Feasibility study to compare steel and adhesive/composite-based emergency repair methods for damaged hulls

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Feasibility study to compare steel and adhesive/composite-based emergency repair methods for damaged hulls

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A feasibility study comparing steel and adhesive-composite-based emergency repair methods for damaged hulls has been undertaken. Potential generic non-metallic repair methods are described, ranging from simple adhesive resin-based sealing repairs to more sophisticated adhesive-assisted structural composite repairs. Two appropriate non-metallic repair methods, one a sealant and the other a sealant/structural repair, are described and costed for the specific case of damage sustained by the BP Schiehallion FPSO, as a result of collision damage with the shuttle tanker, Nordic Savonita, in 1998. It is concluded that simple sealant repairs are feasible in emergency situations and that they may be completed safely in a short time and at low cost. A structural element may also be built into such repairs, where necessary, at a higher cost reflecting the sophisticated materials required and the longer time necessary for completion.

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EXECUTIVE SUMMARY

The Health and Safety Executive has funded a feasibility study to compare adhesive/composite-based emergency repairs and those involving the more conventional, welded steel-type approach. To facilitate this comparison, BP provided information concerning collision damage sustained by their Schiehallion FPSO. This damage was temporarily repaired by boxing in the damaged area from within, using normal steel welding processes. This feasibility study has concentrated on investigating the methods and cost of making similar repairs using the non-metallic materials approach.

During the work, an interim report was provided and this final report represents the completion of the study. The interim report, attached as an Appendix, lists the potential advantages of adhesive/composite repairs and identifies four generic adhesively-assisted, composite-based sealant and semi-structural repairs.

This final report considers two of the four generic repair methods which were felt, on due consideration, to be more appropriate to the damage sustained by the FPSO. It stresses the need for properly trained operatives and the importance of adequate surface preparation prior to making any repair. The first proposal is for a straightforward resin-based sealant repair, designed to prevent ingress of un-pressurised water through the holed area and weld crack. It is estimated that one operator could carry out such a repair in approximately 1¼ hours, at a cost of about £70. If a structural-type repair was considered to be appropriate for the weld crack element, then this aspect could add from about £1700 to £2600, depending upon whether hand lay-up or prepreg methods were to be used. This more sophisticated procedure would also take longer, requiring about 24 and 10½ hours respectively.

It is concluded that the sealing of the holed area and the weld crack could be achieved safely, quickly and cheaply with trained but non-specialist operatives. It is also concluded that structural repairs to the weld crack could be achieved at a rather higher cost and in a time dependent upon whether hand lay-up (quicker) or prepreg materials (slower) were employed.

An exact comparison of costs related to the welded repair carried out has not been made because it proved to be impossible to separate out from the actual overall costs, those strictly relevant to the adhesive/composite repairs considered in the study. Equally, there was insufficient data to enable proper consideration of the relative durability’s of the two repairs to be made. Information relevant to steel repairs may well already exist but that required to predict the useful lifetime of the non-metallic repair would require experimental work to be done.

Finally, recommendations for further work (including the durability issue) designed to make such proposed repairs more efficient, and to have wider applicability, are presented.
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1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 On the 25th September 1998, the shuttle tanker Nordic Savonita collided with the stern of the Schiehallion FPSO, operated by BP Amoco. The damage was localised to the aft starboard side of the FPSO, at upper deck level. The stern, side shell and deck plating were deformed over an area 2m wide by 1m high, extending around 600mm forward into a water ballast tank. The weld between the stern and deck plate had burst over a length of around 600mm, with a hand-sized hole in the corner of the tank. One of the internal stiffeners sustained minor damage and the handrails around the impact area and a floodlight were also damaged in the photographs below.

![Damaged handrails](image1.png)

![Damaged ballast tank](image2.png)

1.1.2 The overall structural integrity of the FPSO was not affected but the damaged ballast tank was no longer watertight. A decision was taken to reinstate the structure to its original condition by replacing the distorted sections of plate and also to reinstate the handrails and floodlight. It was proposed that permanent repairs would be undertaken by welding replacement steelwork in the damaged areas. However, immediately following the incident, a temporary repair was undertaken to reinstate the watertight integrity of the ballast tank by boxing in the damaged area from inside the tank as shown in the photograph below.
1.1.3 This was the background against which the present feasibility study was undertaken to design a practical adhesive/composite-based approach to repair the damage and to compare such an approach with the temporary steel-based repair that was actually carried out on the vessel. The comparison was to consider factors such as logistics, timescales involved, COSHH implications, expected repair lifetimes and costs. As a result of the study, recommendations for a way forward would also be made. Deliverables were to include an interim report Appendix A, in addition to this final report.

1.2 APPROACH TO THE RESIN-BASED REPAIR

1.2.1 The approach to the design of an adhesive/composite-based repair was significantly influenced by the specific nature of the damage sustained. On the one hand there was a ‘hand-sized’ hole which, even though the affected ballast tank was no longer water tight, was not regarded as likely to lead to any loss of structural integrity per se. However, although there was no threat to the structural integrity of the FPSO, it was felt that the split weld between stern and deck plate could conceivably propagate to a degree where the localised stiffness of the structure would be compromised in an undesirable way.

