ARE COMPOSITES SUITABLE FOR REINFORCEMENT OF SHIP STRUCTURES?

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SUMMARY: The application of two large-scale, carbon fibre composite reinforcements, adhesively bonded to an area of a naval frigate prone to serious fatigue cracking, is described. The effectiveness of the demonstrator reinforcements in reducing cyclic stresses was monitored by strain gauge experiments conducted before and after installation. Service durability over a six-year period is evaluated. During this time, the reinforcements were exposed to arduous ocean conditions including severe sea states. In addition, one reinforcement suffered accidental damage requiring *in-situ* repair. Recent laboratory work aimed at improved techniques for the lay-up of marine composite reinforcement is also discussed.

KEYWORDS: marine stress cracking, carbon fibre reinforcement, interface adhesion, joule heating, durability

INTRODUCTION

Over the last thirty years, marine grade aluminium alloys have seen increasing use in both commercial vessels and surface warships, particularly in decks and superstructures. However, it’s use in recent warship construction has diminished rapidly because of problems of thermal softening under fire and endemic cracking in superstructures bonded to steel hulls have more the negated the notion of topside weight saving.

Fatigue-induced cracking of aluminium superstructures remains a serious problem with warships still in service. Cracking is usually caused by a combination of applied cyclic stresses and stress concentration interacting with a region of material weakness. Cracks usually initiate and propagate from areas at or adjacent to butt welds as weldments intrinsically display even lower fatigue endurance than the strain hardened parent plate.

The FFG-7 class of guided missile frigates, Figure 1, of which the Royal Australian Navy (RAN) operates six and the US Navy more than fifty, has a steel hull to which is continuously welded an aluminium alloy superstructure. All ships of this class have experienced endemic fatigue-induced superstructure cracking [1], often severe, after just a year or two in active service. To date more than 200 cracks have been repaired in the four older RAN vessels [2].

Figure 1. Royal Australian Navy FFG-7 Class frigate in the Sydney harbour

Repairs to cracked structures, once confined to methods that involved either direct welding or welded doubler or insert plates, have in recent years been supplemented by techniques involving adhesively bonded metal or fibre-composite reinforcements. Thus a new, more efficient approach to the through life management of such superstructures is emerging, involving the appropriate combination of composite reinforcement and welding. The pioneering work, carried out by the Admiralty Research Establishment in UK [3], involved the repair and reinforcement of Royal Navy (RN) type 21 frigate superstructures using steel and carbon fibre (CF) reinforcements.

In 1993, following extensive laboratory research [4], DSTO applied two 5 x 1 metre carbon fibre composite demonstrator reinforcements to a fatigue-prone superstructure area of the RAN FFG-7 frigate *HMAS Sydney*. This paper describes the reinforcement fabrication work conducted on board the frigate, the stress reduction achieved, and their condition after six years of harsh marine service exposure. New techniques for composite reinforcement manufacture are also considered.

THE APPLICATION OF CARBON COMPOSITE REINFORCEMENT TO A FFG-7 FRIGATE SUPERSTRUCTURE

Background

The area circled in Figure 1 and shown diagrammatically in Figure 2 is the necked-down, midship region of the FFG-7 superstructure that is prone to cyclic fatigue cracking. The history of cracks, coupled with the numerical stress analysis of the region, enabled engineers to determine the precise location, material and the size of CF reinforcements. Thus it was proposed to construct two 5 x 1 metre, 25 layer CF reinforcements on each side of the upper 02-deck as shown in Figure 2. The laboratory development work that followed included: in-house manufacture of a single resin system suitable to perform both as a matrix for the carbon composite and a tough interface adhesive, composite and adhesive property evaluation and large-scale fatigue testing of a simulated deck reinforcement [4].

