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COMPOSITE REPAIRS: PRACTICAL IDEAS FOR AN INCREASE IN CAPABILITY AND OPERABILITY WITH LESSONS FROM THE OIL AND GAS INDUSTRY

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SUMMARY

Composite repairs in a marine environment have been a practical reality for the past 30 years and have been applied in a wide range of commercial and naval applications. Despite the potential to increase capability and availability, there are barriers to implementing structural composite repairs. This paper does not seek to address the advantages or disadvantages of composites; however, it does aim to identify barriers to adoption and a route to implementation where the evidence is that they are the optimum solution. This will be done by synthesising past experience, reviewing organisational best practice, providing illustrative case studies, as well as addressing the barriers to adoption in both naval and civilian contexts.

1 INTRODUCTION

Following significant research conducted both before and during the 1990s and early 2000s [1], [2], [3] and [4], composite repairs have been trialled on a number of marine assets in a number of locations. Even with the volume of research and supporting evidence available, the take-up has not reflected the promise of the early work. Despite this, there have been several instances of successful composite repairs both in oil and gas and naval vessels [5], [6]. This paper seeks to outline the reasons behind the current low adoption of composite repairs, the barriers to adoption, some best practice in getting acceptance and approval and highlight some lessons from the oil and gas industry that have wider benefits to the capability and operability of assets in both civilian and naval contexts.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
CFRP	Carbon Fibre Reinforced Polymer
CALM	Catenary Anchor Leg Mooring
CAPEX	Capital Expenditure
Class	Classification Society (ABS, DNV, BV, Lloyds Register, etc.)
FEA	Finite Element Analysis
FRP	Fibre Reinforced Polymer
FSO / FPSO	Floating Storage and Offtake / Floating Production, Storage and Offtake
FVF	Fibre Volume Fraction
IMO	International Maritime Organisation
ISO	International Organization for Standardization
JIP	Joint Industry Project
MOC	Management of Change [process]
PMC	Polymer Matrix Composites
RAN	Royal Australian Navy
SDIP	Strategic Defence Industry Priority
UK HSE	United Kingdom Health and Safety Executive
VaRTM	Vacuum assisted Resin Transfer Moulding

2 HISTORY AND DEVELOPMENT OF THE INDUSTRY

Within the marine and naval context, this paper considers structural composite repairs made from Fibre Reinforced Polymers (FRP) applied to any marine structure. In general, composites are made from two or more different materials with different physical or chemical properties that, when combined, are stronger than those individual materials by themselves [7]. Structural composites are a subset of Polymer Matrix Composites (PMC) where the mechanical performance is repeatable, with high strength and stiffness, often superior to metals [8].

To achieve this high performance and reliability the structural composite combines the properties of a pre-determined orientation, stack of continuous reinforcing fibres such as; glass, carbon, aramid, and boron, embedded within a matrix which spreads the loads between the fibres and adhered substrate (marine structure).
In the case of structural composites an epoxy-based system is commonly used for the highest mechanical performance from the resin choices available [8], [9]. A structural composite repair ultimately looks at the performance of the combination of the fibres, resins, and metallic substrate as a composite itself [10].

Figure 1. Structural composite repair on ship bottom plate using Carbon Fibre Reinforced Polymer (CFRP) [11]

