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National Aerospace Laboratory NLR

NLR-TP-99564

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This report is based on a presentation at SAMPE EUROPE 2000, Paris on 18-20 April, 2000.

Division: Structures and Materials
Issued: December 1999
Classification of title: Unclassified

Summary

Since a few years, tall masts for luxury yachts are no longer being made exclusively of aluminium. The use of composites materials, in particular of carbon fibre reinforced epoxy material, can lead to significant weight savings of the mast itself, as well as a multifold weight saving of the keel, which is meant to balance the yacht. Also, an increased stiffness of the mast may improve the sailing performance.

As composites technology for composite masts was based on short mast configurations, assembled from several separate parts by discrete joints, Royal Huisman Shipyard in the Netherlands decided to develop a new fabrication concept to manufacture composite masts up to a length of 60 m as a single component. The Structures Technology Department of the National Aerospace Laboratory NLR was asked to support the development of tall composite masts by providing consultancy with regard to the fabrication concept, by evaluating and characterising materials, and by performing the sizing of the mast. For the latter contribution to the design process, NLR used its design optimisation capability B2OPT, based on the finite element method as available in the code B2000.

This paper presents a description of the design of several masts. The fabrication concept is discussed in detail. The results of the first mast development, built for the 48-m yacht Hyperion are highlighted. The ship has been sailing since January 1999 and has been provided with a load monitoring system mounted on the stays, to measure the loads that occur in practice. During its first year, the loading on the masts has reached 90 % of its design loading condition, without any problems.

Contents

(12 pages in total)

1 Introduction

Since a few years, tall masts for luxury yachts are no longer being made exclusively of aluminium. Moreover, composite materials like carbon fibre reinforced epoxy are used. The use of composite materials can lead to significant weight savings of the mast itself, as well as a multifold weight saving of the keel, which is meant to balance the yacht. Also, an increased stiffness of the mast may improve the sailing performance.

The current technology for composite masts merely is based on short mast sections up to a length of 30 meters. Tall masts are assembled from several separate parts, introducing joints that are possible failure locations but also undesirable from an architectonic point of view. Therefore Royal Huisman Shipyard (RHS) in the Netherlands decided to develop design and manufacturing capabilities for composite masts up to a length of 60 m as a single component. The development started in 1997 with a 57-meter mast for the 47-meter sloop Hyperion, see figure 1. The Structures and Materials Division of the Dutch National Aerospace Laboratory (NLR) was contracted to size the mast and to support the development of manufacturing capabilities.

Up to now, the autoclave process is the standard fabrication technique for high quality, highly loaded parts. However, curing a single composite structure of 60 meters in an autoclave seemed not feasible. Because Resin Transfer Moulding (RTM) and wet lay-up were not considered to be a serious alternative, a new and cost effective manufacturing method based on vacuum assisted oven cured prepregs was developed. For this method suitable materials were selected and material properties were determined.

Based on the developed manufacturing method and material properties, a design was made with the finite element method. In order to obtain the lowest weight possible, extensive optimisation was carried out. The mast was manufactured at RHS and installed on the Hyperion by the end of 1998. Based on the same manufacturing process and materials two smaller masts have been produced for the yachts Aphrodite (52.9 m mast) and Pamina (43.8 m mast).

In this paper the design and manufacturing method developed is discussed. Some structural details and the fabrication of the mast for Hyperion are shown in more detail. Finally the experiences with the first mast development are mentioned.

2 Selection of materials and the manufacturing process

Curing a single composite structure of 60 meters in an autoclave is not feasible. Because of quality requirements and process repeatability, wet lay-up was not considered to be a serious alternative. Also, Resin Transfer Moulding (RTM) was not considered for this one-off product because of the risk of fatal errors in the injection process and poor repair possibilities.