1.2.2 One of the advantages of resin-based technologies, including adhesion and the use of composites, is their versatility that allows them to be subtly adapted to meet specific needs. Therefore, it was decided to design a non-structural sealing repair to reinstate the watertight nature of the ballast tank and a reinforcing, structural repair element for the split weld. Both have been separately costed.

1.2.3 An important feature common to both types of repair is that of surface preparation, including priming where necessary, and to that extent the same materials and procedures may be used for each. Naturally, the resins and matrix materials involved are specific to the application, either sealing or structural.
1.2.4 Certain assumptions were made with respect to the environment and circumstances surrounding the particular repair scenario, although it should not be assumed that such repairs could not be made under different conditions. For example, in other circumstances the time taken may be longer – or shorter, alternative materials may have been selected and a greater or lesser thickness of applied composite may have been recommended. The assumptions made were as follows:

a) Steelwork was painted and in reasonably good condition, with no heavy corrosion or pitting.

b) Water was seeping through the weld crack, as a result of rain or green water, and was not under pressure.

c) The hole to be sealed was surrounded by distorted steel protrusions.

d) The steel was assumed to be 14mm thick.

e) The weld crack was approximately 2mm wide.

f) Although the overall structural integrity of the FPSO was not affected, it has been assumed that some structural reinstatement should be attempted in way of the weld crack.

g) In costing the material required, the cost of the composite material used to repair the damage has been quoted and not the total cost required for purchasing the manufacturer’s minimum quantities of fabric and resin. It has been assumed that a central store will hold the material from which quantities can be drawn, depending upon each damage event.
2.0 PROPOSED REPAIR PROCESS

2.1 SURFACE PREPARATION PRIOR TO SEALANT APPLICATION

The process is to commence with the removal of any oil or grease with a solvent-soaked, lint-free cloth (10 minutes to achieve). A particular citrus-based detergent mixed with acceptably small concentrations of organic solvent has been found to be satisfactory when used with good quality, clean cotton waste. The next stage of the process involves the removal of loosely adhering paint and corrosion from the steel substrate by means of a pneumatic or hydraulic-powered tool, fitted with an abrasive brush employing nylon bristles embedded with silicon carbide particles. Since the damage was caused by an external impact, the perimeter of the hole will comprise either freshly sheared steel and/or parts of that surface normally forming the external surface of the hull. The edges of freshly sheared steel will require minimal surface preparation, if any. The remainder will probably be heavily coated with paint, of which some will be tenaciously retained on the surface, although patches may be missing entirely. Loosely adhering paint – both external and internal – should be removed to about 50mm beyond the perimeter of the damaged area if possible. Because of the emergency (nonpermanent) nature of the repair, it will not be necessary to remove obviously sound and apparently strongly retained paint layers. One operator should complete this element of the work in 20 minutes and the whole task in 30 minutes.

2.2 APPLICATION OF SEALANT

2.2.1 Sufficient putty (designed to function in the wet and bond to wet steel) should be mixed to fill the hand-sized void. Parts A and B of the two-component putty mix are supplied at either end of a single transparent plastic bag, separated centrally by a clip for storage purposes. Mixing is achieved by removal of the clip and mixing within the bag by hand, using a kneading action. The two components are differently coloured and an indication of effective mixing is inferred when the mixed resin system has the appearance of a uniform, streak-free colour. If the contents of a second or third bag are required, these too should be similarly mixed. To mix a 250g batch will take about 5 minutes.

2.2.2 The corner of a mixed bag of putty is then cut off and mixed material is squeezed out for use as required. The working life, or pot-life, of the mixed resin will be about 45 minutes. Initially, putty should be applied to the prepared surface surrounding the damaged area, ideally with a gloved hand and ensuring the presence of a continuous layer of putty over the prepared steel. 10 minutes should be allocated for this purpose.

2.2.3 To assist in the retention of the sealant within the void, it is suggested that the bulk of the material should be supported by use of expanded metal bridgework. For these purposes it is suggested that fine mesh chicken wire should be crumpled and pressed into the void in such a way that it is held mechanically within the primed and damaged area. Having shaped the metal bridgework, it should be removed and putty should be pushed into place so as to approximately fill – or slightly overfill - the wire ‘cage’. This assembly should then be pressed into position so as to fill the void. Any minor imperfections may be made good using gloved fingers and more putty may be used and faired in if required. This aspect will take some 15 minutes to complete. The sealing process will take 30 minutes in
total and the whole operation, including surface preparation, should be completed in one hour.

2.2.4 The putty will cure over a period of time, dependent upon both bulk and temperature but it will seal against un-pressurised water immediately, provided that the flow is not so great that too much of the material is mechanically eroded away.

2.3 SURFACE PREPARATION PRIOR TO STRUCTURAL REPAIR

2.3.1 Surface preparation, prior to the use of a composite to achieve a structural repair is to involve three elements, namely:

(a) sealing of the weld crack to prevent water ingress
(b) removal of oil, paint and rust to avoid the presence of a weak boundary layer
(c) priming of the cleaned steel to ensure a strong bond between substrate and composite.

