

New Fiber-Metal Hybrid Laminated Material (MALECON)

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Abstract

For the next generation of ships, the Navy is looking to stealthier hull technologies, specifically those which create lower magnetic, acoustic, hydrodynamic, radar, and thermal signatures. This calls for new materials for combatant vessels, capable of satisfying all these design and fabrication requirements for lighter structures that are in turn more resistant, permit higher speeds of movement and lower energy consumption. Steel has a series of limitations that impede continued improvement in the line of constructing light, resistant and safe structures. Composite materials are light and resistant, but the manufacturing processes are more labor-intensive and costly; in addition they are very sensitive to damage from impact and can present problems of degradation of their mechanical properties through water absorption. Fiber-metal hybrid materials combine the high resistance to impact and durability, and the versatile manufacturing of metals with a specific strength and stiffness in the direction of the fiber, as well as good resistance to fatigue, characteristics of the composites. *Malecón*[®] is a new hybrid multilayered material formed by layers of metal alternating with others of composite and structural adhesives, with improved in-service performance. We hold a patent on this material and its manufacturing system, and international extensions to more than thirty countries are already in due course.

Introduction

The structural material used for the building of combatant vessels has been traditionally plain carbon steel. This material has some well-known advantages when confronted to other alternative materials: low cost; easiness for shaping and machining; good weldability; its behavior and properties have been studied in depth and are well understood; it is very tough and with high impact strength. However, there are some others undesirable aspects for its use in shipbuilding: a remarkably high density, and a corrosion velocity that requires the use of expensive methods for its prevention. High speed ships are weight-sensitive structures, and lightness is a must both for increased velocity and efficient energy consumption. The fabrication processes for welded steel hulls introduce large residual stresses, which lead to large deformations of the individual plates (known as dishing.) Multiple dished plates along the side of the ship are usually referred to as hungry horse deformation, similar to the exposed ribcage of a starving horse. The RCS of the hull is increased by the multiple concave surfaces diffracting radar signals, thus magnifying overall signature. They also reduce fatigue life under repeated cyclic load, also called panting. Stainless steel hulls are expected to result in much higher residual stresses and hence dishing deformations will be larger. The only means to assure tight manufacturing tolerances is to relieve the residual stresses by heat treatment (which is very expensive), or to use some advanced welding technology that could minimize the residual stresses. In some steel hulls, designers resorted to increasing the steel thickness (thus adding weight) to reduce hungry horse deformation.

The alternative structural materials so far proposed for ship construction have been: high tensile steels, high strength aluminum alloys, and composite materials. High tensile steels have been used because of their higher strength and stiffness as compared to the plain carbon steels, allowing the building of lighter structures; on the other hand, are more difficult to weld and prone to fracture. High strength aluminum alloys have a smaller density, but they are less stiff than the equivalent sections made of steel, so the final weight of the structure is not reduced as much as one could imagine comparing only the densities of aluminum and steel (more stiffeners and thicker plates are required); these alloys are much more difficult to be welded, even those designed specifically to be used in marine environment, suffer from corrosion-fatigue problems. Composite materials used for shipbuilding (FRP) have a quite high specific strength, however: manufacturing process is more expensive; impact strength is worse as compared with metallic materials; there are problems of water absorption (osmosis) that diminish the mechanical properties of the material, and fire safety (so important for all kind of vessels but specially for passenger ships) is deeply impaired. As a result of all these considerations, the alternative materials have not been able to displace the use of steel as the main structural material for shipbuilding. They have only obtained a minor use restricted to very specific applications.

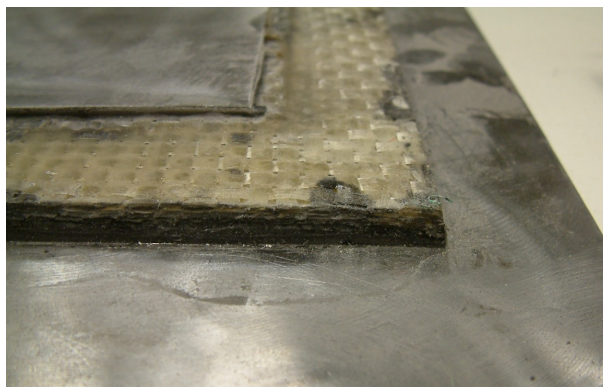


Fig.1. *Malecón*[®]: a new hybrid multilayered material formed by layers of metal alternating with others of composite and structural adhesives.

