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Permanent Composite Cladding of Deteriorating Steel Hulls

III8-2

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ABSTRACT

The 42.7 m (140 ft) steel steam yacht (S/Y) MEDEA was nearly condemned in 1988 because of deteriorating steel hull plate. However, it was recently restored with a structural foam and composite skin bonded to the outside of the remaining steel structure. The composite repair was completed at a cost of $220,000 compared to the $1.7 million estimated to crop and replace the wasted steel plate.

The repair, the events leading up to the repair, including U.S. Coast Guard approval, the structural and production decision making processes involved, and the projected use of an integrated production system for similar future applications are described in this paper. The use of similar processing technology to apply the glass epoxy composite coating on the wooden coastal minehunters (MHCs) is also discussed.

INTRODUCTION

Steel became the marine construction material of choice in the late 1800's due to its stiffness, strength and damage tolerance. Coating systems of that time were crude but, with early ships being overbuilt, excess wastage was acceptable, as were occasional leaks. Current steel construction is to a much tighter standard with very little excess plating for wastage and sophisticated coatings to preserve the relatively thin shell plating.

Composites, mostly fiberglass reinforced plastics (FRP), became common marine construction materials in the 1960's. FRP has the advantages of light weight, corrosion resistance, ease of construction, and lower cost in comparison to steel, wood and aluminum vessels in lengths of 21 m (69 ft) and less. Sandwich composites take some of the FRP advantages one step further by using relatively thin FRP skins (inner and outer layers) "sandwiching" a low density foam or balsa core to achieve adequate panel stiffness at even further reduced weights. FRP vessels have steadily grown in size to where 40 m (130 ft) yachts are common, one 49 m (160 ft) yacht is under construction, and the U.S. Navy is building 55 m (180 ft) MHCs.

The MEDEA, built of steel in 1904, falls between these two extremes of building philosophies. The vessel had been well cared for, but many years of salt water use had deteriorated much of its structure. Permanent repairs of the steel structure were beyond the financial means of its owners, but a repair that combined advantages of both steel and FRP materials was feasible and attractive from the standpoint of both an engineering and cost.

MEDEA HISTORY

Tracing the vessel's history leading up to the actual repair to the MEDEA helps put the repair into perspective. Much of this historical tracking describes working with Coast Guard authorities to achieve acceptable levels of safety for operation in U.S. waters, a procedure that is often misunderstood. More details about the vessel's full history are available from the San Diego Maritime Museum (1), the current owners of the vessel.

The MEDEA was built in England in 1904 of 6.4 mm (0.25 in.) mild steel shell plate with fairly close 500 mm (20 in.) spaced transverse frames. The vessel spent much of its life as a well cared for private yacht, with other periods in the hands of members of British Parliament and the builder's family (2). The MEDEA did service during both world wars and passed through a number of other owners. It was finally purchased and transported from Scandinavia to Whidby Island in Los Angeles for restoration in the early 1970's. It was then sailed under its own power to San Diego and donated to the Museum there in 1971. It was first certificated by the U.S. Coast Guard as a "miscellaneous" vessel under Title 46, U.S. Code of Federal Regulations (46 CFR), Part 90.05-1 (3) in 1977 because it had a steam plant operating in U.S. waters.

Coast Guard Certification

When the MEDEA was first certificated, the Coast Guard accepted a number of existing repairs to the hull plate and framing that had been performed to a standard less than normally required by the Coast Guard. The repairs were permitted because of the vessel's limited service and because of the ample availability of rapid rescue or grounding to avert the consequences of minor flooding. These "temporary" repairs consisted of around 30 doublers, clad welding and epoxy patches to maintain the watertight integrity of the hull.

Doublers are additional plates welded over areas where the original hull plate is severely deteriorated, usually beyond 25 per cent wastage, which is the allowance built into the American Bureau of Shipping Rules for Building and Classing Steel Vessels Under 200 Feet (61 m)(4), (ABS Rules). This is normally allowed by the Coast Guard before renewals are required. It is a simpler repair than cutting out the bad plate and welding or, in the case of the MEDEA, much riveting, to make permanent repairs to the plating. Simple fillet welds and roughly fit plates are used for doublers as opposed to the careful fitting and two side welding normally required for insert plates.