Furthermore, a high fibre volume is required in order to give a mast a good performance to weight ratio. Therefore, a new fabrication method had to be developed. Because the design of the masts depends on the manufacturing method to be applied and the materials to be used, it was decided to start with the development of the fabrication method and the selection of suitable materials.
After screening of commercially available composite materials and possible manufacturing methods, it appeared that the prepreg-oven technique was preferred. With this technique components can be cured under vacuum at a temperature of 60 ºC to 90 ºC in relatively cheap moulds. Since a few years, several competitive materials have become available for this type of cure cycle. With these materials, a thickness of 4 to 7 mm can be cured in one step, so a large mast can be made in 3 or 4 charges. A laminate thickness above 7 mm per cure cycle is not desired, because with limited laminate thickness per cure cycle problems like fibre wrinkling, fibre bridging, resin rich areas and fibre waviness are prevented. Furthermore, the risk of fatal errors in the cure process is limited to a part of the total laminate thickness. This means that local repairs can be carried out easier and concern only a part of the total thickness.
For the selection of the prepreg system a screening program was carried out. In this program material from Advanced Composites Group (ACG), Cytec, Hexcel and SP Systems (SP) were evaluated. From the materials MTM 56 (ACG), M10 (Hexcel) and SE84 (SP) coupons were manufactured and tested to determine compression (ambient and hot-wet), Open Hole Compression (OHC) and Compression After Impact (CAI) properties. The coupons were cured under vacuum using a representative cure cycle with a low heat up rate.
The mechanical properties of MTM56 were superior over M10 and SE84, except for hot-wet compression. The MTM56 contained some chemicals to lower the resin viscosity when slow heat up rates are used. Probably these chemicals caused the relatively high moisture content and therefore lower compression after ageing (10 days water boil) properties of MTM56. The properties of SE84 were better then the properties of M10, especially when the heat up rate was lowered to 0.3º/minute. Furthermore this system has a very versatile cure cycle, which gives possibilities to use it in other structures and processes also. Therefore SE84 was chosen as the resin system for large structures.
For the masts a low cost, simple fabrication concept was developed by RHS. A mould with the contour of the starboard half of the mast is constructed with multiplex templates and thin stainless steel sheets. In this mould a thin composite shell halve of about 4-mm thickness is made. Because the shape of the portside half is symmetrical to the starboard half, the templates are turned around for the manufacturing of the portside shell. The shells are used to assemble the core of the mast by using two strips on the inside, see figure 2. Before the shells are assembled all internal reinforcements for the attachment of spreaders and stays are applied. Also cables etc. are positioned inside the shells, giving the advantage of easy access. After

assembling the remaining laminate of the mast is applied and cured in several steps. The result is a mast section with all systems mounted directly during manufacturing, see figure 3.
The feasibility of the prepreg-oven technique with SE84 and the fabrication concept mentioned was studied by making a demonstrator with the actual cross section of the Hyperion-mast and a length of 4 meter. The feasibility study showed that the fabrication concept worked very well if minor modifications were made to the tooling and if a laminate with large clusters of 0º fibres was avoided. The SE84 UD-prepreg with a ply thickness of 0.3-mm was easy to laminate. By adjusting the temperature in the laminating room the tack of the prepreg could be regulated easily. Non destructive and mechanical tests on the laminate of the demonstrator showed good properties.

3 Numerical design of the masts

At NLR several finite element codes are available for analyses on composite structures. For masts normally the finite element code B2000 (Ref. 1) is used. Within this code an optimisation module is available based on linear analyses (Ref. 2). In principle the analyses of the finite element model of the mast with spreaders and stays is a non-linear problem. This is because the mast is pre-stressed with the vertical and diagonal stags. This rigging translates each sailing load into a compression load at the mast giving a buckling failure. During optimisation a simplified linear model is used which is validated against a full non-linear analysis.
Based on an initial design, a model of the mast is made with 4-node shell elements. During optimisation, critical values for local and global buckling and maximum strain are used as constraints while ply thicknesses of the initial lay-up are used as design variables. As a result of the optimisation the mast is critical both on local and global buckling. To prevent problems with coinciding buckling modes, a safety factor of 1.3 on the critical global values is normally used. Typically, the optimised mast designs have the largest wall thickness in the middle section of the mast, because the lower section is critical only on torsion buckling and maximum strain.
After optimisation a final design is made, in which manufacturing constraints are incorporated also. The final design is analysed separately. In cases when the design is certified by Lloyds, the design is also analysed by (Germanischer) Lloyd. Generally the analyses agree.

4 Fabrication of the mast for Hyperion

To fabricate large structures like a mast or a superstructure RHS decided to build a large “oven” of about 60 meters in length and 10 meters width. The oven has the capability to be heated to a maximum temperature of 85º and can be used as a room for laminating also. The moulds for the products to be made are mounted in the oven. Because of an outlife of 60 days for the SE84 prepreg, the manufacturing of several different products can be combined easily without exceeding the outlife. After laminating, all products are cured in one cure cycle. Before the cure cycle all auxiliary tools are removed.

