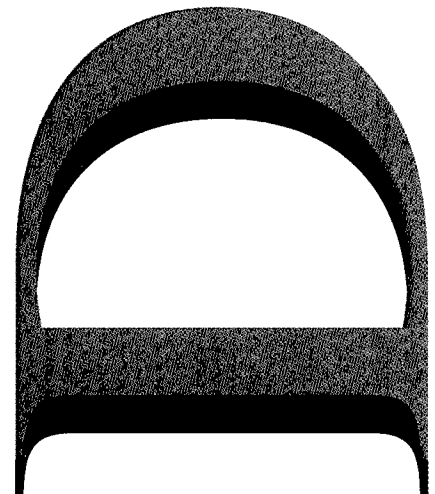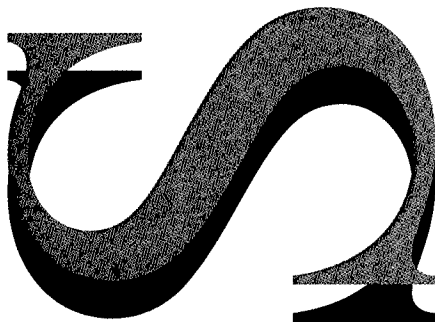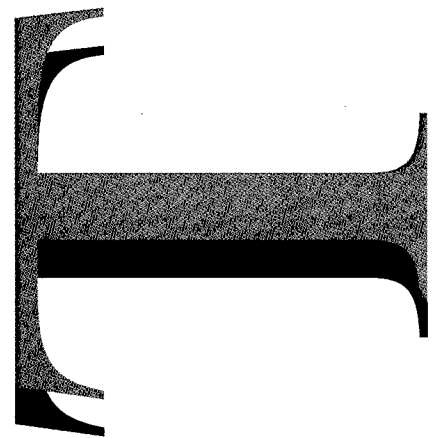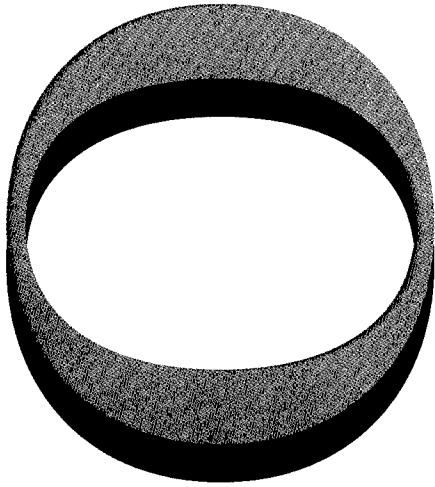AR-010-662

Repair of Damage to Marine Sandwich
Structures: Part I – Static Testing

Rodney Thomson, Raoul Luescher and
Ivan Grabovac

DSTO-TR-0736

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Repair of Damage to Marine Sandwich Structures: Part I - Static Testing

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DSTO-TR-0736

ABSTRACT

Marine vessels constructed from sandwich panels with glass reinforced polymer (GRP) composite skins and PVC foam core are now common. Such structures will inevitably be subjected to damage and any repair technique needs to ensure that the strength and stiffness of the structure are restored. The current recommended Royal Australian Navy (RAN) techniques for the repair of sandwich structures have been evaluated and deficiencies identified. Static tests conducted under four-point bending indicate that the presence of voids in the bondline seriously affect the strength of the repair. Modified repair techniques are proposed to simplify the repair procedure while improving the repair quality and repeatability. The test results show that the modified techniques overcome the problems associated with the RAN repair techniques.

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Repair of Damage to Marine Sandwich Structures: Part I - Static Testing

Executive Summary

Glass reinforced polymer (GRP) composites are being used increasingly in the maritime industry for the manufacture of hulls, superstructures and fittings. In Australia, two Bay Class Minehunters Inshore (MHI) were manufactured entirely from GRP sandwich construction. The Huon Class Minehunters Coastal (MHC) are also being manufactured from GRP, but use a monolithic materials construction. Similarly, fairings on the Collins Class submarines are manufactured from GRP and a variety of other applications are currently being considered. In addition to this, GRP finds extensive uses in the civil maritime industry. These structures will inevitably be subjected to damage and effective repair methods must be developed. This report concerns the repair of damage to GRP sandwich structures representative of those used on MHIs.

The Bay Class minehunters are manufactured from sandwich structures with GRP skins and poly(vinyl chloride) (PVC) foam core. In such sandwich structures, damage can be limited to one skin (defined as Type A damage), to one skin and the core (Type B), or to both skins and the core (Type C). The approach used in performing the repair is critical to ensure that the strength and stiffness of the structure are restored. The aims of this work were to evaluate the Royal Australian Navy (RAN) standard repair techniques for damage to the Bay Class minehunters. The performances of the repair techniques were judged both on their ability to restore the mechanical properties and on the ease of conducting the repair. Methods to simplify the repair procedure while improving the repair quality have also been investigated. These modified methods are described and their development outlined. The results from static tests to evaluate the mechanical performance of the RAN and modified repair techniques are presented.

The RAN Type B repair was found to be difficult to perform and could easily result in a deficient bondline between the existing skin and the replacement core. Static loading under four-point bending indicated that the presence of voids in the bondline seriously affected the strength of the repair, especially when the void was in compression. A modified technique for the repair of Type B damage was proposed which simplified several aspects of the repair procedure and improved the quality and repeatability. Tests showed that the strength of specimens repaired using this new technique was equal to or exceeded the original strength. The RAN Type C repair did result in a repair with sufficient strength, but was found to be difficult to perform. The proposed modified Type C repair technique incorporated many of the simplifications used in the modified Type B repair and restored the strength to the sandwich structure. However, it was observed that the adhesive used in the repair should have an elongation to failure that exceeds that of the core material. The results of this program demonstrated that the modified repair techniques were easier to prepare and more reliable than the current RAN recommended repair techniques.

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1. Introduction

Glass reinforced polymer (GRP) composites are being used increasingly in the maritime industry for the manufacture of hulls, superstructures and fittings. In Australia, the Bay Class Inshore Minehunters were manufactured entirely from GRP sandwich construction. The Huon Class Coastal Minehunters are also being manufactured from GRP, but use a monolithic materials construction. Fairings on the Collins Class submarines are also manufactured from GRP and a variety of other applications are currently being considered. In addition to this, GRP finds extensive uses in the civil maritime industry. These structures will inevitably be subjected to damage and effective repair methods must be developed. This report concerns the repair of damage to GRP sandwich structures representative of those used on the Bay Class minehunters.

Sandwich panels consist of two high strength and stiffness skins separated by a low density, lower strength and stiffness core. These structures can be optimised so that each element operates near its material limit which results in a structure with a very high ratio of bending stiffness to weight. Such structures can be subjected to three damage scenarios. The damage can be limited to one skin (Type A), to one skin and the core (Type B), or to both skins and the core (Type C). The approach used in performing the repair is critical to ensure that the strength and stiffness of the structure are restored.

The aims of this work were to evaluate the Royal Australian Navy (RAN) standard repair techniques for damage to the Bay Class minehunters [1]. These vessels are manufactured from sandwich structures with GRP skins and poly(vinyl chloride) (PVC) foam core [2]. The performances of the repair techniques was judged both on their ability to restore the mechanical properties and on the ease of conducting the repair. Methods to simplify the repair procedure while improving the repair quality have also been investigated. These modified methods are described and their development outlined. The results from tests to evaluate the mechanical performance of the RAN and modified repair techniques are presented.

2. Repair Techniques for GRP/Foam Sandwich Structures

2.1 Damage and Inspection of GRP/Foam Sandwich Structures

Damage to GRP/foam sandwich structures can be assigned to the three groups previously defined and can involve various mechanisms. Type A damage generally involves matrix cracking, fibre breakage and delaminations in the skin. The damage may or may not extend through the full thickness of the skin. Type A damage can also include debonding of the skin from the core. Type B damage involves Type A damage

to one skin combined with crushing or shear cracking of the core. Type C damage involves the same damage mechanisms as Type B except both skins are affected. Type C damage can fully penetrate the sandwich structure [1].

While some instances of delamination and core debonding may be repaired through simple methods such as resin injection, damage to sandwich structures usually requires removal and replacement of the affected material. One of the primary reasons for removal of all damaged material is that damage will tend to grow under subsequent loading. Also, the detrimental effects of water ingress are a particular concern in ship structures and can cause additional damage growth.

Before any material is removed, it is necessary to know the extent of the damage, which can often be difficult to determine with any degree of certainty. Internal damage to the skins and core can extend well beyond any visible external damage. The development of reliable non-destructive evaluation techniques would greatly assist in determining the extent, depth and type of damage in foam cored sandwich structures. Tap testing and ultrasonic A-scan can be used to determine the damage extent in the skins but require an experienced operator. In many situations, the most reliable method is removal of all damaged material starting at the centre of the damaged region, working outwards until sound material is encountered.

2.2 Repair Techniques for Marine Sandwich Structures

Various methods for the repair of marine GRP/foam sandwich structures have been developed. Such structures are most commonly found on small civilian marine vessels, predominantly yachts. Repairs to these vessels are carried out by boat builders who have developed repair methods over many years, often without scientific appraisal. Hence, unlike the aerospace industry, the majority of repair methods for these marine sandwich structures remain undocumented. Some literature is available on the repair of GRP recreational craft [3,4] but these methods were not considered as they have not been validated.

Repair techniques used in the aerospace industry undergo extensive development and testing before being implemented. Some of the approaches used in the aerospace industry can be adapted to marine structures but the materials used differ significantly. Aerospace composite laminates are usually autoclave cured and, as a result, are of high quality having a high fibre volume fraction (>60%) and very low void content (<2%). Marine structures are usually made from glass fibres with polyester or vinylester resin. They often use hand lay-up or vacuum bagging techniques and the resulting fibre volume fraction could be as low as 20% and void content could exceed 10%. Core materials typically used in marine structures, such as foam or balsa wood, are different from the stronger and stiffer Nomex® or aluminium honeycomb normally used in aerospace components. The poorer properties of the marine materials may affect the repair integrity. For example, adhesive shear strength, an important property in the bonded repair of composites, is dramatically reduced by the presence of porosity. A 5% void content reduces the shear strength by 20% [5].