Several studies have shown that for hulls longer than about 60 m, even carbon fiber composites would not provide the required stiffness and strength required for a hull. Composites lack both the stiffness and the in-plane strength required for the larger combatant ship hulls. The structures of long Navy combatants carry loads by the alternating axial tension and compression the hull experiences during hogging (hull bows up) and sagging (hull bows down) modes, the result of traversing waves at sea. Therefore, for long structures the in-plane strength of the composite becomes the critical design factor. For small ships the bending strength (and not the in-plane strength) of the composite is the critical design factor. The composite sandwich construction technology common in smaller ships or boats, cannot provide the necessary in-plane strength for sea loads in long ship hulls.

The implementation of new materials specifically designed for shipbuilding, and not mere application of materials coming from other industries, will eventually satisfy the increasing requirements towards modern ships. Our proposal is the development and implementation of a new structural material, specifically designed to be used in shipbuilding, that overcomes the problems linked to the use of steel, but keeping most of its great values, and, at the same time, not introducing additional problems, as those already mentioned for some alternative materials. Our approach for this new material is based in the so-called Fiber Metal Hybrid Laminates. This kind of material is formed by layers of metal sheet alternating with plies of composite material. For our purposes, metal will be steel, and we will use plies of vinyl ester reinforced with glass fibers. We obtain a

multilayered material with improved in-service performance. The most compelling reasons to use hybrid materials in ships are stealth, lower total ownership cost, and weight reduction. Since construction with hybrid materials is more expensive than with steel, designers need to show a clear advantage to composites and a means to achieve cost savings over steels, either in initial construction costs or in total life cycle costs:

- The material is lighter than steel due to a partial substitution with the lighter FRP, and the amount of reduction in weight is adjustable just controlling the percentage of FRP used.
- We can design the new material to be isotropic or anisotropic, with reinforced properties in certain preferential directions.
- Fatigue behavior can be improved due to the multilayer concept, provide that the nature and strength of the interface between the metal and the polymer would be properly tuned.
- Corrosion could affect to the most external metal sheet, but once it arrives to the reinforced polymer the degradation is more efficiently controlled.
- Impact strength is better than in the case of composite materials because the external face is still a metal, with its high toughness and plasticity, but it is also possible to use intermediate layers specifically suited to resist shock waves.
- Fire safety is improved because after the first metallic sheet the heat find a glassy material (after the polymer has burnt out) with a refractory behavior, that retard the propagation of fire. Polymer is encapsulated between metal sheets.
- It is possible to get a substantial noise damping, as compared with steel or aluminium, by introducing some layers of sound adsorbing materials.
- Manufacturing is still less versatile than the processes used for metals, but it is improved if we compare it with the composite materials, because metal sheets act as moulds as the curing proceed.
- Joining techniques are conveniently improved, combining adhesive joints for the inside layers with welding for the outer sheets.

Hybrid material allows for low maintenance, elimination or reduction of corrosion problems, light weight, ability to use low cost/high performance composites, as well as embedded sensors and fiber optics for health monitoring, and also reduce repair costs through the use of removable panels. This type of materials eliminates the problem of an entire hull delamination, which could result from the ship impacting ice, piers, or other hard objects. Combatants vessels with hybrid construction have the following advantages: superior performance in underwater explosions (UNDEX) with reduction in whipping loads¹; the hybrid hull is perceived to be less vulnerable to internal explosions, because the outer metallic skin would allow relief of internal blast pressure preventing extreme loading of the structural frame; the use of low density composites saves weight, allowing for added additional protection systems; the hybrid material provides options to reduce structural acoustic signatures.

Alternative approaches have been followed in two different directions: hybrid hull design and sandwich materials. Several hybrid hull designs have been proposed. Hybrid hull design combines a mid-section of stainless steel advanced double hull and bow and stern sections made of single skin cross-reinforced composite or sandwich composite. Other option is an all-composite skin along the entire hull reinforced with stainless steel framing in the mid-section. A detailed finite element analysis of whipping shows that for a hybrid hull the highest stressed region is at the joints due to

¹ Whipping loads are created when the length of the vessel bends upward and downward repetitively due to an underwater explosion. While similar to routine sea loading, the magnitude of the bending and the rate are much greater during whipping.

the material mismatch. On the other hand, sandwich materials like *Metawell* and *SPS (Sandwich Plate System)* use low stiffness core materials and the in-plane resistance is accordingly not enough for large vessels. Thus far, *Malecón*[®] is the only alternative that offers a hybrid material approach with a proper in-plane stiffness for new ship building, and not only for repairs.