Clad welding is a method of building up the steel plate thickness by overlaying numerous layers of weld metal in way of localized pitting and pin-holes. This method is not widely accepted for permanent repairs because of the large welding heat input to thin plate areas causing locked in stresses, and because of the susceptibility of the overlapped welds to increased corrosion attack.

When the MEDEA was hauled out for a drydock inspection in 1986, numerous additional holes, wasted areas and loose rivets were discovered. The Coast Guard allowed 12 additional doublers and more clad welding, rivet ring welding, and epoxy patches. But a definitive plan for permanent repairs was also required or the MEDEA would have had its certificate removed.

Repair Proposals

In early 1987 the owners of the MEDEA first proposed the FRP cladding of the vessel. The Coast Guard's San Diego Marine Safety Office initial response to this proposal was that Navigation and Vessel Inspection Circular (NVIC) 7-68, Notes on Repairs to Steel Hulls (5), required repairs that were to "renew as original" the steel hull plate. The Coast Guard was slightly mistaken in stating that the NVIC "required" renewal of the steel plating as original. Because, NVIC is a Coast Guard produced document publishing recommended practice without the official public comment and legal procedure followed for regulations that are promulgated from U.S. Law, a NVIC can not be made a requirement. Nonetheless, most marine industry people accept NVICs the same as regulation, as was the case initially for the MEDEA owners.

The Coast Guard was also going to consider the FRP cladding repair a complete alteration, but invoked the requirements of regulations in 46 CFR 92.07-10 (3), supposedly requiring the vessel to be constructed of steel or "other suitable material, having in mind the risk of fire." Even though imposing that particular regulation on a vessel the size and type of the MEDEA was beyond the applicability of that regulation, the owners of the vessel, especially considering its poor condition, had little basis for appeal.

The Coast Guard finally withdrew certification for the MEDEA in September of 1988, citing the lack of progress towards or a plan for permanent repairs. Bids were sought for making the required repairs in steel, but the estimates ranged from $1.2 to $1.7 million, far beyond the means of the San Diego Maritime Museum.

However, another attempt was made to obtain approval for the composite cladding repair, this time appealing the decision of the local Coast Guard office to Coast Guard Headquarter's, commercial vessel safety technical Office of Merchant Marine Safety, Security and Environmental Protection (Commandant (G-M)), Marine Technical and Hazardous Materials Division (G-MTH). The headquarters office reviewed the proposal based on its overall technical merits and the provisions for "equivalent safety," 46 CFR 90.15-l (4). Approval was given as long as some additional conditions were met, those being to show:

1. An acceptable method for strengthening the internal structure;
2. An adequate midship section modulus with the FRP sheathing; and
3. Sufficient strength of the FRP to steel interface.

THE PERMANENT REPAIR

The basics of the FRP cladding are shown in Figure 1 (6). The MEDEA's steel hull was blasted to white metal and given a thin coat of vinyl ester resin to quickly seal the bare steel. A linear polyvinyl chloride (PVC) foam was vacuum bonded to the hull with a putty resin and faired, and three layers of woven glass fibers alternating with chopped strand mat (CSM) were bonded to the foam. Finally the FRP was faired, then painted with epoxy primer and anti-fouling paint. The repair will be described from the structural aspect and from the aspect of producibility.

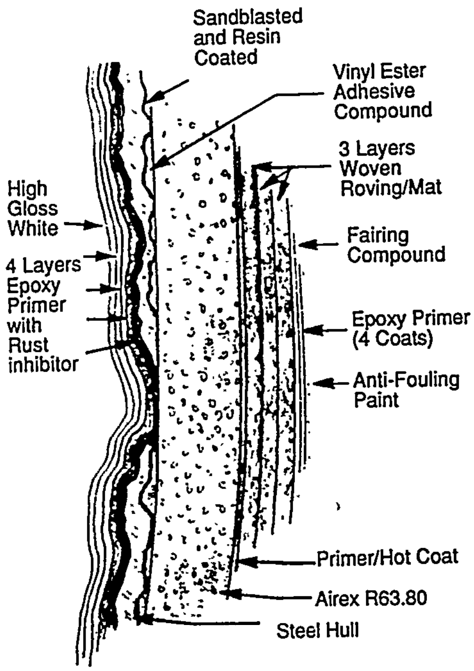

Figure 1
FRP CLADDING

Steel and Fiberglass Composite

The main structural concerns that had to be addressed for the MEDEA were local panel strength and longitudinal hull bending strength. A full description of the structural interactions between FRP and steel skins sandwiching a low density core material for panel stiffness is fairly complex and beyond the scope of this paper, so a brief analysis of the resulting structure will be given with references to works of much greater detail.