Another significant difference between repairs on aerospace and marine structures is the size of the repair. In aerospace, if the damage is greater than a certain size, the part will be scrapped. This is often not practical or economical in marine structures necessitating the repair of large areas, often exceeding one square metre.

Both bonded and bolted repair methods could be applied to repair marine sandwich structures. Bonded repairs were considered to be the most applicable repair technique and offer several advantages over bolted repairs. They are lighter in weight and distribute the load more evenly over a wider area. However, they require careful surface preparation, are difficult to inspect and are more difficult to perform correctly. Bolted repairs are more easily carried out and require minimal surface preparation. However, they add bulk and weight and require holes to be drilled through the structure which can introduce further damage and create stress concentrations. Additionally, bolted repairs are more difficult to implement on sandwich structures and need to be water-tight [6].

A repair technique developed for use in aerospace structures which can be applied directly to marine structures is the scarf repair used on composite laminates. This is the most efficient of a number of bonded repair techniques, shown in Figure 1, and is capable of restoring the strength to the damaged laminate. This repair produces constant shear stress in the bondline between the parent and repair laminates [7]. It is also relatively simple to prepare by grinding back the laminate to the angle required which is normally less than 6°. For thinner laminates (less than 2 mm), an external patch can be used, which is effectively a single lap joint. These are quicker to apply but may only restore 70% of the original strength due to the uneven shear stress distribution (refer to Figure 1). For all bonded repairs, surface preparation is of vital importance.

Damage to sandwich structures often involves damage to the core material. The damaged core can be filled either with a foaming adhesive, a laminate or a new core section bonded in place. The latter method is usually adopted as it best restores the properties of the sandwich structure. The first two approaches may be used where the damage is shallow and covers only a small area. Different approaches to this repair are required for Type B or C damage. The repair of Type C damage also depends on whether access can be gained from both sides. While repair methods have been developed in the aerospace industry, as illustrated in Figure 2 [7], marine structures using closed cell foams rather than honeycomb as the core material present unique problems and require a different approach. The differences arise in the method used to bond in replacement core. Air can escape through the open cells of the honeycomb as it is bonded in place, while with foams air can be trapped in the bondline leading to defects and a poor quality repair. This problem is discussed further in later sections.
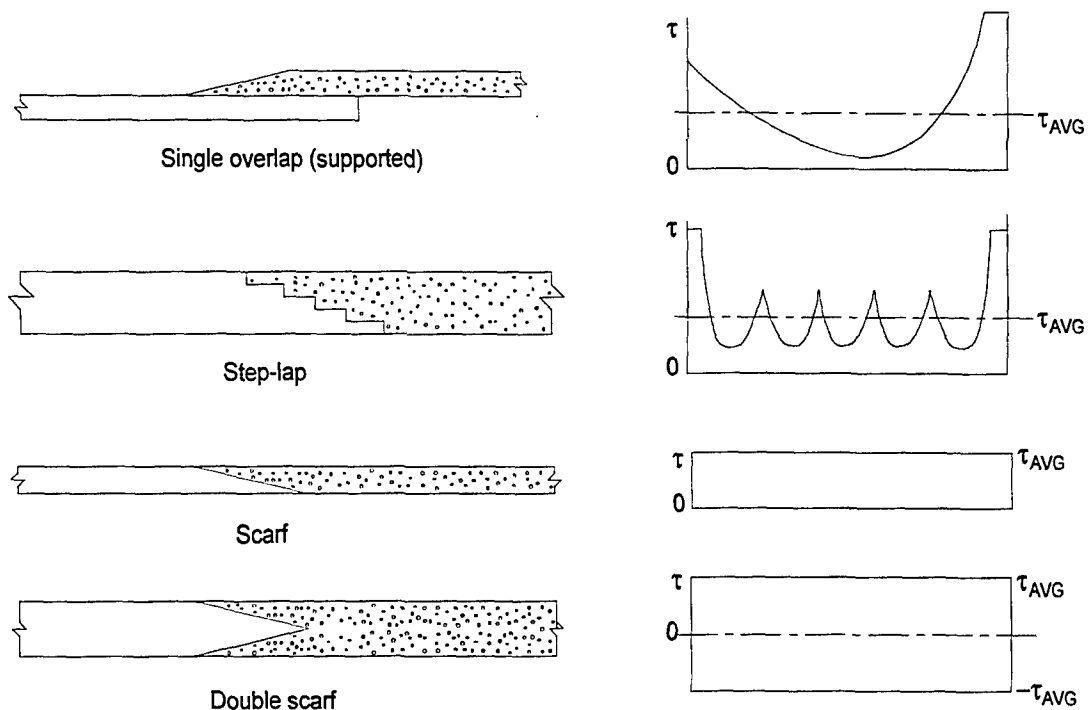
Figure 1: Bonded repair techniques and the associated adhesive shear stress distribution along the joint length (after [7]).

(a)   (b)
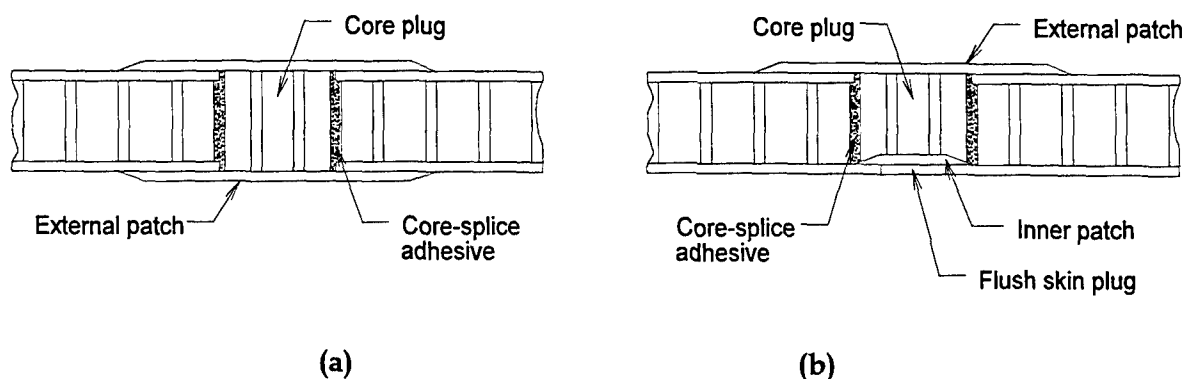
Figure 2: Typical aerospace repair of a honeycomb sandwich structure with (a) access to both sides and (b) access to only one side (after [7]).

Some methods developed for the repair of Type B and C damage to GRP/foam sandwich structures include those of the United States of America Coast Guard [8] and the Swedish Navy [9]. A schematic diagram of the latter method for the repair of Type B damage is shown in Figure 3. The methods currently used by the RAN will be discussed in later sections of the report. A feature of the Swedish method is the use of smaller blocks of foam to reconstruct the core, which is useful on curved surfaces. This method avoids the air entrapment problem but increases the likelihood of defects in

the bondlines between the various core blocks. A need exists for a repair technique in which the core can be replaced in one section wherever possible.
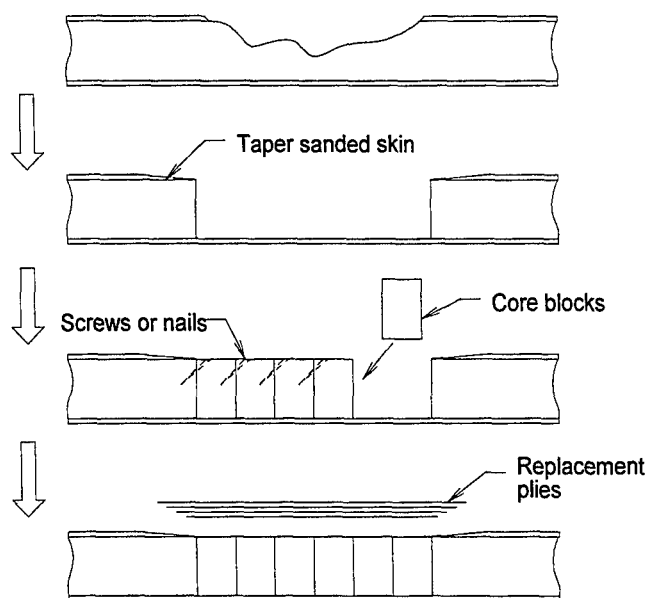
Figure 3: Repair technique for Type B damage to GRP/foam sandwich panels developed for the Swedish MCMV (after [9]).

2.3 Repair of Type A Damage

The replacement of a skin for Type A damage is a straightforward procedure which is best accomplished using a scarf repair. An important aspect of such a repair is the scarf angle which should be less than 6° to ensure good transfer of shear load in the bondline. The surface preparation is also critical to ensure good adhesion between the parent and repair laminates. Provided sufficient care is taken, such a repair should have adequate strength and durability. As mentioned previously, such repairs have been demonstrated in many applications and have proved their suitability. For this reason, Type A repairs were not considered directly in this research. However, Type B and C repairs do involve a Type A repair of the skins, so this repair type was evaluated indirectly.

The RAN Type A repair procedure is shown in Figure 4 and detailed below. In the following procedures, a layer is defined as one ply each of 300 g/m² chopped strand mat (CSM) and 600 g/m² woven rovings (WR).

1. *Remove Damaged Material:* The damaged skin is removed starting at the centre of the damaged region, working downwards and outwards until sound material is encountered.

2. *Repair Preparation:* If the damage is deeper than one layer, taper sand the surrounding skin 20 mm per layer (scarf angle of approximately 6°).

3. *Replace Skin:* Replace the skin using the number of layers removed. Each successive layer is to be 40 mm longer and wider than the previous layer. Apply one extra layer extending 100 mm beyond all damage.