For masts the mould with multiplex templates is mounted to the floor of the oven with aluminium supports. In the mould the starboard and portside shells are made. After incorporation of internal reinforcements and wiring etceteras, the mast shells are assembled with structural adhesive, giving a vacuum tight structural core. The core is placed in rotation supports for laminating the remaining plies, see figure 4. Depending on the wall thickness, the remaining plies are applied in two or three steps. Each step starts with the application of an adhesive film and the required number op prepreg plies. For the cure cycle the entire mast is provided with a bagging film, which is attached to the ends of the core with tacky tape. In order to apply a high, well-distributed vacuum, two vacuum connections on each meter length are applied, see figure 5. After curing the bagging materials are removed, see figure 6.

During the manufacturing of the mast for Hyperion, problems like fibre wrinkling, delaminations and large void concentrations did not occur. Using the method of curing the mast in several steps also gave the advantage of a better pressure distribution and a more uniform thickness. Symmetry of the laminates that are applied in one step prevented deformations due to thermal stresses. The final result was a stiff, straight mast with a good performance to weight ratio. The unpainted mast is shown in figure 7.

The superyacht Hyperion is in service since December 1998. The yacht is provided with a load monitoring system. Up to now, the mast has reached 90 % of its limit load without difficulties. Other masts, designed and manufactured according to the same concept also perform satisfactorily.

5 Conclusions

The new generation of low temperature curing epoxies enables the manufacture of large composite structures with reasonable mechanical properties at affordable costs. Because they can be cured with vacuum pressure only, the processing costs are relatively low compared to the autoclave method. The low temperature curing epoxies used are especially attractive for prototypes and one-off products because moulds can be rather simple and cheap. Furthermore the cure process is rather flexible in terms of temperature and heat up rate, making it very suitable for large structures.

The use of the finite element code B2000 with the optimisation module B2OPT for mast designs leads to significant weight savings. The lay-up is optimised for stiffness in buckling-critical sections and optimised for strength in strain-critical sections. Because the lower section of the

masts are not buckling critical, the masts typically have the largest wall thickness in the middle section of the mast.
With the manufacturing of the 57-m mast for Hyperion it was shown that the fabrication concept developed for masts gives a lightweight, stiff structure without structural joints. The concept also provides excellent possibilities to incorporate internal reinforcements and wiring. Because the laminate is cured in several steps, the risk of fatal errors in the cure process is limited to a part of the total laminate thickness. This means that repairs can be carried out easier and only have a minor effect on the local laminate properties.
The first mast, manufactured for the superyacht Hyperion has been in service since December 1998 and performs satisfactorily, see figure 8. Other masts, designed and manufactured according to the same concept, confirmed that the design and manufacturing concept used leads to masts with favourable properties at affordable costs.