2.3.2 The first stage of the surface preparation involves the mixing and application of sealant putty into the weld crack using a spatula or gloved finger (section 2.2 for details). After mixing (5 minutes required for 250g batch), the sealing of the 600mm crack will be completed in 10 minutes.

2.3.3 Stage two involves preparing the steel surface in the same way as for the sealant repair described above except that, for this structural component of the repair, greater efforts should be made to remove all paint and corrosion. The area to be prepared in this way, prior to repair of the damaged weld joint, is 600mm (weld crack length) plus 200mm at each end making 1000mm in all. The width of substrate steel to be prepared is 250mm on each side of the weld split, or 500mm overall. This process should take one hour.

2.3.4 The final stage involves the application of a paste adhesive primer, together with one layer of reinforcing fabric in the case of the prepreg-based repair (section 2.4 below). This process should be carried out immediately after stage two. Although considered a part of the surface pre-treatment, the time involved with this work element is included in the scheduling of the composite repair process.

2.4 APPLICATION OF COMPOSITE

2.4.1 Two potential composite repair methods (hand lay-up repair and prepreg vacuum bag repair) have been evaluated for the repair of the damaged weld joint. The design of the repair patch has, in both cases, been based on stiffness match criteria, i.e. the stiffness of the patch matches the stiffness of the steel. In view of the judgement that the primary design criterion should be stiffness and not strength, it has been decided to recommend the use of a carbon-based composite laminate as the most practical solution, despite its higher cost.

2.4.2 Carbon fibres are available which, in a unidirectional composite, will give a tensile modulus of about 250GPa, which compares very favourably with steel at about 210GPa. However, the realisation of modulus is dependent upon the composite manufacturing technique. The two candidate manufacturing techniques that have been considered are,
The mixing of the fibre and the resin on site and its hand application over the damage (often referred to as hand lay-up or HLU).

2. The hand application of pre-impregnated composite (often referred to as prepreg material) over the damaged area.

2.4.3 It should be noted that, in terms of HLU, unidirectional composites produced from Toray M40J fibre and epoxy resin (5052) with the following properties have been used to determine the patch geometry:
- Longitudinal tensile modulus (GPa) 132 – 150*
- Longitudinal tensile strength (MPa) 1544 – 1764*

2.4.4 Alternatively, for a unidirectional low temperature-cure prepreg produced from the Toray M40J fibre with 55%Vf, the tensile modulus and tensile strength are:
- Longitudinal tensile modulus (GPa) 207 – 215*
- Longitudinal tensile strength (MPa) 2425 – 2514*
(Data normalised for 55% Vf from data provided by DERA Advanced Composites Group)

2.4.5 Since both the HLU and prepreg fabrics are unidirectional, it will be appreciated that the length of the fabric will be that required to laminate normally to the crack. Allowing for the fact that the repair patch over the 600mm long crack will be tapered, the maximum (‘footprint’) dimensions will be in the region of 250mm by 1000mm.

2.4.6 Considering first the HLU repair process, the operator has to (i) cut the fabric to size, (ii) mix the required quantity of resin and (iii) apply the composite to the damaged structure, the surface of which will have already been prepared. For this particular repair, the overhead location determines that there will be a maximum number of uncured layers that can be applied before the weight is so great that the patch falls off.

2.4.7 For HLU, the industry rule-of-thumb is a maximum of 4mm deposition of composite before stopping and allowing the composite to cure. Once 4mm of composite has been applied to the structure the resin is to be allowed to cure for a period of, typically, 220 minutes assuming an ambient temperature of 18°C. At the end of this cure period, a further 4mm of composite can be applied, and so on until five such applications have been made. Once the composite application has been completed, the system is allowed to cure fully throughout its thickness.

2.4.8 This time involved may be broken down as follows:

1. To cut-up 90 plies would take two operators 3 hours.
2. Mixing of the first resin batch would take 30 minutes (subsequent batches to be mixed in ‘dead time’ whilst intermediate depositions are curing).
3. Installation of repair cloths (to give a maximum thickness of ~20mm) would take 20 hours and 40 minutes.
4. Cure at 18°C for 8 hours to achieve optimised mechanical performance (i.e. the repair would be fit for sea-going operations).

From start to finish, a total of 24 hours and 10 minutes is required for the application of the composite repair, since step 4 (the eight hour cure period) requires little or no operator attention.

2.4.9 Let us consider now the prepreg repair process where the operator has to (i) defrost the prepreg, (ii) cut the fabric to size, (iii) apply a paste adhesive to the damaged structure and allow it to cure (iv) apply the composite to the damaged structure and (v) apply the consumable pack containing vacuum bag and heater mats.

2.4.10 Prepreg material is stable only at lower temperatures and hence must be stored refrigerated and then defrosted prior to use. Since the prepreg material has a tacky surface, it is possible to ‘stack’ a greater number of layers together before temperature consolidation is required. A total thickness of 13mm is required for this type of repair, after which the repair is bagged up. Once bagged up, a vacuum is drawn and the heating cure cycle is started. This is often arranged conveniently to take place overnight, typically 16 hours at 40°C, or in a shorter time if the temperature can be increased, e.g. 3 hours at 70°C.