Figure 4:   RAN method for the repair of Type A damage to GRP/foam sandwich panels.

2.4 Repair of Type B Damage

2.4.1 RAN Technique

The repair of Type B damage to GRP/foam sandwich structures requires the replacement of one skin and the core. The RAN recommended repair procedure for Type B damage to GRP/foam sandwich structures of the Bay Class minehunters [1] is shown in Figure 5 and described below:

1. *Remove Damaged Material.*
    a) Remove the damaged skin, working from the centre of the damaged region outwards until sound material is encountered.
    b) Remove the exposed damaged core leaving the other skin intact.

2. *Prepare the area for repair.*
    a) Prepare the foam core to an angle of 45°.
    b) Sand the edge of the laminate to a taper of 20 mm per layer. This provides a scarf angle of approximately 6°.

3. *Install the replacement foam.*
   a) Use a paste adhesive designed to bond PVC foam.
   b) Use the appropriate grade of foam.
   c) Use the minimum amount of adhesive (bondline thickness 3 mm maximum).
   d) No voids should exist between the undamaged skin and the replacement foam.

4. *Replace the skin.*
   a) Use the same number of layers as the original skin.
   b) Each successive layer is to be 40 mm longer and wider than the previous layer.
   c) Apply one extra layer of GRP extending 100 mm beyond the extent of all damage.

Figure 5:   RAN method for the repair of Type B damage to GRP/foam sandwich panels.

2.4.2 Modified Technique

Two primary deficiencies were noted with the RAN Type B repair technique. The first concerned preparing the core at a 45° angle which proved to be difficult. The second deficiency was entrapment of air between the replacement core and the existing skin during the bonding process. A series of trials were undertaken to develop techniques to overcome these problems. In developing these techniques, other repair methods, outlined previously, were taken into consideration. In particular, the methods used by the United States of America Coast Guard [8] and the Swedish Navy [9] were examined.

In the modified Type B repair technique, emphasis was placed on simplifying the procedure. This was achieved by replacing the core in one section whenever practical and using 90° butt joints. The trials showed that effective, void free core replacement could be achieved using this approach. To avoid entrapment of air when the replacement core was positioned, holes were drilled through the core at a spacing of between 50 mm and 100 mm. A problem associated with the 90° joins in the core was the difficultly in filling the bondline between the replacement and existing core. To overcome this, the repair was placed under a vacuum bag to draw adhesive up around the edges. Vacuum pressure of around 70 kPa (20 inHg) was found to be sufficient and the adhesive should have a reasonably short gel time (30 - 50 min). Also, the correct amount of adhesive should be applied since significant bleed does not occur. Additionally, the adhesive should be applied only to the existing skin and core, not to the replacement core, as this prevents blockage of the holes drilled through the replacement core.

The modified Type B repair method, shown in Figure 6, is described below:

1. *Remove damaged material.*
   a) Remove the damaged skin, working from the centre of the damaged region outwards until sound material is encountered.
   b) Remove the exposed damaged core leaving the other skin intact.

2. *Prepare the area for repair.*
   a) Prepare the foam core to an angle of 90°.
   b) Sand the edge of the laminate to a taper of 20 mm per layer, providing a scarf angle of approximately 6°.

3. *Install replacement foam.*
   a) Use a paste adhesive designed to bond PVC foam.
   b) Use the appropriate grade of foam.
   c) Allow 1 mm all round for the bondline.
   d) Drill 3 mm diameter holes through the core at 100 mm centres (approximately).
   e) Apply the correct amount of adhesive (calculated from the volume of the bondline) to the existing skin and core.
   f) Carefully place the core, forcing it down lightly to remove entrapped air.

4. *Vacuum bag the core.*
   a) Apply a layer of perforated release film and breather over the repair area.
   b) Position the vacuum bag over the repair area, sealing it to the surrounding structure.
   c) Apply vacuum of 70 kPa until the adhesive has cured.
   d) Clean up area for laminating.

5. *Replace the skin.*
   a) Use the same number of layers as the original skin.
   b) Each successive layer is to 40 mm longer and wider than the previous layer.
   c) Apply one extra layer of GRP extending 100 mm beyond the extent of all damage.
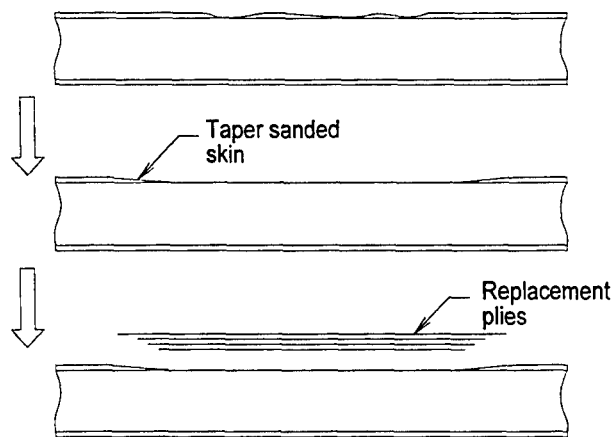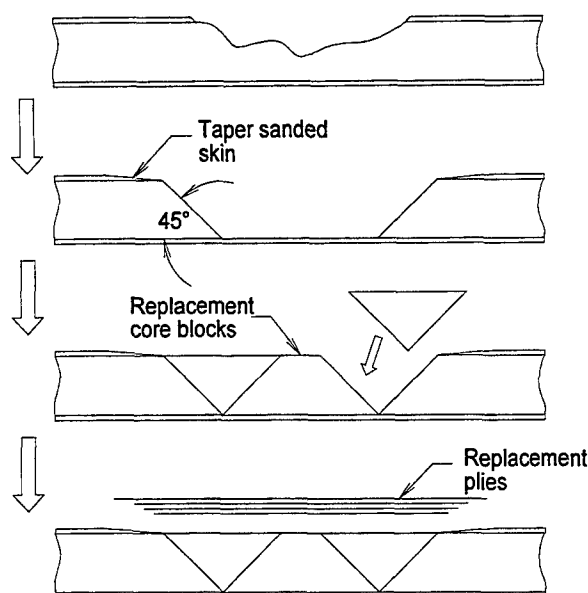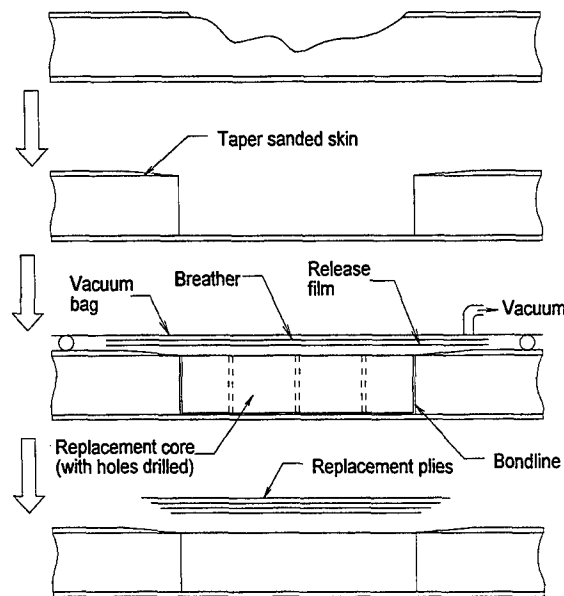

Figure 6:   Modified method for the repair of Type B damage to GRP/foam sandwich panels.

2.5 Repair of Type C Damage

2.5.1 RAN Technique

The repair of Type C damage to GRP/foam sandwich structures requires the replacement of both skins and the core. The RAN repair procedure for Type C damage [1] is shown in Figure 7 and described following.

1. *Remove damaged material.*
   a) Remove the damaged skins, working from the centre of the damaged region on both sides outwards until sound material is encountered.
   b) Remove the exposed damaged core.

2. *Prepare the area for repair.*
   a) Prepare the foam core to an angle of 45°.
   b) Sand the edges of both skins to a taper of 20 mm per layer providing a scarf angle of approximately 6°.

3. *Install the replacement foam.*
   a) Use a paste adhesive designed to bond PVC foam.
   b) Use a backing plate where required.
   c) Use the appropriate grade of foam.
   d) Use the minimum amount of adhesive (bondline thickness 3 mm maximum).

4. *Replace the skins.*
   a) Use the same number of layers as the original skin.
   b) Each successive layer is to be 40 mm longer and wider than the previous layer.
   c) Apply one extra layer of GRP extending 100 mm beyond the extent of all damage.
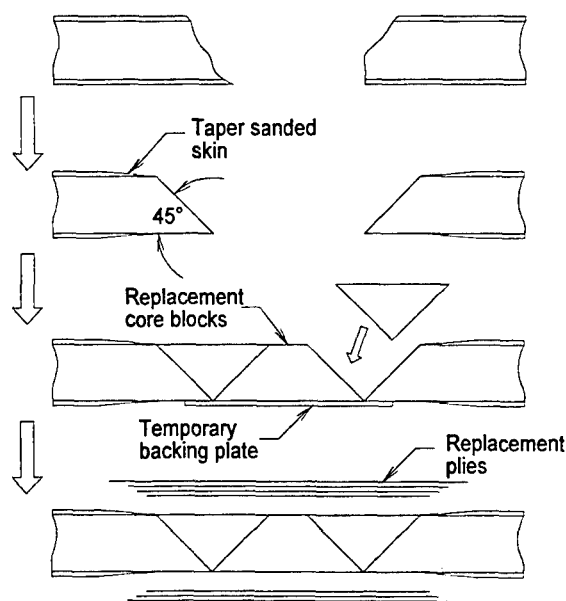
Figure 7:   RAN method for the repair of Type C damage to GRP/foam sandwich panels.