Work conditions onboard naval ships are very different from those in the laboratory. There are no controlled climate or workshop facilities and this pioneering project required a great deal of planning and preparation to optimise the chance of success. All preparatory work, including the fabrication and bonding of carbon fibre reinforcements *in-situ* to the aluminium deck was performed by DSTO staff on the 02-deck of the ship *HMAS Sydney*, Figure 2. This activity took place during the ship's scheduled maintenance at the Garden Island naval dockyard in Sydney in late March 1993. In the preparation phase, it was necessary to temporally remove some obstructing equipment and erect a canopy to protect the work area against rain, wind and the sun. Small embankments were erected on both the port and starboard sides to divert streams of surface rainwater from the work area.

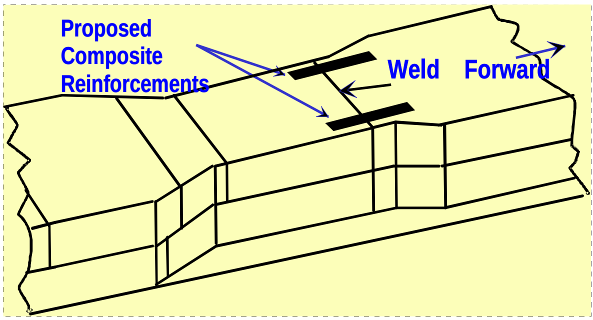

Figure 2. Upper mid-ship region of aluminium superstructure, FFG-7 class frigate.

Reinforcement Installation

Surface preparation

The surface preparation included removal of paint and non-skid material. The 02-deck topography is undulated and in some places contains thicker, welded insert or doubler plates. These aluminium plates are part of a standard engineering solution to resolve predominantly edge-initiated cracking in areas of high stress concentration. An example showing a thick plate insert and a crack uncovered after paint stripping is shown in Figure 3. The crack was re-welded prior to reinforcement application. On both port and starboard sides, the area designated for surface preparation approached 6.6 m^2 (5.5 x 1.2 metre). Some of activities

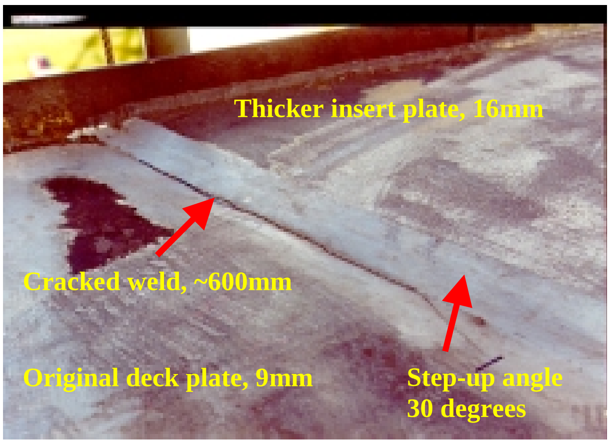

Figure 3. Welded connection between 9 and 16mm plate insert (Note the length of crack)

associated with surface preparation are illustrated in Figure 4(a) and 4(b).

Figure 4(a). Surface grit blasting on 02-deck

In Figure 4(a), the starboard side is shown at the time of surface grit blasting using a suitable industrial unit. To assist with uniform surface coverage a set of adjustable aluminium rails were positioned on each side of work area which helped to guide a multi-purpose trolley with the attached grit blasting head. The step-up angle of ~30 degrees between the thick insert plate and the original deck plating, Figure 3, was reduced to ~10–15 degrees with epoxy filler paste, Figure 4(b). An application of a silane solution over the grit blasted area completed the surface preparation phase. This procedure was identical to that developed for aluminium surface in the earlier laboratory trial [4].