2.4.11 The time required to complete the prepreg repair is detailed below:

1. Defrost the prepreg (typically 2 hours).
2. Cutting the fabric to size (2 hours).
3. Application of the paste adhesive (and one prepreg layer) to the damaged structure (typically 1 hour and 30 minutes).
4. Build-up of the tapered composite patch on the damaged structure (4 hours).
5. Application of the consumable pack containing vacuum bag and heater mats (1 hour).
6. Heating cycle (16 hours at 40°C).

The total time that is required to manufacture the prepreg patch is therefore 10 hours and 30 minutes, with a further 16 hours being required to cure the composite. Again, this latter period requires little or no oversight.

2.5 THE COSTS OF THE RESIN-BASED REPAIR PROCESSES

2.5.1 Sealant repair

1. The cost of materials for the sealant repair will be low at about £30 for putty (retailing at £30 per kg), say £1 for a handful of compressed chicken wire and perhaps another £4 for solvent and rag. A total cost of £35 overall.

2. The estimated time for completion of the sealant repair by one operator is one hour at an estimated man hour cost of £26.
3. The total cost of carrying out the sealant repair to the hand-sized hole in the upper starboard corner of No 9 water ballast tank is therefore estimated at £61.

### 2.5.2 Composite repair using the HLU process

It has been calculated that for each patch manufactured by the HLU process a total of 14.33m of unidirectional cloth will be required. The total cost of the fabric is £346.65 (i.e. £315.12 plus 10% wastage). The total weight of resin will be 0.8kg and its cost (for Epoxy 5052) is £10.60 per kg for the resin and £13.65 per kg of hardener, therefore a cost of £21.34 (i.e. £19.40 plus 10% wastage). The cost of putty will be say £7.50 and surface cleaning may perhaps account for an additional £10 for solvent and rag. The total cost for materials will therefore be £385.49.

### 2.5.3 Composite repair using the prepreg process

The total amount of unidirectional prepreg material required for a 600mm crack is 70.2m (assuming the prepreg is supplied in 300mm widths). Since the prepreg costs £26.50 per m², the cost will be £2040.50, i.e. (£1855 plus 10% wastage). The costs involved for materials used in surface preparation will be the same as for the HLU process, i.e. £17.50.

### 2.5.4 Costs Summary of the two approaches

The cost of the repair is size-dependent whichever process is used. However, whilst the cost of the prepreg repair is dominated by the cost of the materials used, the cost of the HLU is dominated by labour costs. Larger repairs are nevertheless increasingly more expensive on a pro rata basis if the prepreg approach is used, because of the relatively high costs of the basic material. At the time of writing the total combined cost of both the sealant repair for the holed area and the composite repair for the split weld is estimated to be about £1750 if the HLU process is employed, or £2665 if prepreg is used.
Table 1: Total costs of materials and manpower for the 0.6-metre repair

<table>
<thead>
<tr>
<th>Materials costs per 600mm repair</th>
<th>Hand lay-up repair</th>
<th>Prepreg repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>M40J unidirectional fibre (14.3m)</td>
<td>£346.65</td>
<td>N/A</td>
</tr>
<tr>
<td>Epoxy 5052 resin</td>
<td>£21.34</td>
<td>N/A</td>
</tr>
<tr>
<td>M40J unidirectional prepreg</td>
<td>N/A</td>
<td>£2040.50</td>
</tr>
<tr>
<td>Surface preparation materials</td>
<td>£17.50</td>
<td>£17.50</td>
</tr>
<tr>
<td>Consumable materials</td>
<td>£20</td>
<td>£100</td>
</tr>
<tr>
<td><strong>Manpower costs (calculated on a charge-out rate of £26 per hour)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface preparation</td>
<td>£32.50</td>
<td>£32.50</td>
</tr>
<tr>
<td>Prepare fabric (2 people)</td>
<td>N/A</td>
<td>£52</td>
</tr>
<tr>
<td>Cut fabric</td>
<td>£156</td>
<td>£52</td>
</tr>
<tr>
<td>Mix resin</td>
<td>£13</td>
<td>N/A</td>
</tr>
<tr>
<td>Application of paste adhesive primer</td>
<td>N/A</td>
<td>£39</td>
</tr>
<tr>
<td>Application of composite (2 people)</td>
<td>£1074.32</td>
<td>£208</td>
</tr>
<tr>
<td>Application and removal of consumable pack (2 people)</td>
<td>N/A</td>
<td>£52</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td>£1681.31</td>
<td>£2593.50</td>
</tr>
</tbody>
</table>
3.0 CONCLUSIONS

3.1 The cost of the sealant repair to the holed area is low and may be accomplished in a short time, using very basic equipment. If one assumed that the weld crack could be satisfactorily repaired by sealing only, i.e. there were no significant structural implications, repairs to both split weld and hole could be made within 1¼ hours at a cost of, say, £70.