2.5.2 Modified Technique

The primary aims of the modified technique were to simplify the repair and to make it more reliable. Many of the modifications to the Type B repair were incorporated into the modified Type C repair technique. These included the use of 90° joins in the core and replacing the core in one section where possible. Again, the most difficult part of the repair was bonding the replacement core in position accurately without creating voids in the bondline. To avoid the requirement of a backing plate, a lip was left in one skin against which the replacement core could rest. Holes were drilled through the replacement core into the bondline gap as shown in Figure 8. The holes should emerge near the bottom of the bondline gap so air does not become trapped when the adhesive is injected. The spacing between the holes should be twice the core thickness. Bonding the core in place was then conducted in two stages using a caulking gun. First, a bead

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of adhesive was placed around the lip and the core placed in position. The adhesive was than allowed to cure to prevent the core from moving and excessive adhesive leaking during the next stage. The gap between the existing and replacement core was then filled with adhesive by injecting it through the holes using a caulking gun. Following cure of the adhesive, the replacement skins can be laminated.
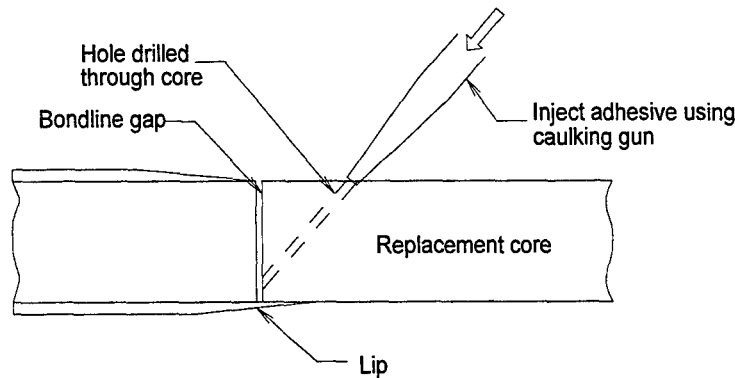
Figure 8:   Adhesive injection method for the modified Type C repair technique.

The modified Type C repair technique is shown in Figure 9 and described below:

1. *Remove damaged material.*
   a) Remove the damaged skins, working from the centre of the damaged region of each skin outwards until sound material is encountered.
   b) Remove the exposed damaged core.

2. *Prepare the area for repair.*
   a) Prepare the foam core to an angle of 90°.
   b) Leave a lip of approximately 10 mm width on one skin around the entire repair.
   b) Sand the edges of both skins to a taper of 20 mm per layer providing a scarf angle of approximately 6°.

3. *Install replacement foam.*
   a) Use a paste adhesive designed to bond PVC foam.
   b) Use the appropriate grade of foam.
   c) Cut a piece of foam, allowing 1 mm all round for the bondline.
   d) Drill 3 mm diameter holes through the core into the bondline gap, as shown in Figure 8. The spacing of the holes should be twice the core thickness.
   e) Place a bead of adhesive around the lip and position the foam, forcing it down lightly.
   f) After the adhesive has cured, inject adhesive into the bondline through the holes using a caulking gun. Clean up the area before the adhesive cures.

4. *Replace the skins.*
   a) Use the same number of layers as the original skins.
   b) Each successive layer is to be 40 mm longer and wider than the previous layer.
   c) Apply one extra layer of GRP extending 100 mm beyond the extent of all damage.
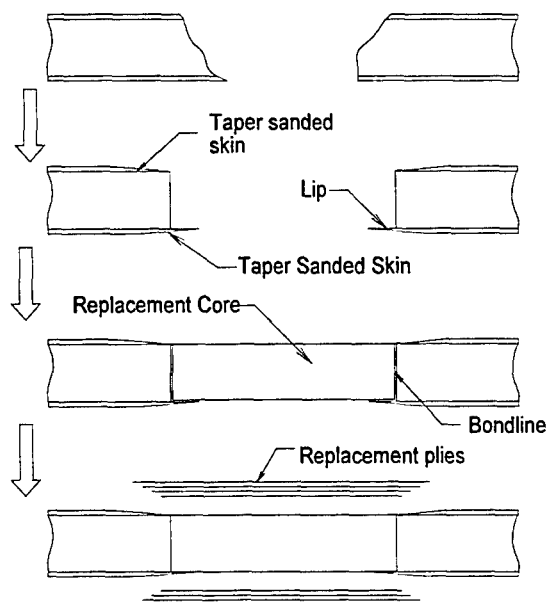
Figure 9:   Modified method for the repair of Type C damage to GRP/foam sandwich panels.

3. Four-Point Bend Testing Approach

3.1 Test Methodology

The four-point-bend test, as specified in ASTM C-393 [10], was selected to evaluate the mechanical performance of the repaired material. This test has been shown to be the most appropriate method for evaluating the performance of marine sandwich structures [11]. The test places the core under shear so will readily identify deficiencies in the core or the bond between the replacement core and existing core or skin. While the skins do carry the bending loads under four-point-bending, these were not anticipated to be high enough to cause skin failure. Two outer support spans were used, 300 mm and 400 mm, which enabled the effect of repair area to be investigated. Tests on Type B specimens were conducted with the repaired skin in compression (normal position) and in tension (inverted position). For the Type C specimens, the normal position was defined as having the lip (refer to Figure 9) on the tension side. The location of the end of the repair was midway between the load and support points, as shown in Figure 10. In this region, the shear stress carried by the core is constant, while the bending stress carried by the skins increases linearly from zero at the outer support to a maximum at the inner support.

The tests were performed using a four-point-bend rig in a Riehle 300 kN testing machine in displacement control at a rate of 3 mm per min under ambient conditions. The load, displacement, acoustic emissions, failure load and failure mode were recorded. In many of the preliminary tests, failure occurred prematurely through local wrinkling of the skin combined with crushing of the core under the loading points. The load at which this type of failure occurs is dependent on several factors which include the local skin thickness, local core stiffness and strength as well as the effective radius of the loading pin. To prevent this mode of failure, aluminium plates of various thicknesses were placed under the loading points. This had some success in distributing the load and preventing premature skin wrinkling failure.
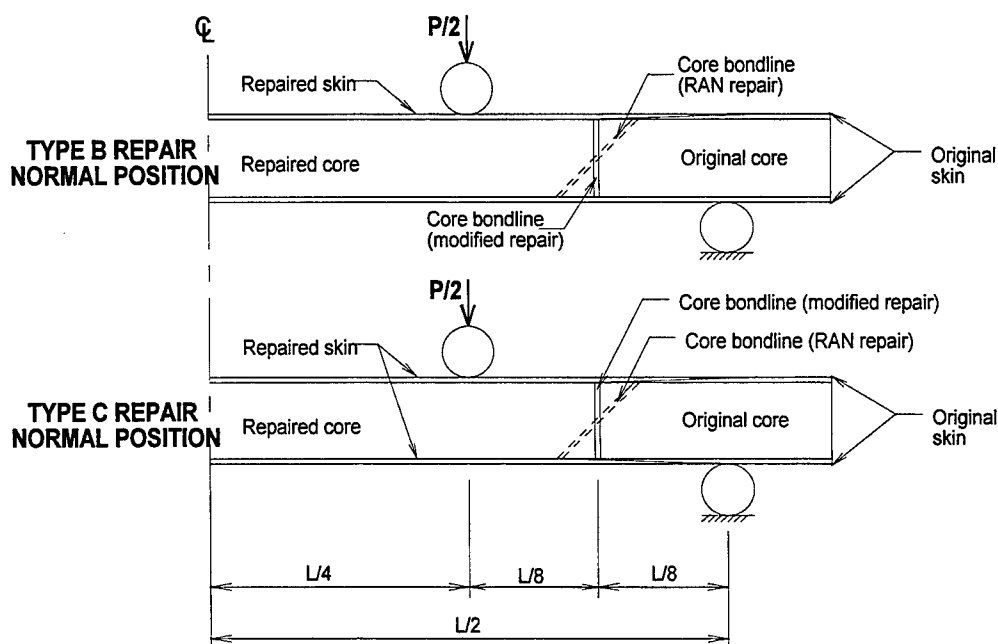
Figure 10: Four-point bend test configuration, where L is the span.

3.2 Materials

The materials used to evaluate the various repair techniques were representative of those used in the construction of the Bay Class Minehunters [2]. The GRP skins were laminated from 300 g/m² chopped strand mat (CSM), 600 g/m² woven rovings (WR) (ACI Fibreglass), using Dow Derakane® 411-C50 vinylester resin (Dow Chemicals (Aust) Ltd). The recommended fibre volume fraction for hand lay-up of the CSM and WR was 17% and 33% respectively. The lay-up of the skins was CSM/WR/CSM, and the resulting nominal thickness was 2.1 mm. The core material used was 30 mm thick Divinycell HT90 rigid, crosslinked, PVC foam (Diab-Barracuda AB (Sweden)) with a nominal density of 90 kg/m³. Two thixotropic paste adhesives were used to bond the PVC foam: Divilette-600® based on ortho-polyester resin and Iso-Divilette® based on

iso-polyester resin (Diab-Barracuda AB (Sweden)). Both adhesives are approved for use in the repair of the Bay Class minehunters [1] but the properties of the Iso-Divilette® are generally superior, especially the modulus and ultimate tensile strain which are 10-20% greater. Iso-Divilette® is not commercially available and supplies in the laboratory ran out after manufacture of the RAN type repaired specimens. Typical mechanical properties of the materials used in the test program are given in Table 1.

It should be noted that the properties of the PVC foam vary directly with the density, and the density can vary not only between sheets, but locally within one sheet. The density, while nominally 90 kg/m³, varied by approximately 3% hence the stiffness and strength of the core varied by a similar amount. Additionally, some defects were found in the core which included bubbles up to 5 mm in diameter. These also have an effect on the strength of the core. Larger defects were usually repaired by the core manufacturer by bonding in a core plug.

Table 1:   Typical mechanical properties of materials used in the repair evaluation (manufacturers data).

