Failures in carbon fibre reinforced composite boat structures.

Introduction

Composite materials are simply those where two or more constituents are combined to produce properties that are not achievable by either on its own. Engineering the properties you want from a material can be very advantageous and using polymer matrix composites (PMCs) is an affordable way to do this.

PMCs have been used in naval architecture for over 60 years; their first large scale military application was GRP hulled small personnel craft just after the Second World War. At first their use was limited as the boats were plagued with problems caused by poor fabrication, but as techniques improved, their use flourished. GRP is now extensively used maritime construction and is often superseded by carbon where high specific strength or modulus components are required. PMCs have many properties that make them desirable:

- Material properties are highly anisotropic allowing the laminate properties to be tailored by orientating the plies in specific directions.
- A broad spectrum of resin/fibre combinations permits properties including chemical resistance.
- Exceptional formability
- Sandwich panels using honeycomb and foams can be formed to give low weight structural members with good bending stiffness.

Designing with composite materials is very different from designing with more traditional materials and can be thought of as a synergistic approach where both the component and the material must be designed together. Once the loads on the structure are known, the material constituents can be selected and the lay-up orientated such that the reinforcement can be minimised in order to keep the structural mass as low as possible. It is fundamental for the product user to realise that high specification composite parts are designed with a specific application in mind, and making changes to the usage or the component itself may result in failure. The following case studies indicate the types of problem that have been encountered:

Examples of carbon fibre failure.

Motor boat hull

A water jet driven motor boat was mounted with its power plant inline with the gear box, two out board impellers and a fixed stator ring. The impellors were contra-rotating in order to reduce the rotation of the flow, and were arranged so that flow first passes through the left hand blades then the right in order to simplify the gearing and hence minimise gear box mass. The power plant and transmission were mounted to the hull on girders. The designers of the boat had intended that the gear box input and output shafts should both rotate clockwise, as built the gearbox shaft ran anticlockwise, resulting in a torque across the gear box far in excess of that in the design case. This resulted in over stressing of the hull beneath the gear box leading to crack initiation and propagation. The boat and all hands were rescued but the vessel broke in two on the shore.

Fracture of sandwich panel hull structure

A race yacht with sandwich skin hull suffered a large fracture of the hull resulting in a hole spanning the water line; the vessel was rescued and towed to land.

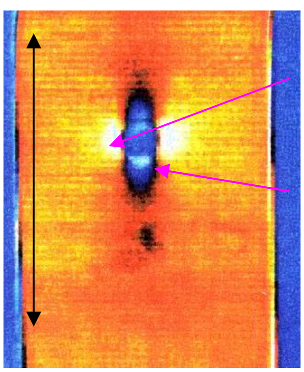
View of holed hull from yacht interior

Cracking of the laminate skins seen where the gel coat has fractured

Hole visible below the water

Examinations of the skin laminates and the aramid honeycomb coring showed that there were no problems arising from manufacture and the skin thicknesses were compliant with standards. The yacht had a very shallow draft, and American regulations at the time stipulated skin laminate thicknesses based on overall dimensions of the vessel and gave no minimum depth from which the recommendations were calculated. The hull was very stiff and the impact of waves on the hull resulted in the cracking and subsequent holing of the sandwich panel.

Mast failure
A large yacht suffered the loss of its carbon fibre mast after only a few days in service. The mast was manufactured in two U-shaped sections adhesively bonded along the neutral axis (port/starboard line). There were various apertures along the mast to allow for access to hydraulics and rigging attachment. Each opening in the mast results in a change in the local stress field and an example of the stress field surrounding an unloaded hole can be seen below. The image is a map of the stresses in a mode I cyclically loaded glass fibre coupon with a 6mm diameter through thickness hole.



Deltatherm image of GRP coupon

Note that the stress directly above and below the hole is less than the nominal stress, however this is only a localised effect and diminishes with distance from the defect as the matrix redistributes load to fibres bisected by the hole. Effects like this are understood and can be modelled however this must be done early in the design process and details that are likely to cause stress concentrations should not be grouped together as they will have a cumulative effect in weakening the structure.

The mast failed under considerable compressive load, induced by tensioning of the rigging and the mass of the mast and rigging itself. The failure occurred at an area containing a large number of grouped orifices that lead to a weakening of the structure at that point.

Failure prediction and conclusions.

In isotropic materials, failure can be predicted by assessing if a component will first collapse or suffer fast fracture; crack propagation can be predicted by stress intensity calculations based on linear elastic fracture mechanics (LEFM). LEFM assumes the materials properties are isotropic and the material responds elastically to loading, allowing for a small (in comparison to the crack length) plastic region at the crack tip. The theory hinges on Griffith’s energy balance which states that when the strain energy released by a crack’s growth exceeds the energy required to produce the crack flank surfaces, the crack will grow. In PMCs, there is rarely a single crack tip and the material is at best quasi-isotropic and so the calculation of critical crack lengths or stress intensities is unreliable, however the technique can be used to find the increase in toughness generated by certain failure mechanisms like fibre pullout and crack deflection .

Cracks can propagate in a number of ways and their paths and interactions are controlled by a number of factors including the mode of loading, fibre/matrix interfacial bond strength and the environment of service. There are so many possibilities it is difficult to predict precisely the progression of a failure. In fatigue situations, it is usual to measure the damage accumulation rather than measure individual crack development.

The reasons for failure can be very wide ranging, but there are several problems to which carbon fibre structures can be particularly prone. Due to the brittleness of the reinforcement, failure mechanisms that increase toughness of the material such as fibre pull-out are less effective as the fibres break before significant crack bridging can be achieved. Delamination (where cracks progress between adjacent plies) often results from an impact and can occur several plies beneath the surface where it may go unnoticed. In tension, the presence of these splits will often cause no problems but in compression, they can cause premature buckling of the structure.

Today the designer has an array of powerful tools to assist with lay-up planning, and the resulting structures can be reliable, light weight and very strong. Although every care is taken to design for all eventualities, accidents happen and it is important that the product user is aware of the effects that bumps, knocks and alterations have on the integrity of a structure.

DRB Materials Technology Ltd is an engineering materials consultancy firm specialising failure investigations, testing and material selection. DRB works closely with marine surveyors and thanks Freeman and Partners of Fordingbridge for their contributions to this article.

Helen Thorneycroft
DRB Materials Technology Ltd,
IRC House, The Square,
Pennington, Lymington,
Hants, SO15 2BQ
drb-mattech.co.uk