An analysis of sandwich composites attempting to adapt relationships from metals fails for two primary reasons.

1. Steel and aluminum are relatively high modulus isotropic materials with the resulting analytical equations becoming quite simplified.

2. Composites are low modulus highly orthotropic materials that respond quite differently under load, especially with even lower modulus, lower density structural cores in a sandwich structure.

The best method of analyzing sandwich composites is to treat the core as an elastic foundation as was proven by Berman et al (7) using three independent methods, each which verified the results of the others. Applying these methods to the repair of the MEDEA shell plating shows that the local panel stiffness of the FRP sandwich clad steel is renewed. The results of that analysis are shown in Table I. These results are compared to the shell plating thickness currently required by the ABS Rules.

Table I.
PANEL STIFFNESS

	THICKNESS mm (inch)	STIFFNESS DEFLECTION RATIO
ORIGINAL STELL SHELL PLATE	6.4 (0.25)	L/313
25 PER CENT WASTED	4.76 (0.1875)	L/132
MEDEA'S PRESENT STEEL	4.45 (0.175)	L/107
MEDEA STEEL WITH FRP SANDWICH	24.3 (.956)	L/156

The deflection ratio stiffness in the table is based on a given deflection over a fixed span under an applied load. Therefore, the higher the number "x" in the ratio "L/x," with "1" being the fixed panel span, the stiffer the panel section. The span for the MEDEA's framing members is 500 mm (20 in) and the applied load was 365 kilopascals (3.5 psi) based on the the head pressure from a mean draft of 2.1 m (7 ff).

Longitudinal hull bending of the vessel was also a concern. Due to the relatively low tensile modulus of the proposed composite repair, one may first assume that the additional FRP skin's contribution to the hull's longitudinal hull bending stiffness was minor. However, because the MEDEA is riveted, the effective plating for bending is reduced by the ratio of rivet hole size to rivet hole spacing, making the contribution of the FRP skins more important. The following additional factors combine to restore sufficient longitudinal strength for the service intended:

1. A wide band of 14.3 mm (9/16 in) solid laminate was planned in the keel area to withstand docking loads;

2. The hull plate below the water was wasted but the side shell and deck plates were still in good condition so that the neutral axis was shifted towards the deck; and

3. Longitudinal hull loading is reduced with the vessel restricted to San Diego Harbor so that severe hull bending due to ocean waves is not a factor.

In an analysis of hull girder bending, the thickness of the FRP plating is added to the steel in the ratio of the elastic modulus. Thus 1/20th of the FRP thickness is effective for hull girder bending and the 4.45 mm (0.175 in) plate gets 1/20th of 7.1 mm (0.281 in) or 0.36 mm (0.014 in) added to it to make the effective thickness 4.81 mm (0.189 in). This addition brings the effective thickness above the 25 per cent wasted minimum of 4.76 mm (0.1875 or 3/16 in) and allows the vessel to retain roughly 90 per cent of its hull girder bending strength.

Part of early plans for repair proposed bonding FRP frames to some of the wasted internal framing members. This plan was dropped in favor of welding new or additional steel frames onto the old frames. Therefore, initial denials to the proposed repair which were based, in part, on fire protection concerns, then became non-issues because all the combustible resin would be applied outside the hull.

The final concern of all parties involved was that the composite remain attached to the steel. Panel bending tests were performed to demonstrate the stress aspects of this question, and Dow Chemical, supplier of the vinyl ester Derakane® SOS4 resin, demonstrated sufficient experience and data to show that the composite could withstand stresses, weathering and marine exposure.