***Malecón*[®] Panel Production**

The fiber-metal hybrid laminated material for naval construction is comprised of steel sheets and laminates of a composite material comprised by a polymer matrix reinforced with glass fibers. The amount, thickness and orientation of each of these sheets and laminates are calculated in order to obtain the appropriate stiffness and strength in each area of the ship. The composition of the laminate can vary in order to adapt the design material to the structural needs of each area of the ship or marine device. However, it is necessary to abide by a series of premises in the design of the material. The more external layers will always be of steel. In this way, it takes advantage of its resistance to impact, protecting the composite material that is located in the interior of the sandwich for possible delamination and microcracking. It also takes advantage of its capacity of supporting higher temperatures than the polymeric matrix of the compound, with a minor loss of mechanical properties and without smoke emission during a possible fire. Inside, other layers of steel can be placed to increase the stiffness of the hybrid material. The composite laminates are always situated in the interior of the sandwich formed by the external sheets of steel. The preferred materials are those that have been demonstrating their good performance in marine environments: polyester or vinylester matrix and reinforcement of continuous E-fiberglass. The fiber can be used in the form of fabric or as unidirectional reinforcement, depending on the preferred directions that are to be reinforced according to the principal directions of the stresses in service. The composite laminates will be grouped in packs with a determined number of layers, always between two steel sheets. The bond between the plies in the composite material laminate, within each package of the hybrid material, is done by means of the adhesion capacity of the polymeric resin that makes up the matrix. The bonds between the composite material core and the metallic sheets are done by using a structural adhesive. This adhesive is placed, at least, between the most external steel sheets and the first pack of composite material, where the interlaminar stresses can reach high levels. The adhesive must be elastic, have a certain capacity of reversible distortion, in order to absorb the difference of mechanical properties of the metal and the composite during bending without breaking. An adhesive of the bi-component polyurethane type is appropriate for this purpose. However, the thickness of the adhesive layer must be controlled (according to the recommendations of each manufacturer for the type of adhesive selected) in order to adapt to the differences of strain without reaching a thicknesses that would cause premature failure of the adhesive bond.

The panels of fiber-metal hybrid laminated material can be flat or curved, in order to be used in different areas of the naval structures and marine devices. The steel sheet, either flat or with the curvature that has been given to it, serves as a mould for the placement of the successive layers of composite material, with which no additional tooling is needed to fabricate the laminate, as is usual in the lay-up of conventional composite materials. Some auxiliary elements are used for the precise placement of the laminates and to hold them in position –acting as stoppers- during the curing and consolidation process of the polymeric matrix, but not an actual mould. The reinforcement is used dry, placed on the steel sheet that acts as a mould and the resin is introduced using vacuum infusion equipment.

In any case, it is essential to assemble the individual panels in order to make the desired structure. For this purpose, the panels are constructed leaving the borders in a staircase form on the four borders, so that the steps of one panel fit into those of the neighboring panel. An elastic adhesive is applied to bond to panels together. The adhesive bonded surface, which is the surface of the

assembled steps, must be sufficient to guarantee a perfect transmission by shearing of the loads from one panel to another. The exact dimensions of these steps are calculated based on the dimensions of the panels and the expected loads in service. The assembly adhesive must have, therefore, a certain capacity to fill gaps and to be able to absorb in this way the manufacturing tolerances.



Fig.2. Vacuum infusion process for manufacturing of the hybrid laminate.

Once the assembly of the panels is done, it is necessary to seal the connections that are on the outside, on both surfaces of the hybrid laminate, and in lengthwise and crosswise directions. These connections do not contribute to the transfer of loads between panels but, above all, serve to impede the entrance of water in the interior of the laminate. The sealing can be done in two ways; either welding the steel sheets together or else using a polymeric sealant. In the case of welding, one must take into account that metal must be provided to fill the gap between the two sheets, trying to penetrate as little as possible so as not to damage the polymeric material that is found below. In the case of using a polymeric sealant, one will be chosen with the capacity to fill the gaps and bear the relative movement between the two sheets without failure. The sealant must impede the entrance of water in the interior of the material during the structure's service lifetime. Once the panels are assembled, they can be painted, following the usual procedures in order to protect the structure from the phenomena of corrosion.

Material Development Test Program

For developing this new structural material for shipbuilding, being a viable and realistic alternative to the traditional materials already in use, it has been necessary to take care of six specific goals:

1. Obtain a sound bonding between the metal and the polymeric matrix, with an adequate durability, according to the scheduled life in-service: interface with a proper strength to transmit shear stresses from one material to the other, but avoiding delaminations.