	Material	Young's Modulus (MPa)	Shear Modulus (MPa)	Tensile Strength (MPa)	Shear Strength (MPa)	Density (kg/m³)
Skins	GRP (CSM/WR/CSM with vinilester matrix)	12000	2600	n/a	n/a	n/a
Core	Divinycell HT90 PVC Foam	52	20	2.6	1.2	90
Adhesive	Divilette-600®	1000	380	10	3	600

3.3 Type B Repair Specimen Fabrication

3.3.1 RAN Type B Repair Technique

In manufacturing the test specimens, a single panel was first fabricated from a 1900 mm x 850 mm sheet of Divinycell HT90 PVC foam. The skins were fabricated using the hand lay-up technique. One skin was laminated onto the foam then allowed to cure before laminating the other skin. The panel was then left to cure for about two weeks and then cut into three sections from which the reference, 300 mm and 400 mm span repair specimens were obtained.

The standard RAN repair for Type B damage was performed on the sections of the panel for the 300 mm span and 400 mm span specimens. Using a diamond, radial arm saw, cuts were made in the appropriate locations but only through the upper skin and core at an angle of 45°. The "damaged" skin and core were removed as shown in Figure 5. The skin was then taper sanded, using a pneumatic hand-held disk sander, in preparation for bonding the replacement skin. Since the skin consisted of only three plies, a taper of 20 mm per ply (rather than layer) was used, giving a total taper of 60 mm.

A new core section was then selected and cut using the radial arm saw to fit the repair area. An allowance of 1 mm was made for the bondline. Bonding of the replacement core was performed using Iso-Divilette® adhesive which was trowelled on the existing skin and core with a spatula to achieve an even covering. The replacement core was then fitted by placing one edge in position and slowly forcing it down to minimise entrapped air. Heavy weights were then placed on the repair to provide bonding pressure. Excess adhesive was removed from the surface.

Following the cure of the paste adhesive, the weights were removed and the join sanded flush. Replacement fibreglass was then cut to size allowing 20 mm overlap per ply for original plies, plus 100 mm overlap for the extra CSM ply. Hand lamination was carried out as described previously. After allowing approximately two weeks for complete cure, the 40 mm wide four-point-bending specimens were cut using the diamond radial arm saw. The specimen configuration and lay-up are shown in Figure 11.
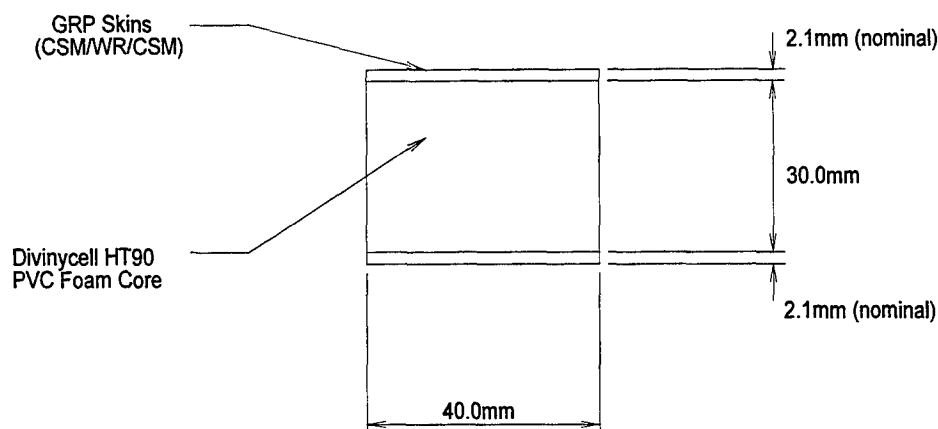
Figure 11:   Test specimen configuration.

Several features of the repair technique were difficult to perform. These related to the 45° bevel on the edge of the existing foam which needed to be accurate to ensure good fit of the replacement core and an even bondline thickness. It was found that the angle was difficult to maintain accurately on both the edge of the repair area and on the replacement foam. This difficulty would increase significantly under field conditions using hand held tools and on a repair with a curved profile.

The quality of the repair specimens was variable. Large voids in the bondline between the replacement core and the existing skin and existing core were noted in a number of specimens. These voids were visible from the sides of the specimens and through the translucent GRP skins. More than two thirds of the specimens had voids in the bondline which represented more than 5% of the total bondline area. One eighth of the specimens had voids which represented at least 50% of the total bondline area.

3.3.2 Modified Type B Repair Technique

A similar approach was used in the manufacture of the modified Type B repair specimens but this time the repair was two dimensional. Instead of a radial arm saw, an electric router was used to cut through the top skin and core in the appropriate positions leaving a "border" around the edge. Following removal of the "damaged" skin and core, the skins were taper sanded as before.

A new section of core was cut to fit the repair area allowing 1 mm all round for the bondline. Holes of 3 mm diameter were drilled through the core normal to the skins at 100 mm centres. The replacement core was bonded using Divilette-600® adhesive with the required mass calculated based on the volume of a 1 mm bondline. The adhesive was trowelled on to the existing skin and core with a comb type spatula to achieve an even thickness. The replacement core was then fitted by slowly forcing it down to minimise entrapped air. The repair was then covered with perforated release film, two layers of breather and a vacuum bag, after which a vacuum of 70 kPa was applied. The replacement skin was then laminated as described previously. Following cure, the four-point-bend specimens were prepared as before.

The quality of the specimens was very good. No voids were visible in the bondline between existing skin and replacement core. In some specimens, there were some small voids and porosity in the bondline between the replacement core and existing core.

3.4 Type C Repair Specimen Fabrication

3.4.1 RAN Type C Repair Technique

In the manufacture of the RAN Type C repair specimens, a similar approach was used as for the RAN Type B repair. The repair was again one dimensional and in this case the saw cuts were made through both skins and the core at the 45° angle. The skins were then taper sanded. The replacement core was cut in three sections: one large section and two smaller triangular sections (refer to Figure 7). To locate the replacement foam, a backing plate was used while bonding the core in place with Divilette-600®. Weights were placed on the repair and excess adhesive cleaned off before it cured. Following cure of the adhesive, the skins were laminated as before, allowing one to cure before applying the other. The 40 mm wide test specimens were then cut.

The RAN Type C repair method was difficult to perform, even under laboratory conditions. Again, the 45° joins were found to be particularly hard to prepare. These joins must be accurately cut for the repair to fit together well and to obtain a uniform, thin bondline. In some places, the triangular section of replacement core was proud, while in other places it was too low. On the positive side, the quality of the repaired specimens was good. Some specimens had voids in the bondline, the largest of which was only 7 mm in diameter. The majority of specimens appeared to be void free.

3.4.2 Modified Type C Repair Technique

In the manufacture of the modified Type C repair specimens, a similar approach was used as for the modified Type B repair. The repair was again two dimensional and in this case the router cut through both skins and the core except for a 10 mm lip which was left around the perimeter of the bottom skin. The skins were then taper sanded. The one-piece replacement core was cut and 3 mm diameter holes drilled through the edges (as shown in Figure 8) at 60 mm spacing. A bead of Divilette-600® was run around the lip, the core positioned and pressed down lightly. Care was taken to ensure that the bondline gap was even around the replacement core. This adhesive was allowed to cure to prevent the replacement core moving during the next stage. Using a caulking gun, adhesive was then injected through the holes in the core to fill the bondline. Excess adhesive was removed before it cured. Following cure the skins were laminated as before after which the 40 mm wide test specimens were prepared.

The modified Type C repair method was found to be straightforward to perform. The caulking gun method to inject adhesive into the bondline was easy to manage but did waste some adhesive. The quality of the specimens was very good with very few minor voids visible.

4. Test Results and Discussion

A minimum of three reference specimens for each repair type and span were tested. Six specimens for each repair type (B and C), span (300 and 400 mm) and position (Normal and Inverted) were tested. Results from only the 400 mm span four-point bend tests are presented in the following section as no significant differences were noted in the 300 mm span four-point bend tests.

4.1 Reference Specimens

The reference standards for each repair type and span exhibited consistent behaviour. Most specimens failed under the loading points through a form of local bucking called skin wrinkling, as shown in Figure 12. This failure mode was characterised by the load reaching a plateau then slowly dropping as the skin buckled, as shown in the load-displacement plot of Figure 13. The subsequent large drop in load was associated with failure of the skin under local bending. Approximately one third of the specimens failed by means of core shear between the inner and outer supports which indicates that these two failure modes occur at similar loads in this test configuration.

There was some variation in the strength of the different groups of reference specimens. This was mainly attributed to variations in the core density, which correspond to variations in the core strength and modulus, as well as minor variations in the properties of the skins. Assuming that the variations are consistent over the entire core sheet, the properties of the repaired specimens should only be compared

with the corresponding reference specimen properties as presented in this report (see later, Table 2 and 3).
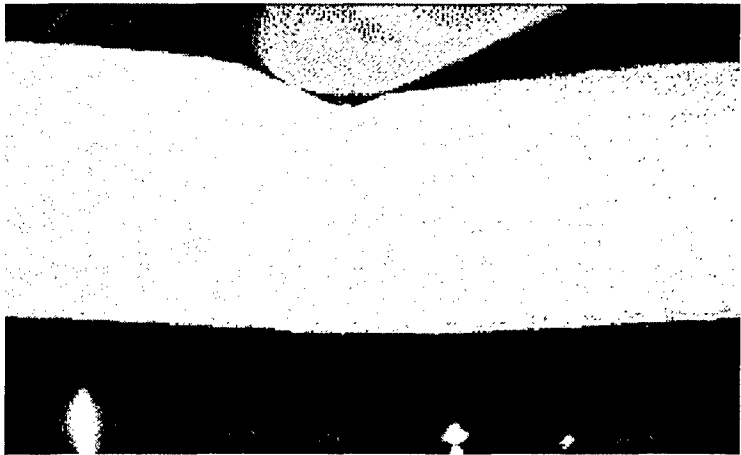