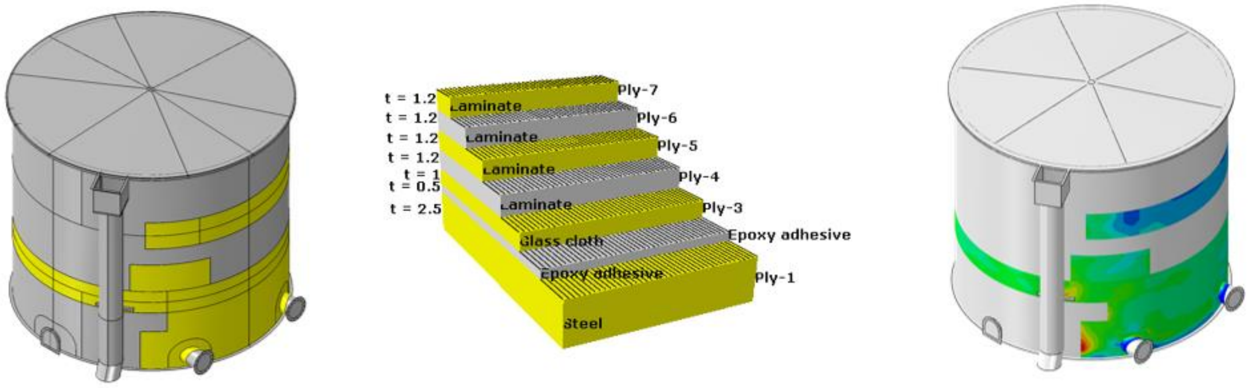

Figure 2. Structural composite repair FEA adhesion review, example [12]

2.1 CONSTRUCTION INDUSTRY

Traditional Wet Lay-Up for structural composite repairs to infrastructure has inherent problems and limitations [8], [9]. However, the system allows for widespread application by low skilled workforces. Infrastructure applications have looked to improve performance through process change [13], [14]. In the 1980s carbon fibre laminate strips were manufactured in a workshop and then secondarily bonded to bridge undersides for strengthening. This improvement from Wet Lay-Up manufacturing meant that the fibre performance was made consistent and reliable, but its adhesive performance was poor. This process allowed for concrete skilled workers to achieve repeatable applications (although not maximising the structural composite's performance). Other occurrences of this approach to structural composite repair involve combined Wet Lay-Up and pre-cured strips [15], [16] applied to concrete and steel infrastructure, including examples such as pre-cured carbon fibre strips applied to London Underground steel structures for strengthening.

The lessons from construction and particular bridge strengthening using composites are;

- Open sharing of information on research and applications allowed for rapid and low risk applications of composites to be delivered into the field.
- Establishing bridge composite strengthening codes was a faster process because of the open sharing and significant cost savings offered.
- With codes in place technology development continued. Improvements and industry cost savings were therefore realised quicker.

2.2 OIL & GAS

In the oil & gas industry the use of composites was initiated with the use of fibre glass pipes, introduced in 1948 [7] and has grown on the use of composite products in CAPEX projects. These are produced in workshop environments and are typically manufactured using pultrusion and filament winding methods enabling high volume manufacture.

For in-field manufacture and repairs to metallic components using composites, the uptake has been strong globally because of the significant commercial benefits, specifically allowing for repairs to occur under operating conditions. This in-field application under live conditions is leveraged in ships to prolong time at sea and reduce or remove the need for dry-docking. In these scenarios the cost of the repair is insignificant compared to the costs associated with time not at sea or lost production. The oil & gas industry has seen similar drivers to the applications of composites on bridges, where a large workforce unskilled in composites is required to undertake repairs. To do this, basic wet-layup systems have been deployed globally offering low cost but low performance repairs. Codes by ISO [17] and ASME [18] for the application of composites to pipelines, pipework, tanks and vessels were put in place in the early 2000s to provide structure and risk management to the application of these repairs. The first iterations of these codes considered basic wet-lay-up processing as this allowed rapid deployment of composites across the industry. Later iterations of the ISO and ASME codes have increased the requirements on installer skills, quality controls and long-term testing of the composite systems. Also included were discussions on consolidation and elevated temperature control as established processing controls for improved composite performance [19].

For oil & gas industry applications on floating assets there have been recent developments of vacuum forming to improve the reliability and performance of composite repairs. DNV (2015) [20], [21] and ABS (2021) [22] have issued guidance notes for structural repair using these systems. Although piping and tank repairs are structural in many ways, the ISO and ASME codes are not generic structural codes for the use of structural composites. Existing codes such as Class rules, do allow for alternative materials if their performance is understood. However, the lack of definition as to how the alternative materials can be proven to be acceptable is a barrier to their adoption.

2.3 NAVAL

Naval applications of composites have taken a different path to the oil & gas industry. The ability to access and control more easily the specialised trade skills required for Structural Composites saw vacuum consolidated and temperature controlled composite repair applications in the late 1980s and early 1990s [1], [23] Applications of composite patches for structural repair, specifically for the prevention of crack growth in underlying metal, has been previously used on warships [6], [24]. The prediction and modelling of this type of repair is well understood with the US Navy Ship Structure Committee [6] stating that "little difference between FEA and experimental results, implying that the finite element modelling is effective, and the results are reliable." The basic composite processing controls learned from the Marine and Aerospace Industries were picked up early for naval applications, compared to the decades later introduction in the oil & gas Industry.

