adhesive thicknesses, or,
- by creating flexibility through an unreinforced core at the edge of the panel as shown in Figure 8.

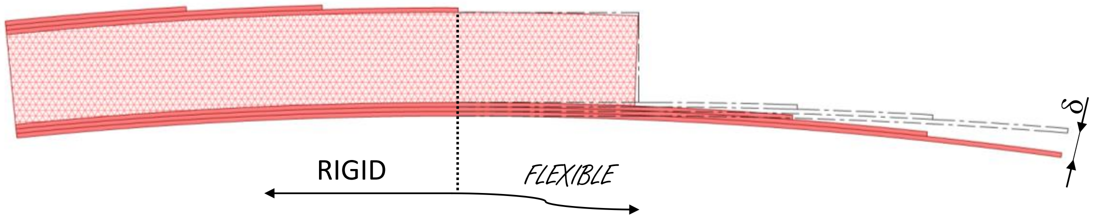


Figure 8: Flexible edges ensuring compliant integration

3) Straightforward assembly

Curved panel assemblies are difficult to assemble with interlocking connections such as tongue and groove connections. 3D Composite Kits have overlapping joints which ensure a straightforward assembly.

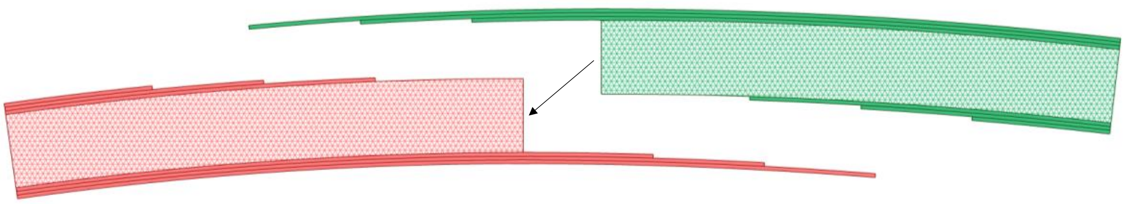


Figure 9: The FlexSkin edge geometry ensures easy integration

4) Joint configurations

Adhesively bonded joints can be strong but are inevitably weak in peel. The connection is configured such that the loads are transferred in shear with minimal peel stresses. The details of the joint architecture vary with budget-, performance- and aesthetic requirements. Stepped lap- and strap-joints are identified as the most interesting way to transfer the loading. The structure is engineered such that the joint will never be the weakest link.

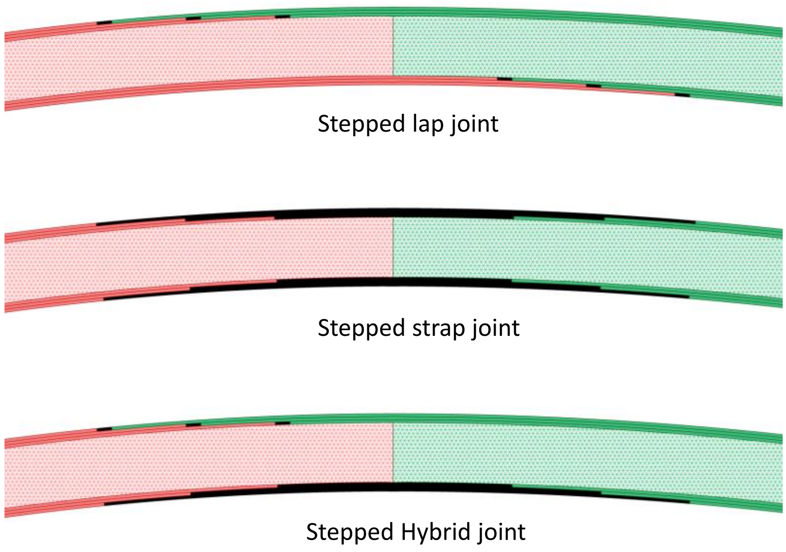


Figure 10: Joint configurations 3D Composite Kits

Stepped lap joints are the simplest joints and only require bonding which makes them the easiest connections to assemble. Stepped strap joints are secondary laminations and are structurally the most efficient joints since varying adhesive thicknesses do not apply. Stepped hybrid joints are the perfect compromise since the single sided bonded lap enables efficient vacuum bagging of the laminated strap.

2.2.3 The 3D Composite Kit applied to a panel assembly ship hull

For the sake of demonstration, we show the panel assembly process for a 50m ship. The assembly process for a large hull is illustrated in Figure 11 and is shown upside down, which is common practice in building composite ship hulls.

It should be noted that every shell structure requires an optimization procedure to determine the panel geometry. This optimization is a balance between the size of the adaptive mould available, logistics, load transfer and aesthetics.