3.2 Assuming that the structural repair is appropriate for the burst weld between stern and deckplate, there is a choice to be made between the use of a hand lay-up process or the use of a prepreg-based method. The former will take longer (approximately 24 hours compared to ~10½ hours for the latter) to achieve but is cheaper and can cure at a lower temperature. The latter has the advantage of being completed in a significantly shorter time. Work would be necessary to clarify the situation and to make the choice easier (Section 4.4 under ‘Recommendations’).

3.3 This exercise has focused on the use of resin-based technology as a potential alternative to the use of conventional welding techniques for the reinstatement of the watertight nature of the starboard ballast tank No 9. However, it is difficult to identify costs relating solely to this aspect from the total costs incurred because they also included those relating to the replacement of a floodlight, hand railings and reinstatement of coatings, etc.

3.4 Although the conventional welded repair carried out immediately after the impact incident with the Nordic Savonita was described as a ‘temporary repair’ there may well be an interest in the relative durabilities of the two repair methods. However, this cannot be quantified without further consultation (with respect to the welded repair) and some experimental work (Section 4.5 under ‘Recommendations’).
4.0 RECOMMENDATIONS

4.1 It would appear that resin-based repairs can be cost effective when compared with more conventional weld-based repairs for a number of emergency/temporary repairs similar to those required in the case of the Schiehallion FPSO. There are also circumstances in which the use of welding techniques may be quite unacceptable (e.g. in the presence of a fire risk) and the use of resins may be the only option. Appendix A lists the advantages – and disadvantages - of using resin-based repairs at paragraph A.1.2 and, whilst it is quite apparent that they will never completely replace the use of weld repairs, it is equally clear that there is most certainly a place for the use of resins and composites. However, there are issues that require further clarification in order that their capabilities may be more fully understood and before their full potential may be realised. In order that these issues may be resolved, it is suggested that consideration should be given to funding work as follows.

4.2 **Point at issue:** ready and rapid achievement of higher temperatures to accelerate cure of resins and development of full mechanical properties.

4.2.1 Work to resolve:

4.2.1.1 Investigate the use of hollow, stiff ceramic microspheres as a resin filler (i.e. in the paste adhesive specified for use in prepreg repairs, or in the first layer of laminating resin used in HLU repairs) to create a thermal insulating layer between laminate and the ‘heat sink’ character of the hull.

4.2.1.2 Investigate the inclusion of ‘drapable’ heater elements within the applied laminate.

4.3 **Point at issue:** problems arising as a result of relative movement during resin cure between one side of a crack or split and the other.

4.3.1 Work to resolve: design and adhesively bond blocks to either side of crack and mechanically join so as to provide the required structural strength after the adhesive used to bond the blocks has cured.

4.4 **Point at issue:** optimisation of repair techniques, i.e. to maximise quality of repair whilst minimising time, effort and cost.

4.4.1 Work to resolve: examine novel geometries for design of adhesive/composite emergency repairs and incorporate strain gauges and Bragg gratings in demonstrator(s).

4.5 **Point at issue:** the longevity of resin-based repairs. Although intended for use in emergency situations, the probable lifetime of such repairs beyond that necessary to survive the emergency period will be of importance in scheduling ‘permanent’ repairs. This work is of importance whatever the resin-based repair method used.

4.5.1 Work to resolve: subject laboratory simulations, or models, of repairs to environmental ageing and monitor degradation of mechanical performance. Such work to be undertaken using ageing techniques designed to realistically accelerate degradation processes.
A.1 INTRODUCTION

A.1.1 Basis of study

On the 25th September 1998, the shuttle tanker Nordic Savonita collided with the stern of the Schiehallion FPSO, operated by BP Amoco. The damage was localised to the aft starboard side of the FPSO, at upper deck level. The stern, side shell and deck plating were deformed over an area 2m wide by 1m high extending around 600mm forward into a water ballast tank. The weld between the stern and deck plate had burst over a length of around 600mm with a hand-sized hole in the corner of the tank. One of the internal stiffeners sustained minor damage and the handrails around the impact area and a floodlight were also damaged.

The overall structural integrity of the FPSO was not affected but the damaged ballast tank was no longer watertight. A decision was taken to reinstate the structure to its original condition by replacing the distorted sections of plate and also to reinstate the handrails and floodlight. It was proposed that permanent repairs would be undertaken by welding replacement steelwork in the damaged areas. However, immediately following the incident a temporary repair was undertaken to reinstate the watertight integrity of the ballast tank by boxing in the damaged area from inside the tank.

DERA has considerable expertise in adhesive/sealant repairs in uncontrolled (e.g. wet and/or cold) conditions and there is also extensive knowledge of the use of structural composites. Based on this knowledge, DERA believes that the use of adhesive/composite-based techniques to effect rapid emergency repairs to damaged tanks and structures is a viable and potentially advantageous alternative to the use of steelwork.

This interim report represents part of a programme of work, funded by the HSE, aimed at undertaking a desk-top comparison of the steel-based and proposed adhesive/composite-based repair techniques. The findings of this evaluation will indicate whether further development of the alternative techniques, i.e. to manufacture and validate practical demonstrators, is justified.