Application Procedure

The actual application of the FRP to the MEDEA was a painstaking manual repair procedure that requires explanation to place into perspective the procedures planned for future similar repairs. All the work was done at Knight and Carver Yachtcenter, San Diego, California. The basic procedure was to:

1. Sandblast the hull to white metal,

2. Brush coat the bare steel with a primer coat of resin,

3. Apply a putty resin to sections of the hull,

4. Vacuum the foam core into the putty,

5. Fair the foam,

6. Apply the FRP outer skin,

7. Fair the outer skin, and

8. Apply the epoxy primer and paint.

Each of these steps will be described in more detail. Then steps to mechanize the process will be explored.

Sandblast the Hull to White Metal and Prime

The repair was performed on an area from the keel to 200 mm (8 in) above the load waterline. To effect this in a continuous process around the bilge and across the keel, the MEDEA was placed on removable blocks under the keel and supported on the sides by pipe secured to the ground and welded to the vessel above the repair area. It was blasted in sections and immediately coated with a primer coat of catalyzed resin to preserve the steel and to provide a prepared substrate for subsequent bonding of the foam. The work was done in sections to:

1. Minimize the area of exposed steel,

2. Reduce the number of keel blocks removed at any one time, and to

3. Expose a reasonable area for bonding on sections of foam.

Apply Resin Putty and Vacuum the Foam Core

The vinyl ester resin was made into a putty by adding a filler of hollow glass microspheres to provide a tough resilient base to bond the foam into, and to fill bumps and hollows, in the pitted steel plate. The vacuum bag process was used to bond the Airex linear foam onto the vessel in sections. For this application, contoured sections of foam were used. Contoured Airex R62.80 foam is in the form of 1.2 by 2.7 m (4 ft by 9 ft) sheets with cross cuts every 32 mm (1.25 in) through 90 per cent of its thickness. This allows the sheets to drape easily over curved Surfaces.

The principles of the vacuum bag process are that the foam core is placed into the putty in areas of 20 - 30 square meters (70 - 100 square feet) at one time. It is then covered by bubble pack to allow air to flow out then sealed all around with a plastic sheet. A partial vacuum is pulled through the bubble pack which allows outside air pressure to evenly press the foam into the putty until the putty cures. The process is time consuming but absolutely necessary to ensure a thorough bond.

Fair the Foam

With the MEDEA having riveted construction, plate overlaps for riveted connections are inevitable. In addition, there were many areas where the squared sheets of foam could not be cut to fit the curves of the hull exactly. Where the foam was raised up, it was ground and sanded roughly even. Where hollows and cracks were encountered, additional vinyl ester putty was used to fill the areas until a relatively fair surface was presented to apply the FRP skin. The foam was also tapered and faired at the edge of the repair area and in way of sea chests and through hull fittings. Panel stiffness was retained where the foam was ground down because the grinding took place at the edges of the panels where the steel plate overlapped, and not in the center of the panel span.

Apply the FRP Outer Skin. Fair and Paint

The application of the 3 layers of chop strand mat (CSM) stitched to woven roving that made up the FRP outer skin was by a modification of the basic hand laminating process. This is a process of:

1. Spraying catalyzed resin onto the surface,
2. Laying dry fiberglass reinforcement into the wet resin,
3. Spraying more resin onto the dry glass surface,
4. Rolling the composite to thoroughly wet out the glass, then
5. Drawing off the excess resin with a squeegee.

There was one major exception to the normal laminating process. Much of the work was done overhead. This made the work more difficult and messy, but because the interior of the MEDEA was totally intact and in a nicely restored condition, the hull could not be turned over to allow all the laminating work to be done down-hand. Estimates from the repairer are that this added roughly 20 percent to the labor cost of the laminating work.

The fairing of the outer FRP skin was done by first sanding the FRP surface then applying a series of Pro-Line@ epoxy primers and filled fairing compounds and sanding to achieve acceptable fairness. Then final epoxy primer and antifouling paint was applied.

The internal areas of the vessel were also blasted to white metal and thoroughly coated with epoxy primers and paints. Where internal structure was extensively wasted, new frames were "sistered" to the existing structure.