2.4 DEVELOPMENT TIMELINE

A timeline of the key developments and in-field applications for naval and oil & gas applications are highlighted below.

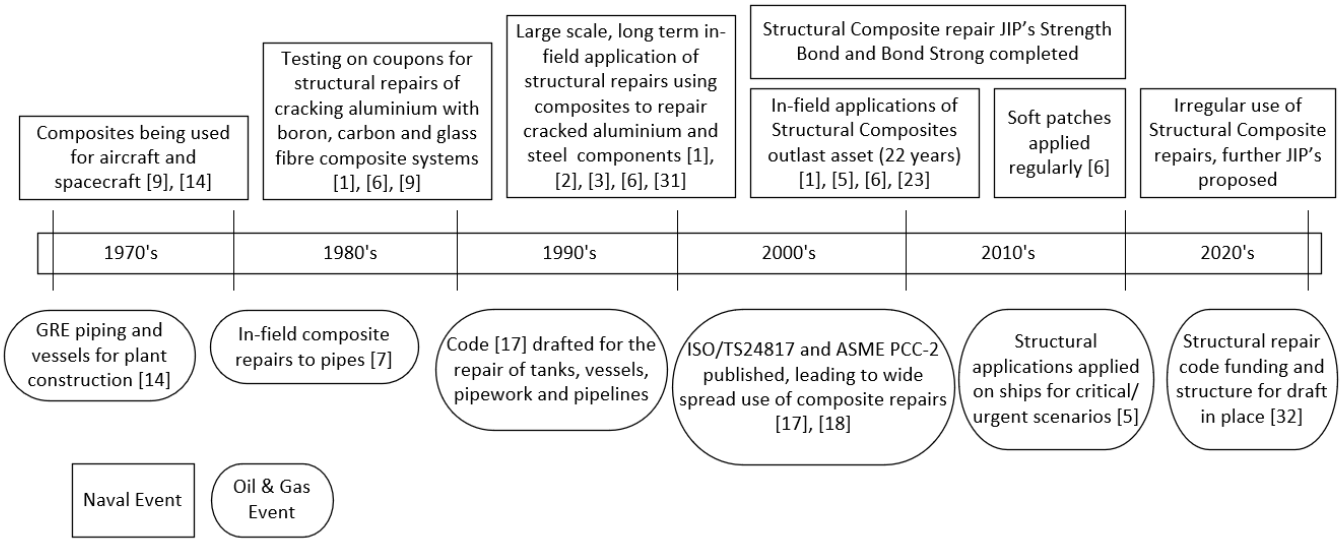

Figure 3. Structural composites development timeline

3 CURRENT INDUSTRY GAPS (NAVAL AND OIL & GAS)

3.1 STATE OF THE INDUSTRY

In general, understanding of the gaps in structural composite repairs across naval and oil & gas industries is muted due to all parties; operators, class societies, and vendors not sharing information about their composite repairs. The UK HSE review of composite repair on offshore assets [19] found that the records of composite repairs were poor, noting that although a detailed repair register is a requirement of ISO and ASME codes, these records are not well kept or maintained in the oil & gas industry.

Although there is a significant body of academic data on composite repairs spanning more than 50 years [1], [6], [14]. The information on structural composite repairs in the field is available but hard to find. This makes the education process of supply chains slow and costly. In turn this means that it is harder to provide evidence to demonstrate that currently novel and contentious applications for structural composite repairs do in fact show reduced risk during engineering, installation and over the life of the repair [25], [26].

From industry and academic data reviewed as part of this paper the technology supporting structural composites is available for industry use. The industry gaps appear to be in education, understanding, procurement and engineering approval processes (including code compliance and understanding of the approval system) [10, [14], [25].

3.2 BARRIERS TO ADOPTION

Despite a wealth of supporting research and isolated individual applications, there is not a widespread adoption of composites to repair naval structures [26]. The barriers can be grouped in various areas as illustrated in tables 1 - 4.