A.1.2 Advantages of using adhesives and composites

Adhesives and composite materials offer a number of advantages for the repair of marine structures, namely:

- Cold working and hence absence of threat from fire or explosion
- Potentially cost effective compared to conventional welding/mechanical repair methods
- Composites may be formed into rigid structural materials *in situ*. This facility to fabricate - at the site of damage - large-area, stiff structures from compact, lightweight and flexible component materials represents a great advantage for transportation where access is restricted.
- Adhesive/composite structures may readily conform to irregular shapes and surfaces.
- Uniform and efficient load transfer between substrate and repair
• Excellent resistance of composites to corrosion, chemical attack and outdoor weathering
• Repair material can be applied, and removed if necessary, without damaging steel substrate material

However there are also disadvantages, including the very obvious fact that both the modulus and strength of polymeric materials are inferior to the values shown by steel. This means that the capability to restore a proportion of mechanical strength will be very much dependent upon hull thickness and geometry local to the damaged area. A further but perhaps less obvious feature of adhesively-assisted repairs is that satisfactory properties will not be achievable if there is significant relative movement between adherends during the curing process. This effect is of greater importance where an attempt is being made to restore structural strength. The effect may be less significant where a sealing repair only is the objective.

As a result of earlier DERA research and practical experience, materials have been developed that may be used for emergency sealant repairs of this kind. Similarly, there is considerable experience in the use of composite patch repairs for structural applications. However, additional work would no doubt be necessary in order to adapt established methods and procedures for FPSO requirements. The use of adhesive/sealant resins and the hand lay-up of organic-based composites for emergency repair purposes requires some basic training but specialised or highly developed skills are not required. This means that, after appropriate training, repairs of this kind could generally be undertaken by available manpower, either ship’s company or on-board contractors.

In summary, the use of adhesive/composite repair processes has a number of advantages over more conventional approaches and, because materials have already been developed for similar marine applications, such repair techniques may be readily adapted to meet the current needs.

A.2 OPTIONS FOR EMERGENCY REPAIR

A.2.1 Introduction

The aim of this section is to describe possible adhesive/composite-based repair techniques for the repair of collision damage sustained by FPSO or other similar vessels. The potential repair techniques are discussed in the following subsections.

All of the potential repair methods require a number of materials and certain basic equipment. These include:

• Degreasing materials (clean rag and degreasing agent – either organic solvent or water-based surfactant)
• Surface preparation tool (pneumatic drill fitted with rotary abrasive brush employing silicon carbide grit embedded in nylon bristles) and 3M Scotchbrite-type abrasive pads.
• Suitable expanded metal bridging material together with temporary retaining adhesive (e.g. Araldite Rapid or double-sided acrylic tape)
• Appropriate two-part, low viscosity primer
• Two-part epoxy sealant.
Preferably, these materials would be stored together in a suitable marked container and kept at temperatures below ~25°C. The resinous materials will have a shelf life but this will be a minimum of 6 months and could be several years. The toxicity of the repair materials will be low, largely as a result of very low vapour pressures. It is recommended that gloves should be worn in order to avoid the possibility of dermatitis that could result from prolonged skin contact with resinous materials.

One or two suitably trained persons, depending upon the location and magnitude of the damaged area, could carry out the repair. The repair process will always commence with surface preparation of the damaged area. This may involve preliminary removal of oil or grease, using the appropriate agent, followed by removal of any weak boundary layer (paint, corrosion, etc.) using the abrasives available. If required, expanded metal will then be pressed to shape over the repair and held in place using rapid adhesive or double-sided acrylic tape. If desirable – and allowable – bulk removal of protruding steelwork may be required.

Where putty is to be used, the repair proper may initially require the mixing and brush application of the recommended primer to the prepared damaged substrate. This will then be followed by mixing and application of the two-part putty. Where resin-saturated foam or polyester resin materials are recommended, primer coats will not normally be indicated.

A.2.2 Repair methods

The following four techniques could all be applied from within a structure by trained operatives from the ship’s staff. However, if internal access is not possible or desirable (e.g. if there is a risk from petroleum vapours) then the techniques could be adapted for external application. Depending on the location, this could require specialist personnel such as divers or abseilers.

The first three techniques all involve the use of a specially formulated putty and range from a purely sealant repair to what, in certain circumstances, could be regarded as both a sealant and full structural repair.

The fourth technique is for a purely sealant repair but differs from the others in that the seal is instantly created and does not depend for its effectiveness upon the cure of the resin component. Such a repair method would therefore be especially useful either underwater or for areas exposed to significant quantities of green water.

A.2.2.1 Putty (sealing only)

This repair method involves the use of a moulding compound, containing relatively long discontinuous fibres, which is applied by hand to the damaged area. The function of the putty is to seal and fill damaged areas. Depending upon the size of the hole, and in order to provide an adequate bridging capability, the use of the putty may involve the incorporation of expanded metallic mesh.

Technical description

- Requires no removal of deformed substrate
- Formulated with an appropriate resin/adhesive to work in wet or dry conditions, to cure at ambient temperatures and within appropriate time-scales
• Will not withstand hydrostatic loading during cure
• Low risk, readily achievable.