- Metal surface treatment
- Polymeric transition material to accommodate the properties of the dissimilar constituents
- Compatibility between the surface treatment and the interface

2. Develop a surface treatment adequate for the combination of materials to be joined, but feasible in the usual circumstances of shipbuilding: the working conditions in a shipyard are different from those found in a clean room for aerospace purposes; the goal is to obtain a treatment less sensitive to a dirty surface, humidity and temperature.

- Increase tolerance to dirty surfaces
- Increase tolerance to humidity
- Increase tolerance to temperature

3. Evaluation of the performance of the hybrid laminates using mechanical and environmental testing: before passing to prototype testing in a real ship, it has been necessary to fully characterize the mechanical and environmental response of the material using standard testing procedures.

- Stress-strain curve in tension and compression
- Shear yield strength
- Blunt notch strength
- Fatigue behavior
- Residual strength
- Damage tolerance aspects
- Degradation in marine environment

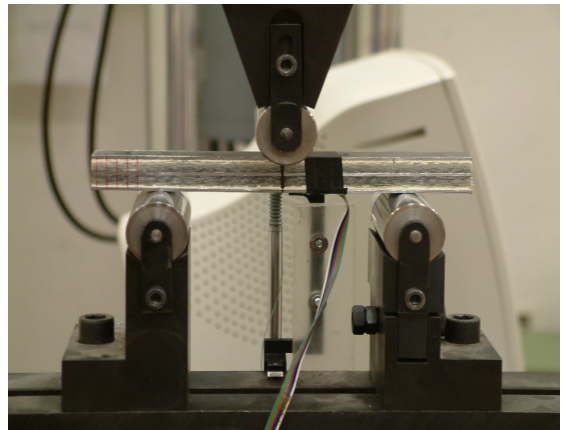


Fig.3. Bending test specimen and fixture

4. Accommodation of the design tools (finite elements) to obtain accurate prediction of performance for the new material: data from mechanical testing have to be used during numerical modeling, using finite elements, in order to validate the behavior of panels prior to testing in real conditions; new design strategies have to be addressed to obtain the maximum performances from this new material.

- Static strength of stiffened panels
- Buckling and post-buckling behavior
- Detailed design concepts
- Cut-outs design
- Numerical modeling
- Codes and Standardization

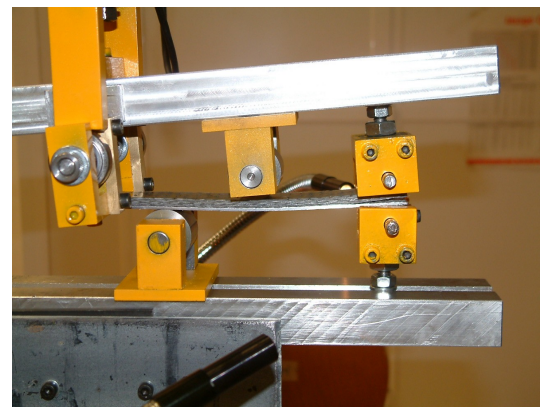


Fig.4. DMMB test specimen and fixture

5. Propose economically viable manufacturing processes: manufacturing of small specimens for testing does not guarantee that the same processes should be used for the manufacturing of bigger panels more adequate for shipbuilding; it has been necessary to explore valid solutions for manufacturing in the shipyard, especially new joining techniques suitable for these materials.

- Flat panels
- Curved panels
- Machineability
- New joining techniques: panel to panel; stiffener to panel



Fig.5. Assembly of curved panels

6. Safety, repair and maintenance issues: everything related with safety could be decisive to allow the extended use of this new material; also is important to explore topics related to repair and maintenance issues.

- Inspection and maintenance
- Fire safety
- Impact properties
- Corrosion
- Repairs
- Recycling

Prototype testing

A test specimen was prepared in order to test the failure modes of flat subcomponents with four panels joined together. The four panels were constructed leaving the borders in a staircase shape, so that the steps of one panel fit into those of the neighboring panel, and were bonded using a structural adhesive.

The hybrid material flat specimen was mounted in a three-point bend fixture and loaded in compression along the central adhesion line. The specimen was instrumented with strain gages, for measuring strain in selected points, and variable differential transformers (LVDTs) to measure cross section deformation. In particular, the compression can lead to instability problems if the joint is not properly designed: local buckling of the outer sheet metal and global buckling of the panel. HBM *Spider 8* was utilized for the data acquisition of all signals from the strain gauges, while the LVDTs and the cell load were controlled by the testing machine software. Test data was recorded by three personal computers.

Acknowledgements

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