The tables compare two types of composite repair and a traditional "like for like" steel repair. The difference between the two types of composite repair is that an ISO 24817 compliant repair is mainly for pipework or for instances where a defect may result in a loss of containment (watertight integrity) but not affect the structural integrity of the asset. A "structural composite application" is one where the defect repaired using composites can be considered to take all loads (local and global) that the original structure is designed for.
The colouring of the tables gives an indication of the areas where the most significant barriers to adoption are experienced.

Table 1. Technical barriers to adoption

	ISO 24817 Compliant applications, O&G Industry	Structural Composite Applications, Naval or O&G	Traditional steel or similar, Naval or O&G
Capacity for structural integrity	> 30 years of in-field evidence and a structure for new product to be tested and engineered	Although not always accepted, a comprehensive body of academic and in-field evidence is available	Capacity is available and well understood.
Materials	Existing test standards and program to classify material performance	Available products are continuously evolving, and installation performance varies.	Globally available, easy to obtain and comparatively cheap with material properties well defined
Life span	Defined life to 20 years, with inspection, maintenance, and re-validation processes	Difficult to demonstrate in a repair context or get accepted despite known materials	Readily accepted as "permanent"

Table 2. Production and design barriers to adoption

	ISO 24817 Compliant applications, O&G Industry	Structural Composite Applications, Naval or O&G	Traditional steel or similar, Naval or O&G
Level of engineering skill required	Low - Engineering skill directed to following ISO 24817 [17] or ASME PCC-2 [18] direction.	High level of engineering skill needed and understanding of material properties, failure modes, rules and regulations.	Low level required, with limited or no calculation or sophisticated engineering required.
Design workforce	With the code direction operational teams can conduct their own reviews.	Limited in availability and generally not knowledgeable of both composites and structures.	Widely available in most ports and jurisdictions worldwide.
Production and installation workforce	There are clear installation experience and skill requirements in the codes.	Not widely available. Training is not generally available.	Widely available in most jurisdictions worldwide.
Industry knowledge understanding	Level of familiarity has contributed to unsophisticated approach where only low risk applications are utilised.	Lack of embedded corporate experience, knowledge or understanding. Lack of willingness to share or publicise applications.	Embedded corporate experience knowledge and understanding within many organisations. Success stories are widely shared as part of general publications.

Table 3. Regulatory barriers to adoption

	ISO 24817 Compliant applications, O&G Industry	Structural Composite Applications, Naval or O&G	Traditional steel or similar, Naval or O&G
Approvals (regulatory and other)	Operational and third-party approvals are well established.	The approval process is not clear and generally by "special consideration" even for situations that aren't novel or contentious.	Clear routes to approval with established and understood timelines. Special consideration only required for novel and contentious situations.
Guidelines	Established and well used, even if incorrectly.	Limited or non-existent Complicated	Widely available or codified (IACS 47) [27] Simple needing low level of technical ability to understand and implement"

Table 4. Project barriers to adoption

	ISO 24817 Compliant applications, O&G Industry	Structural Composite Applications, Naval or O&G	Traditional steel or similar, Naval or O&G
Impact on operations	Small and limited with the avoidance of hot work. Can be compatible with not decommissioning critical systems or spaces.	Small and limited with the avoidance of hot work. Can be compatible with not decommissioning critical systems or spaces.	Can be considerable particularly given the need for hot work and the impact on potentially "clean" spaces.
Schedule	Well understood and easy to define.	Difficult to predict. Lack of generalised embedded industry knowledge and understanding makes forecasting of time and resource to achieve approval difficult and unreliable	Well understood and easy to define.
Project risk	Low	High	Low
Appetite for use	High Often used in applications incorrectly because the appetite is so high.	Low Effort required to adopt and overcome barriers is high.	High Default position. Normally unquestioned.

3.3 BARRIERS DISCUSSION

A key learning from the oil & gas industry is to utilise composites regularly in areas where the barriers are low. By doing this the operations, engineering and approvals teams increase their understanding and capability to manage the risks associated with composite repairs. Practically this means, repairs to pipework following the established ISO 24817 repair code and existing Classification Societies' product approvals before approaching scopes for repair of vessel structures [22]. A visual representation of this is seen in tables 1 - 4, where the application of composites for pipework, even critical pipework, can be relatively barrier free.