Figure A1 below illustrates schematically the repair method for an internal repair.

![Diagram of internal repair method]

**Figure A1: Putty repair method**

**In-service application**

It is anticipated that upon identification of a leaking structure, ship’s staff (or other suitable personnel) will mix and apply the putty to the damaged area. Initially, basic surface preparation will be carried out. This will include the removal of loosely attached macro material, followed by the removal of any surface contaminants that might otherwise be the source of a weak boundary layer and lead to imperfect sealing. The putty will then be applied. The selected putty will be capable of curing in the presence of water and hydrocarbons. In order to bridge larger gaps, expanded metallic mesh may have to be incorporated. The mesh may be used either by pre-embedding it within the putty prior to pushing into place, or the mesh may be attached (e.g. using Araldite Rapid or double-sided acrylic tape) after preparation of the damaged area. In either case, the strength of the bonded and sealed repair will depend upon the bond created between the putty and the steel substrate.

**A.2.2.2 Chopped fibre suspension spray (sealing/semi-structural)**

This repair method involves the use of a short fibre-based composite material applied by a spray gun. The method involves two steps, an initial sealant (unreinforced putty - see 2.2.1 for details) applied to the damaged area, followed by the spray application of uncured composite onto the faired surface of the putty to which it adheres.

**Technical Description**

Spray moulding techniques simultaneously deposit a resin (say polyester) with a chopped glass fibre. There are now several commercial spray systems available, although basically each performs the same function, i.e. chops the glass roving into specified lengths, usually about 20-50mm, adds the resin and catalyst at the gun, and sprays onto the mould a mixture of chopped strand glass fibre and catalysed resin. Further consolidation with a roller would be required to
produce a semi-structural composite.

Notes:
- Two step process
- Allows for optimisation of sealant
- Will not withstand hydrostatic loading during cure
- Low risk, readily achievable

Figure A2 below illustrates schematically the repair method for an internal repair

![Figure A2: Putty with additional sprayed short fibre composite skin](image)

**In-service application**

Upon identification of a leaking structure, suitable personnel will prepare the damaged area and mix and apply the putty as described in 2.2.1 above. However it will be necessary build the putty layer such that a smooth, faired surface may be created prior to application of the composite spray coat.

To achieve this with a reasonable putty thickness, it may be necessary to cut away distorted steelwork. Once the faired putty has cured, the short-fibre composite is deposited over and beyond the damaged area up to the desired thickness.

**A.2.2.3 Laminated composite (sealing/(semi-)structural repair)**

This repair method uses structural composite material to reinforce a damaged area after the application of sealing putty. Following application of a sealant, continuous fibre composite is used to restore some structural strength to the damaged area. Depending on the damage event this method may or may not constitute a full structural repair.

**Technical description**

Again, the initial seal and fairing of the damaged structure is to be achieved using unreinforced putty. The surface can then be sanded to give a contoured finish upon which to laminate. Three existing composite manufacturing routes are available that could be suitable for the application
of a composite backing sheet. These are discussed below:

**Wet lay-up patch repair technique** This technique creates the composite patch by applying fibre mat and resin to the structure independently. This particular method is susceptible to variation in patch properties and, for vertical or overhanging locations, there will be a limiting number of cloths that can be applied before their weight causes drainage problems, leading to the patch pulling away from the surface. However, the wet lay-up technique does permit patches to be manufactured quickly and simply and is particularly suited to surfaces involving complex curvature.

**Single stage co-cured repair technique** This technique involves the application of low temperature (typically 50ºC to 70ºC) cure prepreg material and structural adhesive directly onto the metallic structure. The two are co-cured together to give a strong, reliable repair, using a relatively simple technique. Co-cured repairs have a degree of tack and will self-adhere to the previous layer. Vacuum consolidation may be used but will only be required for more demanding structural repairs. The co-cured repair technique does not offer the same degree of freedom as the wet lay-up process since the prepreg material has a limited shelf life, must be stored in a freezer and heat (e.g. using heater mats, hot air blowers or infrared heaters) is required to initiate the curing cycle. However, the single stage co-cured repair technique is very efficient and user friendly.

**Resin Infusion under Flexible Tooling (RIFT) technique** The RIFT technique involves the application of a dry pre-form stack over the top of the sealing putty. This is subsequently infused with a low viscosity resin system whilst contained within a vacuum bag. As with the wet lay-up process, this method also offers a high degree of flexibility in terms of fibre placement, especially around complex structures. It also practically eliminates the hazards associated with exposure to liquid resins. In addition, this technique also offers a significant reduction in both human and financial resources. This aspect alone could make the RIFT technique attractive to the commercial sector in the marine industry.

**Patch guidelines for laminated composite repair** The overall size of the patch required to re-instate some structural stiffness to the damaged area is derived from:

1. the stiffness of the steel, which also governs the composite overlap distance either side of the fatigue crack, and
2. the overlap length required to reduce the peel stresses to zero at the outer edge of the patch.