Similar to the build of a metal ship, decks, ribs and bulkheads form the assembly jig of the hull (or a block of the hull). Panel edges are always supported by decks, bulkheads, stiffeners or ribs. The panels carry primarily shear loads (torsion) and out-of-plane loads. Panels are assembled in a staggered manner such that each row of panels is staggered by half a panel. The staggered configuration ensures a strong assembly.

Panels can obtain recesses for secondary laminations. The recesses can be large (centreline & top edge) or small (in between panels). The key of this technology is that the panel assembly forms the mould for the continuous reinforcement that runs over the entire centreline and the top edge of the hull (gunwale). These continuous reinforcements, which consist primarily of unidirectional fibres, carry the majority of the longitudinal loads preventing the ship from hogging and sagging. The reinforcement at the centreline is in most cases on the outer side since this is pragmatic and out of sight (below waterline). The continuous reinforcement at the (visible) top edge will generally be located on the inside and will be laminated when the ship is turned around (Figure 11b).

The final step of the hull manufacturing will be the panel-assembly of the upper deck.

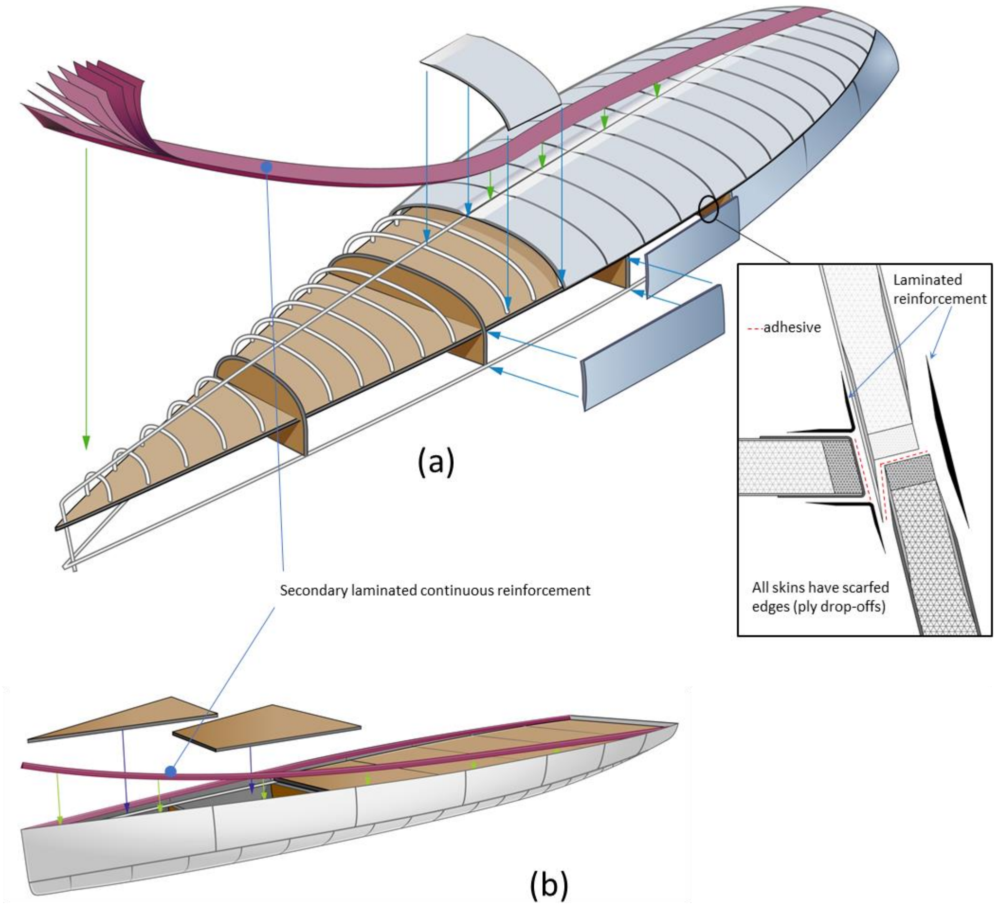


Figure 11: Illustration of the panel assembly method for a composite ship

3. FINAL REMARKS

3D Composite Kits enable the assembly of large composite shell structures from panels without the waste, cost and lead-time of tooling. The key technologies that have been developed to for the manufacturing of 3D Composite Kits are: an adaptive mould, on the mould heating, Curve Works proprietary manufacturing procedure and the FlexSkin joints to ensure a cost-effective composite panel assembly. The manufacturing approach applied to a ship has been described and offers enormous potential in allowing composites to become a viable choice for large structures.

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