The biggest barrier to implementing composite repairs in an operational context tends to be the approvals and justification of the design approach used for the composite repair [25]. The challenge is multifaceted and difficult to address in the normal time constrained and risk averse context of a project involving a repair.

The following is an expanded list of the regulatory or approvals barriers:

- Not all Class Societies have developed guidance [10].
- Those guidelines that do exist may not have been widely adopted within industry with well publicised and numerous examples of implementation.
- Within the approval organisation, acceptance may need to be done by a specialist section that may not be clearly identified or local to the place where the repair is being completed.
- Many guidelines place restrictions on the use of composite repairs. The justification for these is not necessarily apparent or in line with published experience or the capabilities of composites (e.g. more than 6mm of remaining steel required in the context of corrosion, or composites may not be used in areas where fatigue is suspected, or they may require demonstration that the repair is "non-structural" for approval).
- There are limited research funds and actors to develop structural design guidelines.

3.4 CONSEQUENCES OF BARRIERS

The consequence of the barriers to adoption is a self-perpetuating cycle. The lack of industry knowledge and understanding without common embedded experience of where composite repairs can be successful perpetuates a perception of high-risk unproven products and techniques. This means that composite repairs are not adopted and hence the cycle continues.

4 PROCEDURE TO HELP ENSURE A SUCCESSFUL REPAIR

4.1 CHOICE OF CODE

The choice of code will depend on the nature of the repair. There are many established codes for the repair of pressure vessels that are frequently used to justify the design of structural repairs that are not considered structurally effective for global loads. For long life (>5 years) repairs of structure that have to be effective against such loads, Class rules need to be considered. Given that not all Class Societies have current guidelines, it may be that guidelines or rules from a Society that is not Classing the asset in question may be acceptable.

Given the previously discussed barriers to adoption, notably the difficulty in being able to define a timeline for a repair to be accepted, early engagement of the acceptance authorities is key.