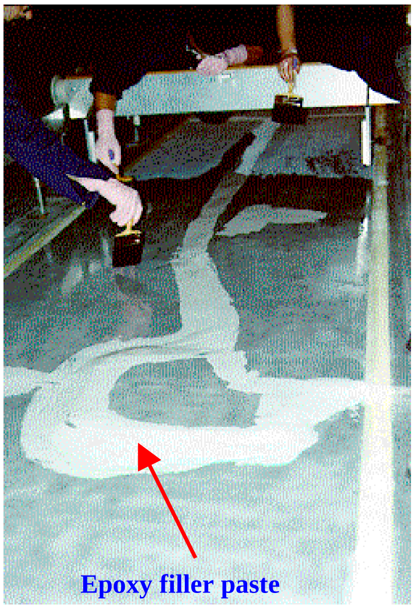

Figure 4(b). Application of silane solution

Fabrication of adhesive bond layer

There are two reasons why this step is separate from an all-in-one CF composite production. Firstly, bonding the carbon fibre composite on to an aluminium substrate was found in the laboratory work to cause the carbon fibre to make contact with the aluminium. This happened repeatedly in spite of special attention being focused to resolve the problem. Research has shown [5] that in presence of an electrolyte (eg. salt water) two materials of dissimilar electro-potential will create a galvanic cell resulting in localised corrosion. Secondly, an in-house method has been developed to carry out *in-situ* composite post-cure by application of Joule heating (see later). In this case, no contact of carbon fibre with the aluminium substrate can be tolerated. (Ambient curing engineering thermoset resin systems require a post-cure to complete cross-linking and thus acquire ultimate properties, especially glass transition temperature). The modified vinyl ester resin system chosen for this work was developed by DSTO [6] to meet essential criteria such as low viscosity, high fracture toughness and good adhesive peel and shear properties.

Using a simple, purpose-developed tool, the fabrication time of the adhesive bond layer had been significantly shortened. For example, the dispenser Figure 5(a), can distribute a relatively uniform quantity of resin per given area in minimal time. Although pot life for the vinyl ester resin can be modified by addition of reaction retarding additives, it is often the ambient deck temperature which cannot be easily controlled. In Sydney for example, a sunny mid-day temperature in March can produce a deck temperature of up to 60^{o}C. At this temperature, the resin reaction would be too fast and thus work must be carried out either early in the morning or later in the day.

Figure 5(a). Resin dispensing and spreading

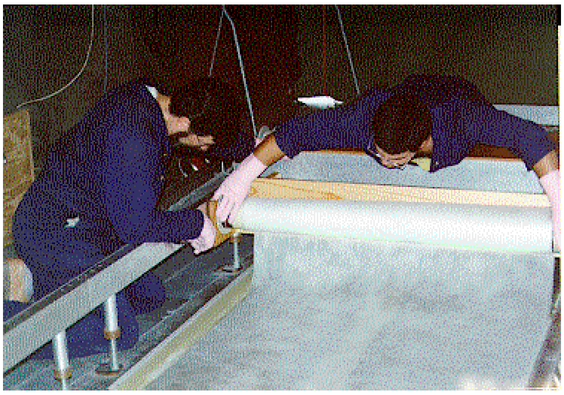

Figure 5(b). Unrolling and laying of glass fibre reinforcement

Figure 5(b) shows the mobile trolley fitted with tubes onto which the various materials needed for each stage were wound. Hence, this method allowed quick and precise laying of a scrim material, glass tissues (2 plies), a peel ply and the release film. After placing the breather/bleeder cloth under the vacuum bag, the application of vacuum makes the resin impregnate all layers, with excess resin being absorbed into the bleeder layer, Figure 5(c). If the resin reaction is retarded, the degree of overnight cure is closer to 50% or less. Once the peel ply is removed, a relatively low degree of resin cross-linking makes it possible to achieve a strong primary and secondary bonding at the interface between the adhesive and the composite layers. The size of adhesive layer was extended beyond the area of composite by an additional 100mm in width and length (ie. 5.1m x 1.1mm).