This description has been illustrated schematically in Figure A3.
Three critical zones, A, B and C, have been identified on the diagram in Figure A3.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Key parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Structural reinforcement</td>
<td>The overall length and height of this zone is required to match the overall stiffness of the steel structure, i.e. this zone carries all the structural loading within the patch.</td>
</tr>
<tr>
<td>B</td>
<td>Overlap length</td>
<td>The overlap length is a function of the patch height (zone C) and its primary role is to minimise the peel stresses at the extremities of the patch, although it will contribute to the overall strengthening to the structure.</td>
</tr>
<tr>
<td>C</td>
<td>Patch height</td>
<td>The patch height is determined by matching the stiffness/thickness ratio of the steel with the composite repair.</td>
</tr>
</tbody>
</table>

The approach detailed above ensures that the structural loading element of the patch (i.e. zone A) is controlled throughout the manufacture of the patch, i.e. continuous contact with the metallic surface is achieved from the outset and subsequently controlled through the remaining fabrication cycle until height C is achieved. In essence, this is the critical region of the patch, although zone B, the overlap region, does play an important role in distributing the loads from the steel into the composite patch.
Notes:
- Two step process
- Semi-structural or possibly fully structural repair
- Thickness of putty required may not be feasible
- Will not withstand hydrostatic loading during cure
- Low risk, readily achievable but not possible in certain circumstances

In-service application

It is anticipated that upon identification of a leaking structure suitable personnel will mix and apply the putty to the damaged area as detailed in 2.2.1. In order to achieve the required fairness of form, it may be necessary to use large amounts of putty to build up an adequate thickness. Otherwise some removal of steel may first be required, depending upon the degree of distortion and extent of metallic protrusions. Once the putty is cured and faired, some surface preparation of the surrounding area is necessary prior to the application of a continuous fibre reinforcement via one of the above three methods.

A.2.2.4 Rigid pressure pad with Resin Impregnated Foam (RIF) sealant (sealing only)

This repair method employs an adhesive-soaked reticulated, flexible foam which is applied to a damaged area, using a stiff backing plate to enable compression of the RIF. This approach leads to adhesive bonding of the RIF to the prepared plate surrounding the damaged area, and to the sealing of the damaged hull against leakage. The great advantage of this technique is that a seal is instantly achieved which is not dependent upon the resin being cured.

Technical description

This repair method has three key elements—a backing plate, RIF and a clamping/compression mechanism. (each will be discussed in turn).

Backing plate The backing plate could be manufactured from composite or metallic material. Ideally it will be lightweight, to facilitate manipulation during the repair process, and have sufficient strength to allow compression of the RIF.

RIF Flexible, reticulated polyurethane foam of suitable thickness is cut to size with scissors, attached to a backing plate and placed horizontally on a table with the foam side uppermost. A quantity of the two-component impregnating resin, at least equal in volume to that of the foam pad, is then mixed. The resin is worked into the foam pad using palette knives until all the resin has been incorporated. The pot-life of the resin may be as little as ~30 minutes. For this reason it may be necessary for two people to work together on the impregnation process. Once the impregnation process is complete, the pad will be placed in position and compressed to one half to one quarter of its original thickness. If foam of appropriate thickness is unavailable, two or more layers of RIF may be applied and compressed.

Clamping/compression mechanism A number of clamping/compression mechanisms exist which require access from one side only and these include:
(1) Threaded bar and locking screw nuts (plastic or metallic)
(2) Threaded bar with a barbed locking ‘cap’ similar to a cable-tie arrangement, or to fixtures
designed for use on hollow walls
(3) The use of suction pads may be suitable in certain circumstances, especially where non-intrusive methods are indicated. The load required to compress resin-impregnated foam (RIF) will be affected by the temperature at which the repair is carried out (i.e. higher resin viscosity is associated with lower temperatures).

Notes:
- Thickness of RIF dictates maximum surface irregularities that can be accommodated in the repair
- One step process and instant seal repair
- Requires clamping method
- Will withstand hydrostatic loading during cure
- Low technical risk, has been used in North Sea environment
- This repair may be applied above or below the water line. The repair method is illustrated schematically in Figure A4 below.

![](image)

**Figure A4: Single sided pressure pad with RIF sealant**

*In-service application*

It is anticipated that, upon identification of a leaking structure, appropriate personnel will assess the damage area and cut a suitable piece, or pieces, of foam from a stock roll. Resin will then be mixed and applied to the foam attached to the backing plate. The backing plate is then positioned into place and secured firmly by one of the above clamping/compression methods suggested above. This will then remain in situ until a permanent repair is carried out.

**A.3 SUMMARY AND CONCLUSIONS**

An initial review of the damage that occurred to the Schiehallion FPSO has led to the identification of four potential adhesively-assisted composite-based sealant and semi-structural repairs. The repair methods outlined in the report are generic in the sense that they could be used for other similar types of damage and could be adapted for internal or external application.

The exact sequence of repair events will be a function of the damage type and its location. This interim document has highlighted how a phased approach to repair could be used, i.e. putty to provide a watertight seal and then some form of structural backing depending on the nature of the damage sustained.