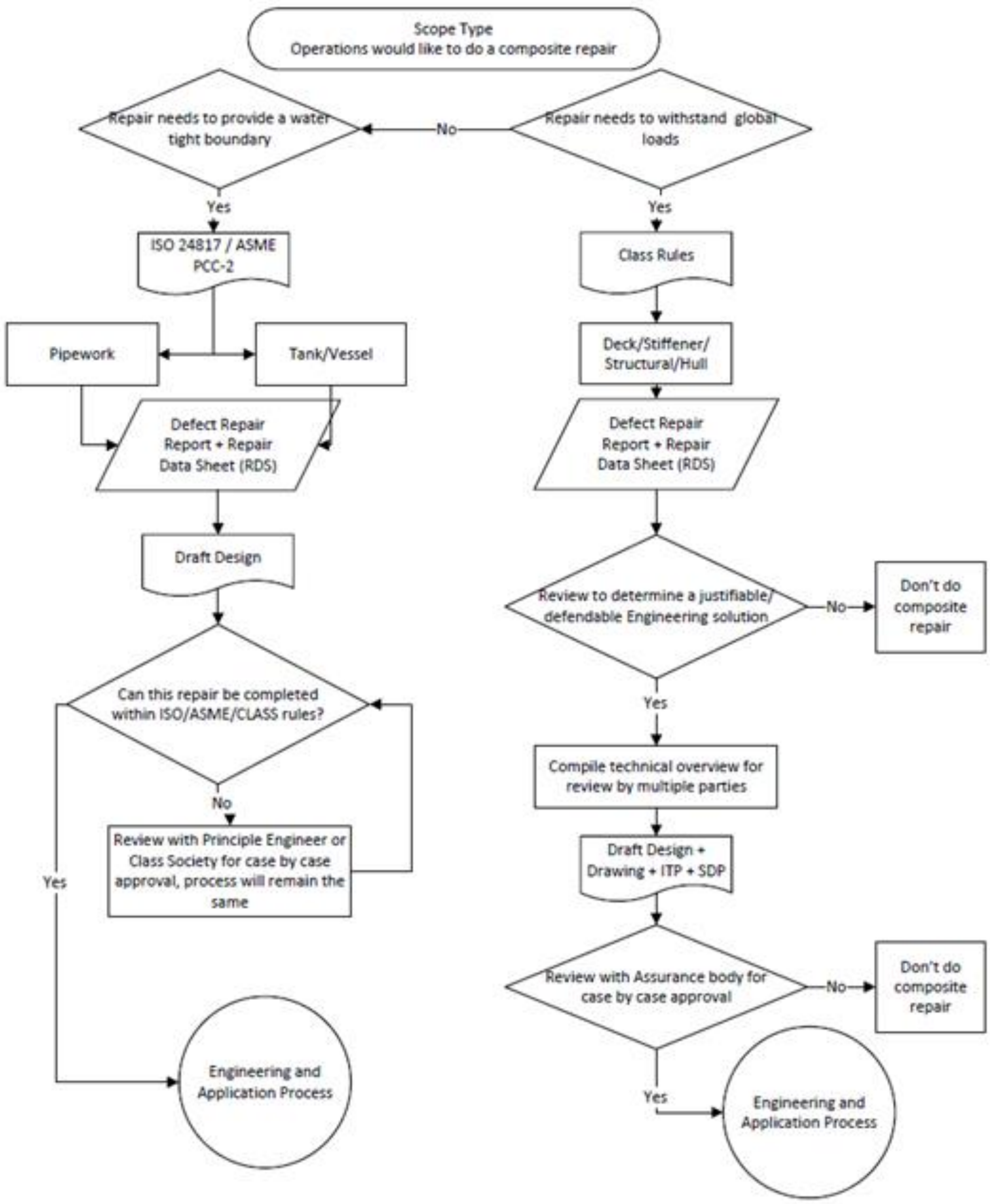

Figure 4. Typical composite repair selection and execution process.

4.2 USE OF FINITE ELEMENT ANALYSIS (FEA)

For simpler repairs that are not subject to global loads, Finite Element Analysis (FEA) is not normally required, with simple code checks defined in the ISO/ASME rules. However, care must be taken with the definitions of the inputs as some interpretation is required as codes developed for pressure vessels do not necessarily describe vessel structures clearly and do not address failure mechanism review [10].

For repairs that have to be demonstrated to withstand global loads, the use of FEA is recommended [28], [29], [30]. Ideally a pre-existing FEA model of the asset exists. Preferably this will have been previously accepted by the Class Society for the vessel in question. A local model of the composite repair should be built that can demonstrate that stresses and strains are below acceptable limits for the required load cases and combinations. Although for steel, there are established guidelines for developing and approving FEA models [28], the local model of a composite repair will need close liaison between the Class Society and the composite designer to ensure it is acceptable.

5 CASE STUDIES

It should be noted that both navy case studies presented here involve ships that were not Classed and where the Design Authority was "in house" with the Naval Authority supportive of the proposed composite repairs.

5.1 TYPE 42 COMPOSITE REPAIRS

On the now decommissioned UK Royal Navy Type 42 destroyers, from 1997 to 2003, composite patches were applied in 35 locations following a standard repair that was developed for where the two fitted lift trunks intersected with 1 and 01 deck (Officers and Senior Rates Food Lifts). Fatigue cracking would often be observed in this location. To produce an effective steel repair, a major redesign of the food lift trunk structure would be required, whilst like for like repair involved intrusive hot work on multiple compartments.

As an alternative, a reinforcement by Carbon Reinforced Plastic was developed. This was possible given the then current knowledge of composite repairs within the UKMOD and the fact the structure was not considered critical and caveated that any cracks had not propagated into primary structure [2], [31].

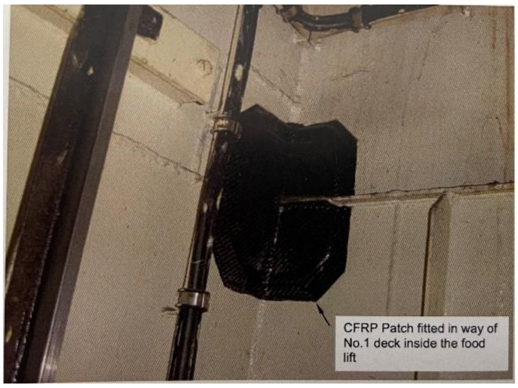

Figure 5. Carbon fibre repair patch fitted to a UK T42 Destroyer [31]

The learnings from this case study are:

- Although traditional steel repair or redesign was possible, a composite repair was a more optimised solution.
- A composite repair was feasible because of the knowledge of the Design Authority and the Naval Authority meant that it was not onerous from an approvals point of view.
- Application of composites to fatigue cracking is a successful way to prevent crack growth.