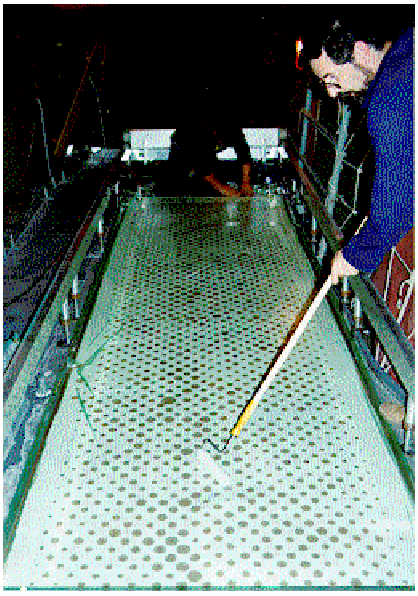

Figure 5(c). Vacuum bag consolidation of adhesive bond layer

Fabrication of CF composite reinforcement

The third stage in the reinforcement production for the aluminium deck included bonding and consolidation of CF reinforcement on top of the adhesive bond layer. The procedure involving resin distribution, laying of 25 plies of carbon fibre unidirectional cloth and consolidation under vacuum bag, was identical to that given previously. This task was carried out over a two-day period simply because resin distribution and laying of 25 plies, each 5m in length, is a time consuming process which could exceed the resin pot life. Furthermore, instability in the weather, which can cause uncontrolled raise of temperature, posed an additional and unacceptable risk of premature reaction of matrix resin. In an attempt to speed-up the resin wetting process, only selected layers (ie. 0^{th}, 2^{nd}, 10^{th} ply) were coated with a predetermined quantity of resin. Under the vacuum bag, the resin permeated the dry reinforcing material, resulting in a good quality, bonded composite reinforcement.

Post-cure of CF reinforcement

As pointed out earlier, a post-cure is desirable to achieve close to ultimate properties in a nominally ambient curing thermoset resin system. This could be achieved by a variety of methods, but considering the size of composite that is bonded to aluminium structure, some methods had severe shortcomings. Solar heating, for example, is the most economical way which will in time achieve partial post-cure, but the process is uncontrolled. Alternatively, a large heater blanket (ie. at least 5 x 1 metre) is expensive, requires a large power input (240 VAC) and is an inefficient method to heat-up the adhesive bond layer due to the large heat-sink effect of the aluminium superstructure.

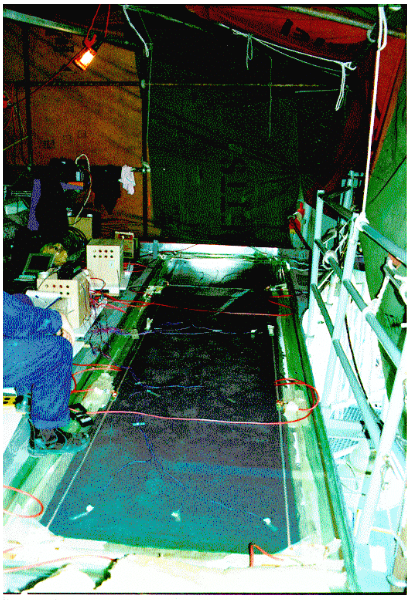

Figure 6. Composite post-cure by resistance heating

The in-house developed method is a low voltage (<120 VAC) based, resistance heating (Joule heating) utilising the electrical conductivity of carbon fibre [7,8]. Two braided copper strips running on both sides parallel to the length of CF composite were used for the power connection. The current output, provided by four transformers, was designed to post-cure the composite over a four-hour period at a temperature between 70 – 75^{o}C. The heat-up rate and the heat distribution over a large surface area were monitored through a feedback control loop utilising surface-bonded thermocouples, Figure 6. Surface heat loss was minimised by covering the composite with a blanket. The method proved to be very efficient, inexpensive, safe and above all generated heat where it was needed assuring a post-cure in both the composite and the adhesive bond layer at the reinforcement/deck interface.