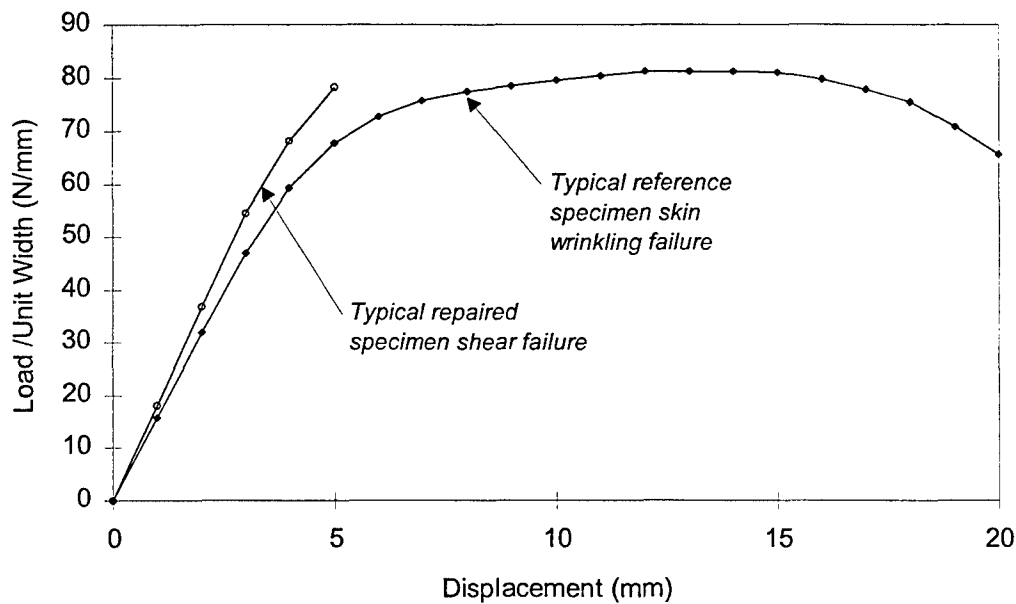*Figure 12:*   *Typical local skin wrinkling failure mode.*

Figure 13:   *Typical load-displacement curves for reference and repaired specimens. (Displacement is the relative displacement between the loading and support points of the four-point bending fixture.)*

4.2 Type B Repair Tests

4.2.1 RAN Type B Repair Technique

Some variability was observed in the behaviour of the repaired specimens tested in the normal position. The maximum load achieved was influenced by the integrity of the bond between the existing skin and the replacement core. All specimens failed through core shear, which initiated from a defect in the bondline in some of the specimens. The load displacement behaviour of a typical repaired specimen that failed under core shear is shown in Figure 14. The additional ply in the repaired skin in the region under the loading point also helped to prevent local failure through skin wrinkling. As shown in Figure 14, the core shear failure occurred between one support and loading point at a 45° angle (in the direction perpendicular to the maximum tensile stress). Core shear failure was characterised by sudden, catastrophic failure of the specimen. The skin was usually debonded from the core at either end of the shear failure.

A large degree of variability was observed in the behaviour of the repaired specimens in the inverted position. Most specimens failed through core shear but the maximum load carried depended on the integrity of the bondline. In a number of specimens, shear failure initiated from a visible defect in the bondline, an example of which is shown in Figure 15. One specimen in which the void covered approximately 50% of the bondline carried only 60% of the reference load. The position of the void as well as the void size influenced the load carried by the specimen. Other specimens suffered debonding of the original skin from the replacement core which, being under compression, proceeded to buckle as shown in Figure 16. One specimen failed through local skin wrinkling under the loading points.
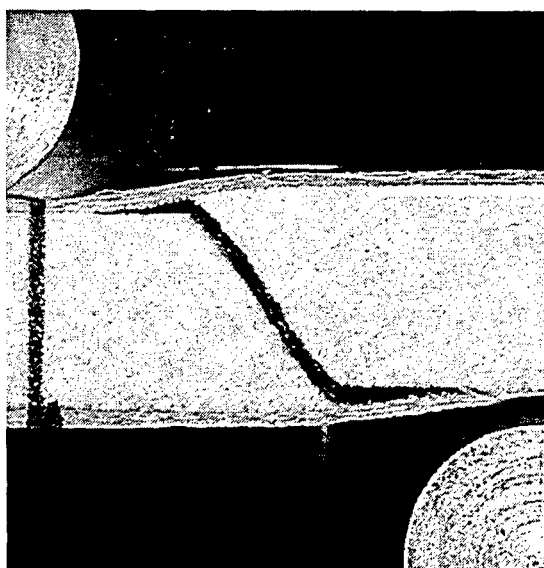
Figure 14:   Typical core shear failure in the normal position for specimens repaired using the RAN Type B method.
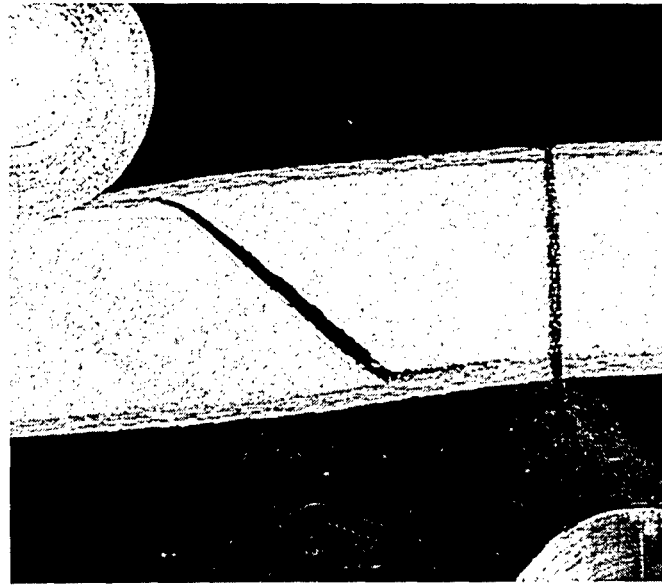
Figure 15: *Shear failure of a RAN Type B repaired specimen in the inverted position initiating from a defect in the bondline.*
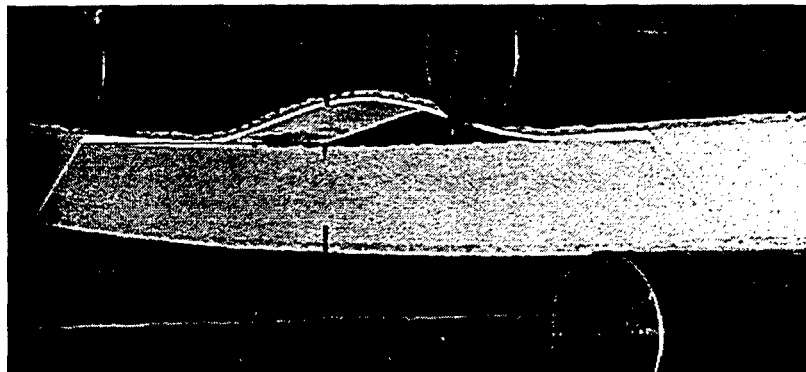
Figure 16: *Typical debonding failure of a RAN Type B repaired specimen in the inverted position.*

4.2.2 Modified Type B Repair Technique

The behaviour of the repaired specimens tested in the normal position was consistent with all specimens achieving a similar maximum load. Two specimens failed through local skin wrinkling while the remainder failed through core shear. The extra ply in the skin due to the repair in the loaded region helped prevent local skin wrinkling failure. One specimen was deemed to fail prematurely due to the presence of a void in the join between the existing and replacement core, as shown in Figure 17. This specimen failed at a load approximately 10% lower than the average. It was noted that in most of

the shear failure specimens, the core to skin debonding that occurred following failure at the ends of the core shear failure often resulted in some delamination in the skins.

Figure 17: Failure of modified Type B repaired specimen from a defect in the bondline.

Approximately half the repaired specimens tested in the inverted position failed through core shear and the remainder through local skin wrinkling. The core shear behaviour was very similar to that experienced with the specimens in the normal position. The only difference was that, due to geometry, the skin to core interface failure occurred either at the skin-Divilette interface, the Divilette-core interface or within the Divilette.

4.2.3 Discussion of the Type B Repair Technique Performance

The RAN repair technique for Type B damage was difficult to perform, even under laboratory conditions. The primary difficulty arose in finishing the core joints to a 45° angle which must be accurately maintained to ensure good fit of the replacement core and a consistently even, thin bondline. Under field conditions, preparing the repair area would be more difficult with the use of hand held tools. Additionally, repairs would normally have an elliptical profile. The modified method, which eliminated the 45° joins, was significantly simpler to prepare. The use of vacuum to bond the core into position added another step to the repair, but the results indicate that this additional process is justified in achieving excellent repair quality. Most facilities where such repairs would be performed would have access to vacuum equipment.

A comparison of the results for the 400 mm span Type B repaired specimens is presented in Table 2 and Figure 18. The superior performance of the modified Type B repair technique is clearly demonstrated. The averaged strengths of specimens repaired using the RAN Type B technique were up to 14% lower than the reference specimens when tested in both the normal and inverted positions. However, the scatter in results was much higher in the inverted position which was due to the

bondline between the core and the existing skin being positioned on the compression side of the beam. The 45° bondline was also under compression in the inverted case. This made the presence of any defects more critical as they tended to open up, buckle and grow under load. Generally, if the bondline were defect free, the strength of the repaired specimens exceeded that of the reference specimens due to the influence of the extra ply laminated in the repaired skin. However, the presence of defects seriously reduced the strength of the sandwich structure, especially when the affected bondline was under compressive loading. These tests demonstrated the importance of a defect-free restoration of a sandwich structure to produce an effective repair.

Table 2: Summary of the average strengths of Type B repair specimens.

Test Group	RAN Repair		Modified Repair	
	Number of Specimens	Maximum Load (N/mm)	Number of Specimens	Maximum Load (N/mm)
Reference	3	75.4 ± 0.6	3	73.2 ± 2.0
Repair -Normal	6	75.4 ± 1.3	6	78.0 ± 4.2
Repair - Inverted	6	64.5 ± 33.2	6	77.4 ± 1.2

The strengths of specimens repaired using the modified Type B technique were generally greater than the reference specimens. The average strength of specimens tested in both positions was up to 10% greater than the reference standards. The scatter in the results was also very low. This indicates that the bond strength of the repair was adequate while the extra ply used in the repair added to the strength.