5.2 HMAS SYDNEY

HMAS Sydney was the third Adelaide Class guided missile frigate built at Todd Pacific Shipyards (launched 1980). The first four ships of the class experienced some significant fatigue cracking in the aluminium superstructure. For the follow-on ships, lessons learnt meant that improved production and design details addressed the cracking issues from the earlier vessels. For HMAS Sydney, in 1993, two carbon fibre "strip" reinforcements were bonded to 02 deck on the port and starboard sides. Subsequent work and investigation showed that the strips were effective against fatigue. Only minor repair and maintenance ended up being required between 1993 and 2000. The strips were still in place when the vessel was paid off in 2015. Both, FEA modelling and physical strain measurements showed that the critical stress concentrations had been reduced [1], [6]. This was confirmed by the absence of any deck cracking occurring within the boundaries of the composite patches.

This is an example of "permanent" repair using composites that lasted for the life of the asset. Although like for like costings are not readily available, the remediation for the design and build issues experienced for the initial vessels of this class came at a considerable cost. The cost of the carbon strips was much less and significantly less intrusive.

Figure 6. HMAS Sydney [24].

The learnings from this case study are:

- At the time, the academic teams were the only composite trade experienced personnel available to complete the installation. Finding verified competent structural composite teams is critical to the success of composite repairs [1].
- To achieve the performance structural composites can provide requires controlled consolidation (vacuum bagging) and temperature control [1].
- Structural health monitoring utilising strain gauges and ultrasonic inspection are a valid long term and reliable for inspections [1], [20], [21], [25], [32].
- Maintenance and repair of structural composite repairs can occur successfully over the life of a repair such that the composite outlasts the underlying substrate [1], [5], [6], [25], [32].

5.3 CALM BUOY AUSTRALIAN OIL AND GAS CASE STUDY

A Catenary Anchor Leg Mooring (CALM) buoy in Australian waters had developed holes through corrosion. The repair needed to have the following characteristics:

- Class approval
- Small footprint
- Be applied under the water line and on a live leak
- No lifting of equipment or materials
- No hot work.

The treatment of the CALM buoy hull as a tank for the purposes for ISO 24817 provided a route to approval, with justification that the structure of the hull was fit for service once the repair was complete.

The installation of the composite repair under live conditions and under the water line required a novel installation method, in part a VaRTM system [8], [9]. This method was not part of the initial ISO 24817 specification and structural composite code compliant performance. However, with close collaboration between the operator, Class and vendor the material performance testing guidance provided by ISO 24817 was used to create a short-term (<4weeks) test program to demonstrate the novel installation would produce adhesion performance equal to or greater than that required by ISO 24817 and Class approval requirements. Multiple patch repairs were installed under live leak situations and the composite repairs remained in place until the asset was decommissioned. This repair was completed before 2015 but the details of the repair are lost due to the industry wide poor information sharing problem.

The learnings from this case study are:

- Although the use of composite repair for a hull is not compliant with a pipework or pressure containing code, the usefulness of this repair code and the defined test programs to confirm adhesive and structural composite performance provides the basics from which to design naval or other structural repairs.
- The importance of close working relationships between composite vendors, the execution team (with composite trade qualifications), Class engineers & surveyors, and the operator's engineering team are crucial.
- A rapid verification test program is an effective way to build confidence and knowledge in the performance of structural composites.

6 HOW COMPOSITE REPAIRS CAN CONTRIBUTE TO AUSTRALIAN CONTINUOUS NAVAL SUSTAINMENT

Within Australia a government policy for continuous naval sustainment has been clearly articulated and published [34]. It is suggested that facilitating structural composite repairs can help deliver several aspects of this policy. This is demonstrated in Table 5 where compliance is mapped to some of the requirements. Providing the naval sustainment environment with the direction to deliver the capability to complete composite repairs is a suggested route to delivering on the stated naval sustainment policy.