Composite protection and surface finish

The location of both composite reinforcements on 02-deck (port and starboard side) is on a walkway used by both ship's crew and maintenance personnel. In addition, this area is often used as an offloading point from an overhead crane and for the erection of scaffolding required for the maintenance of the ship's main mast. For these reasons, together with exposure to the harsh marine environment ie. solar effects, water, salt etc., a GRP protective layer for the reinforcement was designed and tested in the laboratory. Out of four matrix resin systems considered (epoxy, modified vinyl ester and two polyurethane formulations) the in-house modified vinyl ester was chosen after comparative impact damage tests ranging in kinetic energy level from 11 – 56 Joule. The choice of the DSTO resin also assured total compatibility with both the adhesive bond layer and the carbon fibre composite. The fabrication procedure was again identical to that applied to the adhesive bond layer and CF composite. In the design, a provision was made for an extra edge protection to the composite reinforcement extending an additional 100 mm in width and length to coincide with the size of adhesive bond layer.

Figure 7. Applied epoxy based primer

The final surface protection applied by DSTO staff was a good coverage of an epoxy based primer which additionally sealed the edges, especially at the interface between the GRP protective layer and the aluminium deck, Figure 7. This was followed by a standard navy paint scheme that included the final non-skid layer applied to the walkway, Figure 8.

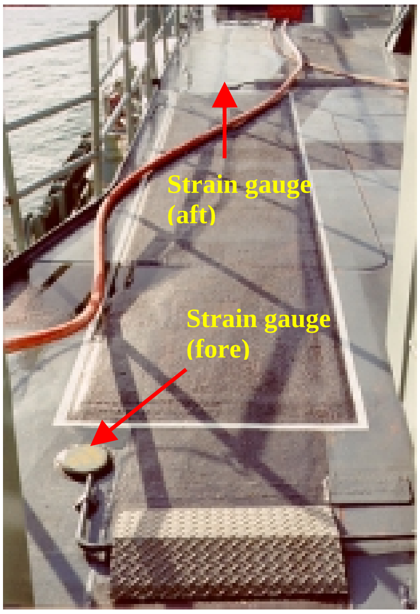

Figure 8. CF reinforcement in service – starboard side

Stress Measurements

According to the original engineering estimates, a 25-ply CF composite was needed to reduce the stress concentration in the upper, mid-ship region (Figure 2) by approximately 20%. Theoretically, a stress reduction of this magnitude was expected to stop or significantly relieve cracking episodes re-occurring most commonly due to inherent weld flaws on the 02-deck plating.

To confirm patch effectiveness it was decided to measure strain levels in the reinforced region during active service conditions. This comprised a collection of strain output data over time for given sea-states and ship speeds during alternating conditions of longitudinal hull bending (sagging and hogging). Thus, measurements were conducted before and after installation of the composite reinforcement using a combination of uni- and multi-directional strain gauges installed at predetermined 02-deck locations, Figure 9. For a better understanding of the complex stress distribution in the region, additional strain gauges were positioned across the 02-deck and down the sides to reach the 1-level.

The data analysis [9] and the effectiveness of the reinforcement is illustrated in Figure 9.

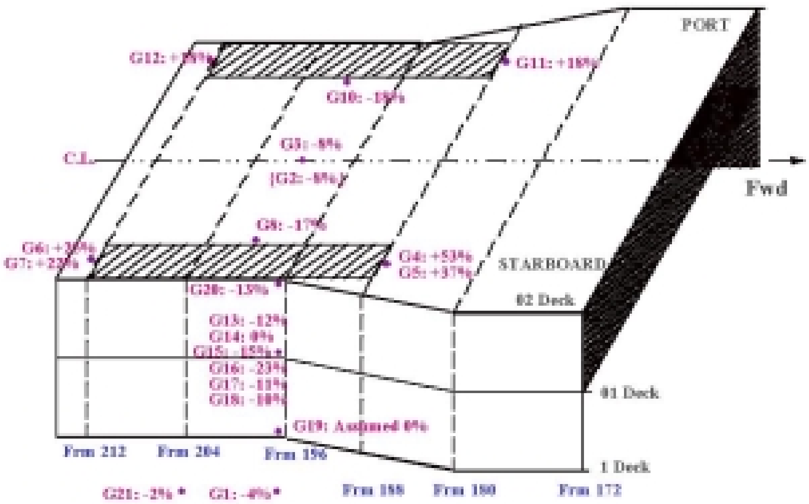

Figure 9. Changes in strain intensity level after composite reinforcement (neck-down region)