The stiffness of the repair was also of importance since an overly stiff repair could lead to load redistribution and the potential for failure at the edge of the repair. The stiffness of the RAN Type B repair technique under four-point bending was approximately 10% and 20% greater than the reference specimens when tested in the normal and inverted positions, respectively. The modified Type B repair technique was approximately 8% stiffer than the reference specimens in both positions. In the RAN technique, the 45° bondline increased the shear stiffness of the core by a small amount. However, the most significant increase in stiffness was due to the extra thickness of the repaired skin, which was identical for both repair techniques. The additional skin thickness reduced local indentation under the loading and support points during four-point bending. The scarf repair on the skin in the RAN repair extended further than in the modified technique and, in the inverted case, extended under the support rollers reducing the amount of indentation. It was therefore concluded that the stiffness under bending of the two repair techniques was very similar.
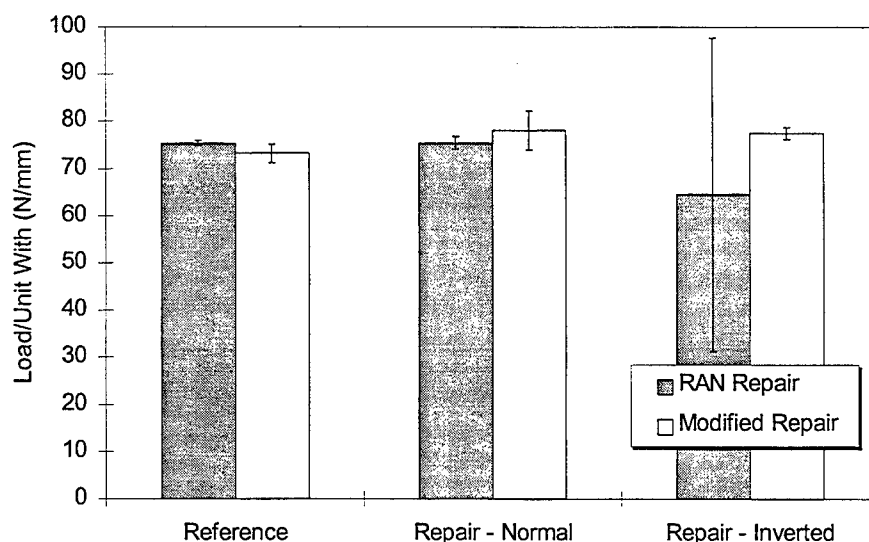
Figure 18: Bar graphs showing the average strength and standard deviation for Type B repaired four-point-bend specimens.

4.3 Type C Repair Tests

4.3.1 RAN Type C Repair Technique

The repair specimens tested in the normal position exhibited consistent behaviour. Just over half of the specimens failed through core shear while the others suffered interface failure between one of the 45° bondlines and the core, as shown in Figure 19. This mode of failure usually occurred in the core directly next to the bondline unless there was a void or porosity in the adhesive in which case it could run through the bondline. In most of the shear failure specimens, failure initiated from a crack in one of the 45° bondlines, as shown in Figure 20. It was observed that the adhesive failed under tension resulting in a crack which then propagated slowly into the core until catastrophic growth and failure occurred. The other shear failure specimens may have failed through a similar means which was not visible on the specimen edges.

The repaired specimens tested in the inverted position exhibited consistent behaviour and most failed under compression at the interface failure of one of the 45° bondlines. In a number of cases, the bondline could be seen opening up prior to failure. This mode of failure was identical to that experienced in specimens tested in the normal position as shown in Figure 19. One specimen failed through core shear which passed through a defect in the bondline.
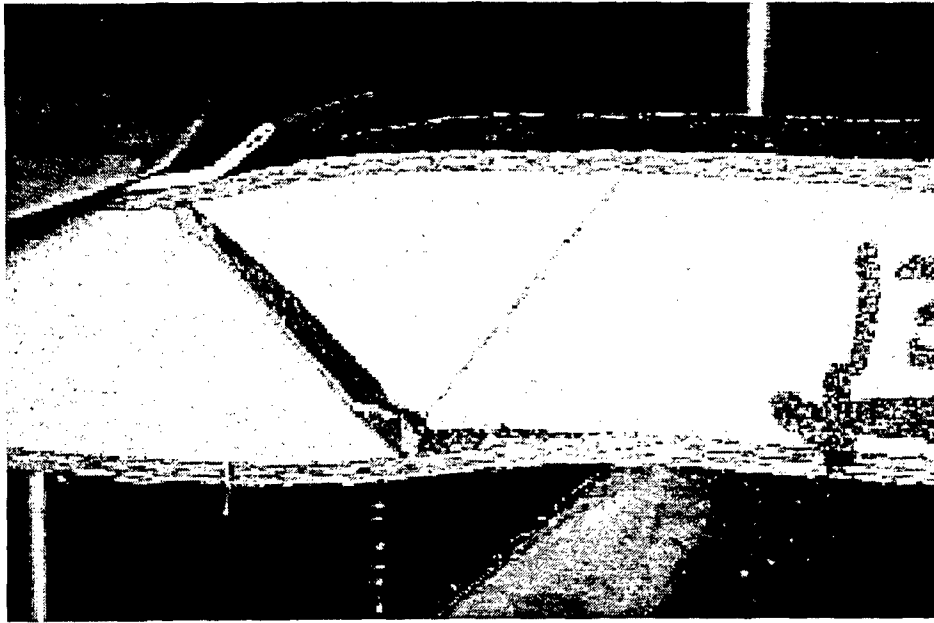
Figure 19: *Typical bondline interface failure of a RAN Type C repaired specimen tested in the normal position.*

Figure 20: *The crack (circled) which developed in the bondline in a RAN Type C repaired specimen tested in the normal position.*

4.3.2 Modified Type C Repair Technique

The repaired specimens tested in the normal position reached similar maximum load and failed through core shear which usually occurred as shown in Figure 21, running

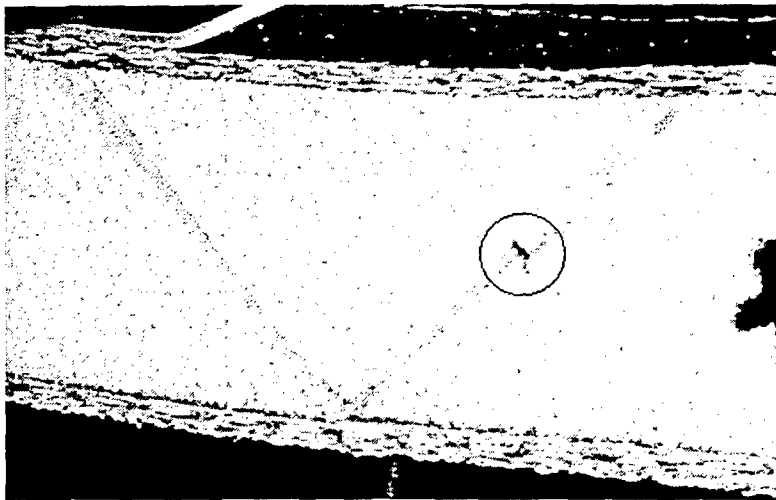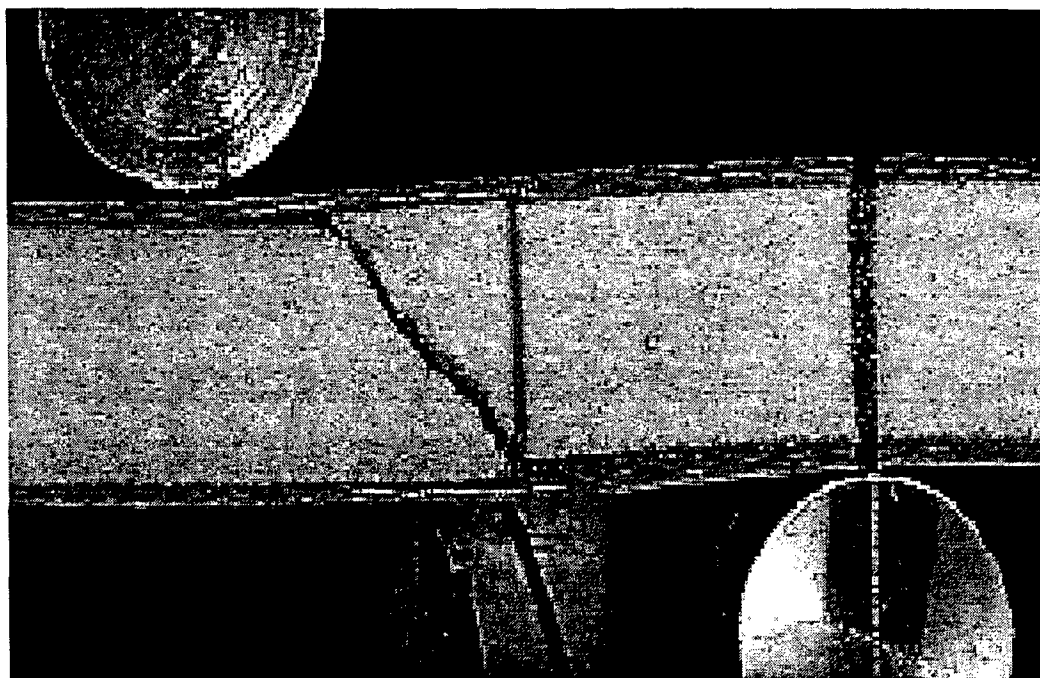through the bottom of the join in the core. One specimen failed through local skin wrinkling under the loading points.

Figure 21:   Typical shear failure of a modified Type C repaired specimen tested in the normal position.