When comparing to the civilian context, it is believed that a "top down" approach to addressing the barriers to adoption detailed in Tables 1 – 4 is possible. This is because within the naval sustainment environment, the reduced total number of assets, all regulated by a naval authority (as compared to a civilian regulator), coupled with a singular maritime doctrine [35] means that a clearer sense of purpose can be fostered when compared to the civilian fleet. This means that all the key stakeholders that can influence the barriers to adoption can deliver an environment where these are reduced or eliminated. i.e. the naval regulators, capability managers, suppliers and end users can all respond to a direction to ensure that composite repairs are an available capability.

Table 5. Composite repairs and compliance with Australian continuous naval sustainment.

Requirement	Source	Route to closure	Actions required
"Certification that enables seaworthy operation"	SDIP 2 page 3 [36]	Accept existing academic and other research as well as documented field trials thus building on existing standards and codes, develop naval standards or guidelines that provide a route to certification.	The requirement to be able to conduct composite repairs on naval ships be declared as a key capability
"Enhance performance and reduce costs"	SDIP 2 page 3 [36]	Life of structure can be extended. Complete work scopes faster, while out of dry-dock, with a smaller labour footprint and reduced impact on the asset systems and personnel.	Ensure that the ability to complete composite repairs is no more onerous, from an approval's perspective, than a steel repair.
"Support industry-led collaborations between industry, researchers and end-users"	Defence Industry Development Strategy Fig 3 page 18 [34]	Through sharing of knowledge and experience of actual repairs	Sponsor a JIP to facilitate and publish information sharing on composite repairs in naval and commercial assets.
"Achieve availability targets while maximising the speed of upgrade"	Defence Industry Development Strategy Fig 3 page 18 [34]	Provide projects supporting the sustainment of naval assets the ability to choose composite repairs if it is the best technical solution for their asset.	ANP 4412-4315-4 [37] and other documents to be updated to include composite repairs.

7 RECOMMENDATIONS

7.1 INDUSTRY WIDE

The following four recommendations are believed to be key to addressing the barriers to adoption detailed in Tables 1 - 4. It is thought implementing these will break the current self-perpetuating cycle preventing the adoption of composite repairs. Once the cycle has been disrupted, other barriers such as perceived project risk and lack of appetite for use will fall away.

- Create a database of current composite repairs that is available to industry and contains details such as: date of repair, vessel IMO number, Class Society, temporary or permanent repair, fire rating (A0, A60 etc.), material used, structure being repaired (watertight bulkhead, main deck, parent plate, transverse frame, longitudinal stiffener etc.). This would be ideally suited to a Joint Industry Project (JIP).
- Within guidelines remove any unnecessary restrictions on the use of composites or provide a clear route to provide justification on a case-by-case basis.
- Form a JIP with the objective of developing and industry wide standard for implementation of repairs of structural steel using structural composites in a marine field. This would be an equivalent to IACS 47 [27].
- When communicating strategic requirements to the education sector as to what the marine industry requires, ensure that the need for education and practical training for composites in a marine context is included.

7.2 IN AN AUSTRALIAN NAVAL CONTEXT

Three clear recommendations are made in order to facilitate the ability for composite repairs to be made available to RAN sustainment organisations:

- At a senior level within defence, it is recommended that the ability to conduct composite repairs of naval assets be explicitly declared as a key capability. In an Australian context the justification for such a statement would be to provide a route to deliver on the Australian Defence Industry Development Strategy. In particular, 'SDIP 2 Continuous naval shipbuilding and sustainment' [36].
- Ensure that any structure repaired using composites is considered as having the same baseline as a traditional like for like steel repair (no Baseline Configuration change).

- Clarify and explicitly define the route to certification. In particular ensure that approval of standard composite repairs need not require a higher level of approval than a steel equivalent.

8 CONCLUSIONS

Given the parallels between oil & gas and naval assets (and organisations), there are similar advantages to adopting composite repairs to ensure ongoing commercial viability or capability and availability of the assets. Noting this, it can be seen that the barriers to the wider adoption of composite repairs (in both industries) are not necessarily related to their technical properties or general performance. By adopting some of the recommendations in this paper, more options will become available to deliver an optimum repair, improving capability and operability. Furthermore, these will also support the delivery of a number of the requirements of the Strategic Defence Industry Priorities.

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