Seven strain gauges were installed on the 02-deck. The output of the four gauges located at the ends of each reinforcement show about 20% increase in strain level. In contrast, the deck area between Frames 188 - 212, indicate a corresponding reduction in strain. Installation of CF composite reinforcements also affected strain distribution in the vertical plating welds at frame 196. The three strain gauges (rosettes) positioned at each superstructure level (ie. 1, 01 and 02) also show a beneficial effect of reinforcement in the longitudinal strain which includes the most critical Frame 200.5 [1]. The anomaly in the output of strain gauges G4 and G5 (02-deck starboard side, fore) indicate the influence of a crack (see Figure 3) present during the initial collection of experimental data.

CF Reinforcement Through-Life Maintenance

Close interaction between the DSTO reinforcement team and the RAN crew has assured constant monitoring of the CF reinforcements in service. Since April 1993 the ship has been exposed to extremely harsh marine conditions including very high temperatures in the Persian Gulf, storms off Karachi and high level sea-states around the Australian coast. Late in 1995, it was noticed that the exposure to the elements caused localised de-bonding between the GRP protective layer and the deck. After initial inspection, it was decided to rectify the problem and develop a better sealing method for the GRP/aluminium interface.

Weathering of the GRP/aluminium interface

In January 1996, after almost three years in service there was a need for the first maintenance service to the CF reinforcements. The type of damage sustained by the composite on the 02-deck is evident in Figure 10 and insets a) and b). Local de-bonding at the GRP/aluminium interface and a small scale tearing, especially around corners, was consistent on both composite reinforcements. It is believed that a combination of factors (mechanical wear and tear, mismatch in thermal expansion between GRP - aluminium and presence of sea water) caused the failure of the bond. No damage to the surface of either CF reinforcement was noticed.

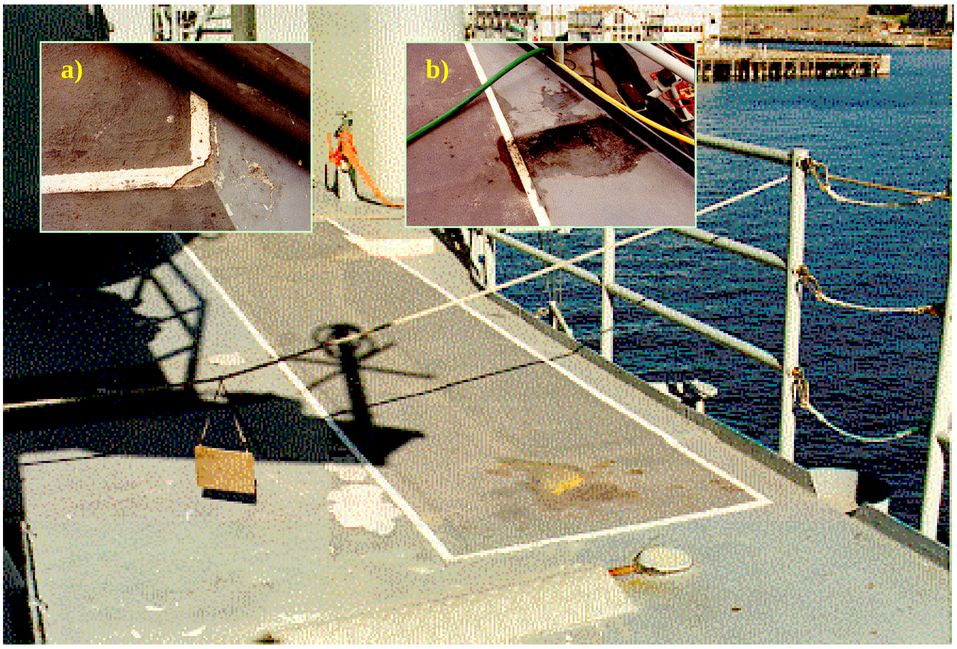

Figure 10. Weathering of composite reinforcement on 02-deck. A typical damage Inset a) and b)

Uneven surface of the deck also causes local water locks to form, see Figure 10, inset b). Once the surface protective paint system is breached, this condition, if left unattended, will in time result in progressive deterioration of the adhesive and corrosion of the aluminium surface.