The behaviour of the repaired specimens tested in the inverted position was consistent with all specimens achieving a similar maximum load before failing through core shear. In most specimens, a cracking noise was heard at 85% - 95% of the ultimate failure load associated with a crack developing in the adhesive that had filled the injection hole (refer to Figure 8). When tested in the inverted position, this column of adhesive, which was at an angle of approximately 45°, was loaded in tension. Thus, this adhesive column failed under tension in a similar manner to the 45° bondline in many of the RAN Type C repair specimens tested in the normal position. The presence of the crack created a stress concentration in the foam core which then proceeded to fail. This effect was observed in three specimens in which the column of adhesive was visible on the edge, as shown in Figure 22. It was likely that every specimen would have had an injection point on at least one end since they were at 60 mm spacing and the specimen width was 40 mm.
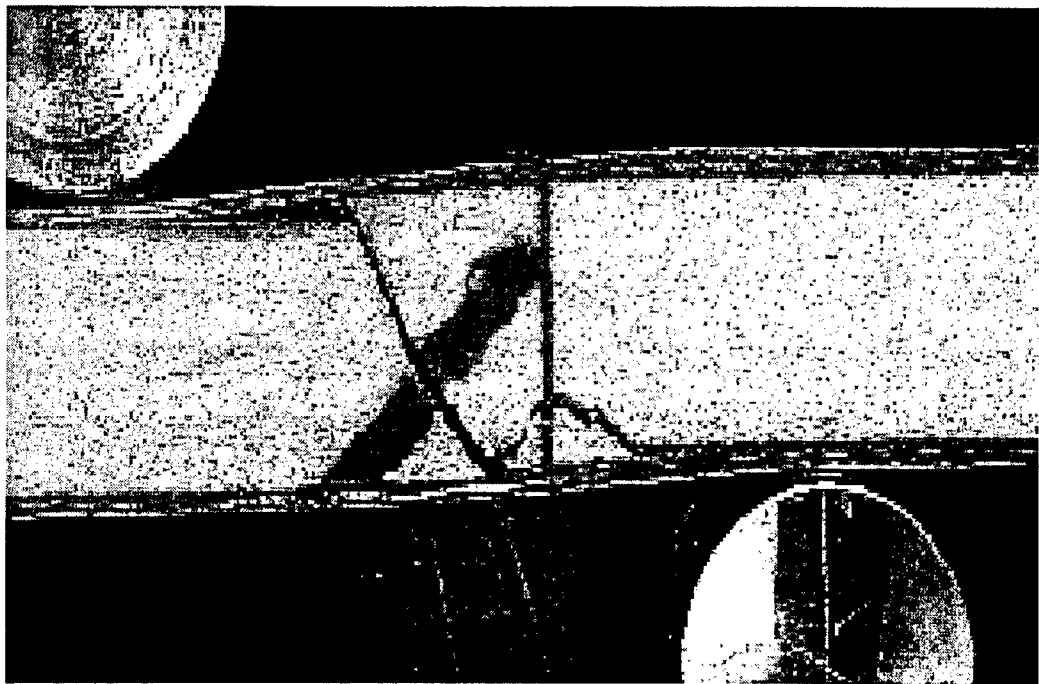
Figure 22: *Typical failure of a modified Type C repaired specimen tested in the inverted position showing failure initiation from a crack in the injection adhesive.*

4.3.3 Discussion of the Type C Repair Technique Performance

In preparing the Type C repair test specimens, it was observed that the RAN technique was more time consuming and demanding to prepare. A real repair which could be elliptical in shape would be very difficult because of the 45° joins in the core. On the other hand, the modified technique was very straightforward to perform. A comparison of the strengths of the two Type C repair techniques is shown in Table 3 and Figure 23 for the 400 mm span tests. It is apparent that in general, both repair techniques effectively restored the strength of the specimens and, with respect to the effectiveness of the repairs from a strength perspective, little separates the two methods. However, the modified method proved to be superior from a processing viewpoint.

Table 3: *Summary of the average strengths of Type C repair specimens.*

Test Group	RAN Repair		Modified	
	Number of Specimens	Maximum Load (N/mm)	Number of Specimens	Maximum Load (N/mm)
Reference	3	70.3 ± 1.3	4	72.3 ± 4.2
Repair -Normal	6	68.2 ± 2.0	6	78.3 ± 3.6
Repair - Inverted	6	76.5 ± 3.7	6	76.6 ± 0.7

100
90
80
70
60
50
40
30
20
10
0

Load/Unit With (N/mm)

RAN Repair
Modified Repair

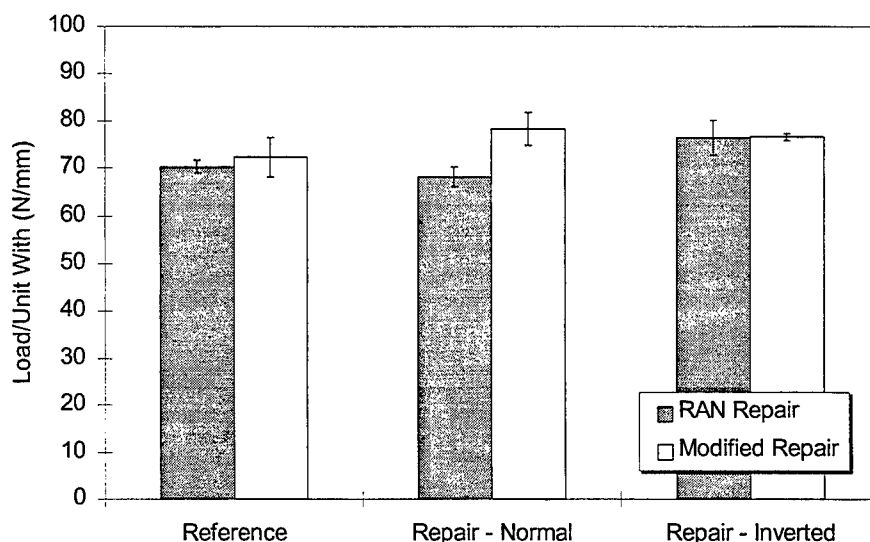Reference   Repair - Normal   Repair - Inverted

Figure 23: Bar graphs showing the average strength and standard deviation for Type C repaired four-point-bend specimens.

The strengths of the RAN repair technique for Type C damage were generally similar to, and in most cases greater than, reference standards. The reduced strength of some specimens was attributed to interface failure along the 45° bondline under compression. This indicated that the bondline between the existing and replacement core was the weak link in this repair. The standard deviation for the strengths was less than 5% in all cases indicating consistent repair quality.

The strengths of the modified Type C repair technique were also similar to, and in most cases greater than, reference standards. The strength of specimens loaded in the inverted position appeared to be affected by the failure of the column of adhesive in the injection points. This column failed under tension which then became a focal point that contributed to shear failure of the core.

An identified problem was the failure of the adhesive at a lower strain level than the core itself resulting in failure of the bondline when aligned with the direction of the tension component of the shear stress in the core. This failure process was the case with the core to core join in the RAN Type C repair, Figure 20, and the injection port in the modified Type C repair, Figure 22. Following failure of the bondline, a crack grew in the surrounding core, ultimately causing shear failure. To prevent such premature failures, the elongation to failure of the adhesive should exceed that of the core. In the case of a rigid, crosslinked PVC foam core, elongation to failure of the adhesive should be at least 5% [11]. Divilette-600® has an elongation to failure of 1.5-3%. Iso-Divilette®, and another product, the high performance Divilette-NQ®, have higher elongation to failure which could explain why this failure mode was not experienced during the RAN Type B tests.

The consequences of the adhesive failing at a lower elongation than the core material, however, may not be great. Variations in the strength of the core material of approximately 8% were noticed throughout the testing program. As mentioned in Section 3.2, a variety of manufacturing defects were also observed, some of which significantly affected the core shear strength. Manufacturing flaws in the foam core are likely to be a greater problem than the elongation to failure of the adhesive.

Similar conclusions can be drawn concerning the stiffness of the Type C repair techniques as for the Type B repair techniques. Hence, it can be stated that the stiffness of both repair types was similar.

5. Conclusions

The current recommended RAN repair techniques for the repair of Type B and Type C damage to GRP/foam sandwich structures have been evaluated. The RAN Type A repair technique was also indirectly evaluated as part of the other repairs. The performance of the repair techniques was judged both on the ability to restore the mechanical properties and on the ease with which it could be conducted.

The RAN Type B repair was found to be difficult to perform and resulted in a deficient bondline between the existing skin and the replacement core. Four-point-bend tests on repaired specimens indicated that the presence of voids in the bondline seriously affected the strength of the repair, especially when the void was positioned on the compression side of the specimen. A modified technique for the repair of Type B damage was proposed. This technique simplified several aspects of the repair procedure and improved the repair quality and repeatability. The core was replaced in one section and 90° butt joins were used. Holes were drilled through the replacement foam core to prevent air entrapment and vacuum bagging used when bonding the foam in place. Tests showed that the strength of specimens repaired using this technique exceeded the original strength.

The RAN Type C repair did result in a repair with sufficient strength, but was found to be difficult to perform. The modified Type C repair technique incorporated many of the simplifications used in the modified Type B repair. However, instead of using vacuum, the adhesive was injected into the bondline using a caulking gun. This method proved to be capable of restoring the strength to the sandwich structure. However, it was observed that the adhesive used in the repair should have an elongation to failure that exceeds that of the core material. The results of these tests demonstrated that the modified repair techniques were easier to prepare and more reliable than the current RAN recommended repair techniques.

6. Acknowledgments

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19. ABSTRACT

Marine vessels constructed from sandwich panels with glass reinforced polymer (GRP) composite skins and PVC foam core are now common. Such structures will inevitably be subjected to damage and any repair technique needs to ensure that the strength and stiffness of the structure are restored. The current recommended Royal Australian Navy (RAN) techniques for the repair of sandwich structures have been evaluated and deficiencies identified. Static tests conducted under four-point bending indicate that the presence of voids in the bondline seriously affect the strength of the repair. Modified repair techniques are proposed to simplify the repair procedure while improving the repair quality and repeatability. The test results show that the modified techniques overcome the problems associated with the RAN repair techniques.