6 References

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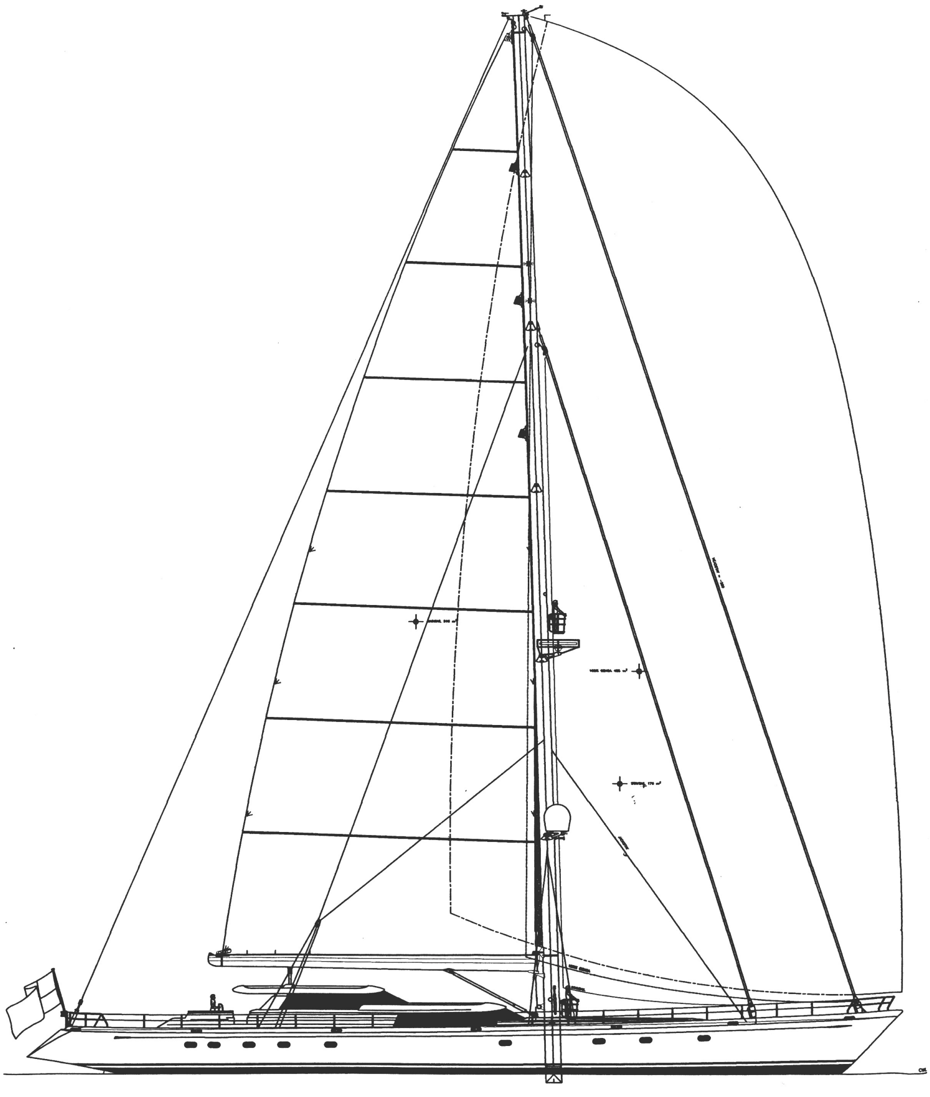

Fig. 1 The yacht Hyperion

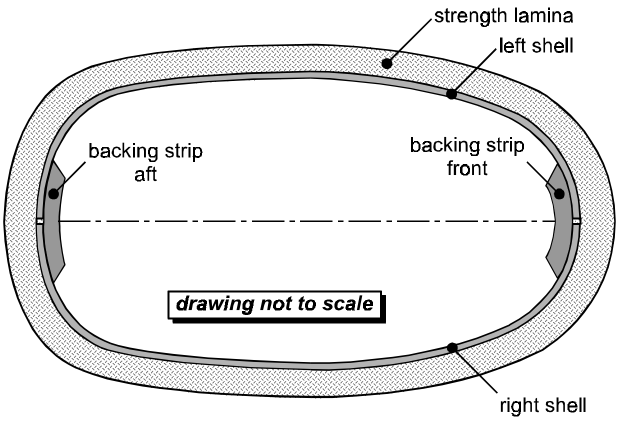

Fig. 2 Cross section of a mast, manufactured according to the method with two thin shells

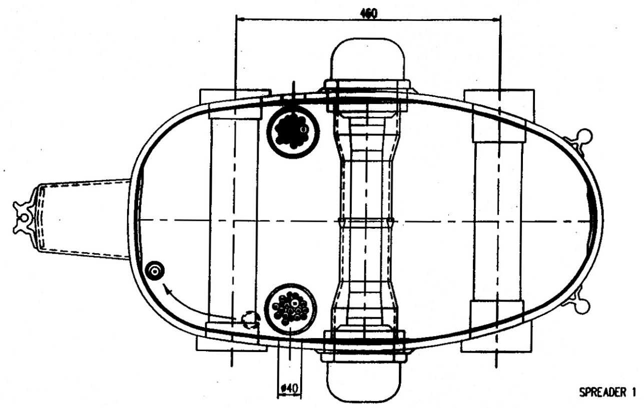

Fig. 3 Cross section of a mast with connections for diagonals and spreaders (pitch 460)

Fig. 4 Mast on rotation supports during laminating

Fig. 5 Preparation of vacuum bag prior to curing

Fig. 6 Removal of vacuum bag and bleeder material after curing

Fig. 7 The mast for Hyperion before painting

Fig. 8 The superyacht Hyperion sailing on the North see