To prevent progressive environmental degradation, it was decided to remove 150mm of GRP protective layer around the periphery of both reinforcements irrespective of their condition. The immediate bare surface of aluminium and composite was cleaned, prepared and the adhesive bond layer reconstructed using identical materials. The procedure used to produce the new 200mm wide GRP layer (allowing 50mm overlap), thus rebuilding the GRP/aluminium interface around the boundary of both reinforcements, was identical to that discussed earlier. In addition to the GRP reconstruction work, it was decided to include an enhanced edge sealing method developed in our laboratory. Besides a suitable epoxy and polyurethane-based paint, a glass reinforced polysulphide elastomer was also introduced to account for differences in thermal expansion and additional protection against water ingress at the critical GRP/aluminium interface, Figure 11.

Physical damage to the CF composite – Port side

In January 1998 the port side CF reinforcement suffered mechanical damage during a maintenance schedule. High-pressure rotary water jet equipment, used for surface paint removal, had accidentally collided with the composite reinforcement. The type and the extent of damage are shown in Figure 12.

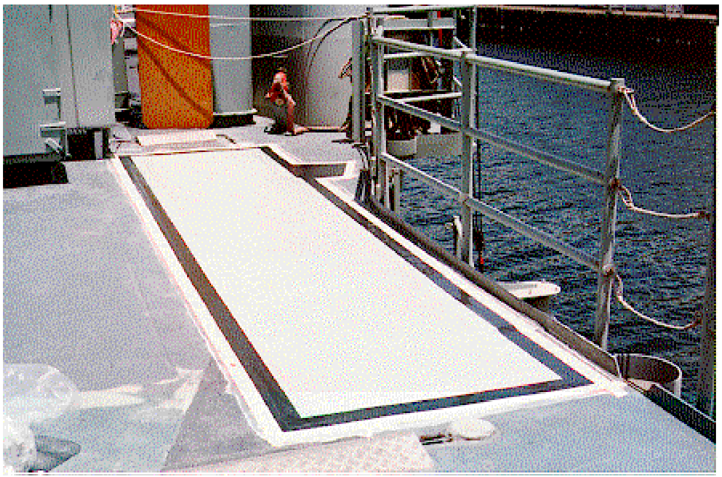

Figure 11. Additional edge protection – polysulphide elastomer

The circular groves shown in Figure 12 represent the most serious damage. In some places cuts have penetrated through the composite and exposed the aluminium deck. Furthermore, it was established that excessive water pressure had also caused local delamination within the composite. The total area affected and prepared for repair was close to 900mm in length and 400mm in width, Figure 13.

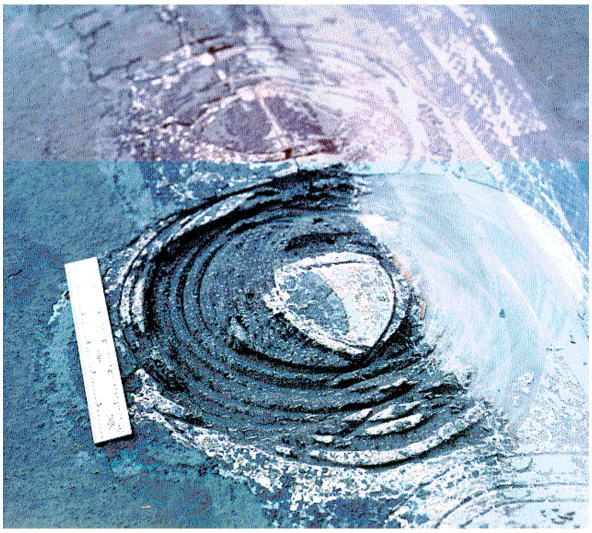

Figure 12. Physical damage to CF composite

Figure 13. Composite repair area

The repair procedure again first included the reconstruction of adhesive bond layer followed by rebuilding of a matching CF composite structure. The reconstruction and vacuum consolidation of a GRP surface protection included the repair of an approximately 1m long edge-sealing strip and completed the task. At the time of writing this paper no further incidents have occurred.