RESULTS

The finished repair to the MEDEA exceeded the expectations of the owners. Besides satisfying the Coast Guard's concerns for certification, the vessel has a more solid feel when underway. The volume of the light weight composite repair gave the vessel more buoyancy, which would normally be a benefit to an older vessel because older vessels tend to gain weight with time from added equipment and structure. However, the San Diego Maritime Museum Executive Director, Captain Kenneth Franke, stated they may need to add ballast to return the MEDEA to its normal draft. An additional benefit from the repair is that the faired surface eliminated the original shell plate overlaps on the underwater surface.

The MEDEA earned back its Coast Guard certificate on April 24,199l with special provisions for examining the repaired surfaces for delamination and separation from the steel hull. According to Captain Franke, regular inspections have shown the repair to be in good order.

The entire repair, including docking and undocking, and internal repairs and coatings was completed for an actual cost of $220,000. However, many factors contributed to keeping this figure fairly low. Parts of the materials were donated or discounted, pier fees at the repair location were waived, and much of the engineering and administrative support was donated. The repairer estimates that these considerations reduced the actual cost by about one half. The repairer also estimated that the $220,000 figure would probably apply solely to the exterior composite work had this been an unsubsidized commercial contract.

PRODUCIBILITY ASPECTS

The repair that was performed on the MEDEA was done to the technical satisfaction of all the interested and performing parties. However, one item in the installation procedure warrants review for the application of advanced FRP processing technology in the form of fiberglass impregnators. The details of how these machines work were described by Raymer (8), but the basics are that the dry fiberglass material is pulled through a resin bath to wet out the fabric, then the fabric is applied directly to the mold surface. Advantages of impregnators over normal hand lamination procedures are:

1. The resin is completely and mechanically forced into the fabric,

2. Resin waste is vastly reduced,

3. Spraying of resin is eliminated which reduces volatile organic compound (VOC) emissions and reduces worker exposure,

4. The already wetted material is applied in an almost continuous semi-mechanized process,

5. Laminate structural quality is improved, and

6. Labor savings on the order of 50-75 percent are realized.

However, all existing impregnators are designed to introduce the wetted fabric from above the surface being laminated. For new construction in FRP, this usually involves building the structure from the outside of the hull surface to the inside, using a female mold, or from the outside surface in on a male mold. The MEDEA was basically a male mold that was not capable of being overturned, making the application direction of the FRP outer skin largely in the upward direction.

This problem is not unlike that of applying the fiberglass and epoxy coating used for wooden minesweepers. This coating, or sheathing, is applied to a nearly completed wooden vessel that is, like the MEDEA, not capable of being turned over to allow downhand application of the coating. Application of this composite coating causes similar problems to those encountered in the MEDEA project with the added complication of worker sensitivity to epoxy resins.

This particular problem, that of applying FRP in an upward direction, was addressed by Venus-Gusmer of Kent, WA in a general proposal to Peterson Builders. For a number of reasons, that project was never completed, but preliminary engineering work showed the feasibility of the method. The basic aspects of the process are:

1. Modifications to the machines described in (8) were designed to redirect the wetted fabric out the top of an impregnator;

2. The impregnator was to be mounted on an electric industrial truck- with a telescoping boom; and

3. Resin and catalyst were to be pumped to the impregnator from a remote station and mixed at the impregnator.

Details of the existing costs and projected cost savings for application of this technology to coating wooden ships is not available for release. Projected savings, including labor, reduced disruption time, and reduced emissions are difficult to quantify, but could reasonably pay for the system over 2 - 4 ships.

Such a system allows all the advantages offered by impregnators. Investment in such a system, including an impregnator, pumps and an industrial truck, for occasional projects such as the MEDEA is not likely to be justified. However, much of the equipment is available for lease or could be made available for lease.

CONCLUSION

The FRP cladding of the wasted steel plating on the S/Y MEDEA proved that an adequate repair of a steel structure can be made with innovative use of composites. The sandwich composite structural repair was able to satisfy the concerns of the Coast Guard so that the vessel was recertified. The repair within the financial means of the owners. Even if donations and other considerations were not used, the FRP repair would have cost less than one third that of steel renewals.

Applications of mechanized FRP impregnating equipment could make similar repairs and FRP work an even more cost effective proposition.

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