Non-Destructive Evaluation of the Adhesive Interface

Two assessments of composite reinforcement adhesion have been made using a Non-Destructive Evaluation (NDE) technique. The first examination was carried out in February 1994, approximately a year after installation of reinforcements, and the second in October 1995. On both occasions, evaluation of the integrity of the adhesive bond was assessed using an ultrasonic flaw detector operated at a low frequency. A single crystal probe was employed using the water stand-off method, Figure 14.

Figure 14. NDE assessment of adhesive interface

Although the tests were conducted approximately 18 months apart, the findings indicated that no detectable deterioration (ie. de-bonding) of the adhesive interfaces had occurred.

HMAS Sydney – 02 Deck Crack Monitoring, Post-1993

Six years on, no cracking has been reported in the highly exposed region of 02-deck to which the composite reinforcement was applied. Thus a high degree of confidence and credibility has been acquired by both the DSTO research team and its customer the Royal Australian Navy for a novel technique which has many distinct advantages over the commonly used conventional welded repairs.

Technique Improvement

In view of changes in safety regulations taking place at the workbench level, especially in the second part of this decade, together with ever-increasing financial constraints on research, subsequent work in the development of marine composite reinforcement required modification. Retrospectively, the work carried out in 1993 was demanding both in terms of time and labour. Furthermore, the semi-automated technique required workers to be exposed to chemicals to a small extent. At present, commercial financial constraints, coupled with newly introduced work safety rules, can no longer tolerate the requirements and conditions of the work conducted in 1993.

There are two new approaches being perfected by DSTO focusing on improved composite reinforcement techniques. One approach is to employ the limited shelf-life, carbon fibre/epoxy prepreg systems in conjunction with epoxy-based, aerospace structural film adhesives. These materials cure at elevated temperatures and the DSTO heat generating method, based on the Joule heating principle, has been successfully used to produce marine composite reinforcements. The other approach is also very efficient and user-friendly. In contrast to the above prepreg systems this novel method, based on vacuum infusion, involves a room temperature cure of the wet resin system as used in 1993. The difference is an added flexibility in terms of a fibre wetting process and composite fabrication methodology, which practically eliminates hazards associated with workers exposure to chemicals. In addition, this technique also offers a significant reduction in both human and financial resources. This aspect alone could make the composite reinforcement technology potentially attractive not only to naval fleet operators but also to a large commercial sector in the marine industry.

CONCLUSION

DSTO research and development of carbon fibre reinforcement of marine structures has been successfully demonstrated on *HMAS Sydney*. After reinforcement, no further cracking has occurred in the region of interest and, six years on, the reinforcements remain in good condition despite exposure to severe marine conditions.

DSTO have also successfully developed significant improvements to the original composite reinforcement process by upgrading the productivity in laying-up of large composite reinforcements. Concurrently, these new processes offer additional cost cutting incentives to

fleet operators as the technique becomes simpler and faster to execute. At the same time, these improvements observe new regulations applicable to safe working practices to the extent that they at present comply with the new stringent Occupational Health and Safety requirements now in force in Australia.
Therefore, if we consider material efficiency and compatibility, efficacy of stress redistribution and shielding of underlaying vulnerable regions including durability of the reinforcement the answer to the title of this paper is YES, …Composites are suitable for Reinforcement of Ship Structures.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions made by Dr. Alan Baker, Richard Bartholomeusz, Bernard Phelps, Paul Elischer, Joe Donato and Howard Morton of DSTO. In addition, the assistance offered by Defence staff in Canberra and the Navy officers on *HMAS Sydney* in carrying the project through to its completion is greatly appreciated.

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