Repair of Damage to Marine Sandwich Structures: Part II - Fatigue Testing

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ABSTRACT

Sandwich construction panels, comprising glass reinforced polymer (GRP) composite skins and PVC foam core, are in use in the current generation of naval vessels of the minehunting class. Such structures will inevitably be subjected to damage and any repair techniques need to ensure that the strength, stiffness and resistance to fatigue crack initiation of the structure are restored. In a previous study the recommended techniques, outlined in Defence Instruction (Navy) ABR 5803 for the repair of sandwich structures, have been evaluated under static four-point bending and deficiences in the repair techniques which affected sandwich strength and stiffness were identified. A modified repair technique was proposed to simplify the repair procedure for GRP sandwich panels and to overcome the problems associated with RAN repair technique. In this study the repair techniques were scrutinised by measuring the cracking resistance of repaired sandwich panels under fatigue loading. The modified repair technique, in comparison with the RAN repair technique, was found to fully restore the fatigue cracking resistance of sandwich construction panels to the level observed for the undamaged panels.

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Executive Summary

Glass reinforced polymer (GRP) composites are now widely used in a variety of applications. For naval applications, certain vessels (e.g. minehunting vessels) are built using composites in a sandwich configuration, which has proved to be a very efficient method of ship construction. A sandwich structure basically consists of three parts; two stiff and relatively high-density GRP skins or faces separated by a thick, light and structurally weaker core. This provides a composite structure that is usually much stiffer than the sum of stiffnesses of individual components.

Present and future RAN vessels, constructed using such composite materials, could experience damage to hull and superstructure by either long-term fatigue or accidental impact. To repair such damage the RAN has issued a repair manual, Defence Instruction (Navy) ABR 5803 specifying a repair method which is primarily based on the experience of other navies. This method was examined by AMRL and compared with a simplified repair technique, developed previously by this laboratory, in terms of efficiency and practicality in restoring mechanical properties of the repaired structure.

The repair techniques and test results obtained using both methods in a *static* test program were presented in a DSTO Technical Report DSTO-TR-0736. This present report extends the above study and compares the two repair methods in terms of flexural fatigue resistance of foam sandwich specimens subjected to *cyclic* loading. This limited-cycle test program demonstrated that the AMRL repair method produced a repaired structure with a higher fatigue resistance than that resulting from using the original repair procedure, while being simpler and faster to carry out. Moreover, the repair technique fully restored the fatigue performance of the sandwich construction panels to the level observed for the undamaged reference panels.

The outcome of this work is the development of a reliable and cost-effective repair procedure for foam/sandwich composite structures. This repaired structure is stronger and more durable than those produced using the existing repair techniques.

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***Dr. M.Z. Shah Khan** is currently a Senior Research Scientist in Maritime Platforms Division. He has researched on the fracture and fatigue behavior of metallic materials in support of the structural integrity of Army platforms and Naval Ships. His current interests are in the study of fracture, fatigue and behaviour under dynamic loading rates of naval composite materials.*

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1. Introduction

The technique designed for repair of damage to the Bay Class minehunters (Minehunter Inshore, MHI) was the focus of previous studies [1 and 2]. The aim of that work was to evaluate standard repair techniques for GRP vessels manufactured from GRP skins and poly vinyl chloride (PVC) foam core. Two repair methods were assessed, the standard repair technique [1] and a modified repair procedure [2]. The static test results of defect-free repairs (Type B and Type C) showed a complete restoration of flexural strength in all test panels. Although, the effectiveness of the repairs from a strength perspective showed no significant differences, the modified repair procedure developed for type B and type C damage is considerably simpler, easier to perform and more economical. This replacement procedure eliminates problems encountered in the standard repair. The modified repair technique also increases the quality of repair by minimising defects in the bondline occurring due to air entrapment [2].

In this article, an extension of the mechanical property assessment work focusing on cyclic fatigue testing is described. The study converges on the longer-term behaviour of cellular foam core materials [3] when the foam sandwich beams are subjected to fatigue loading. In the sandwich structure studied, the foam core material is the weakest element. Thus, specimen failure is manifested through various mechanisms closely associated with core shear fracture, excessive shear deformation of the core, adhesive failure at the core/skin interface or any combination of above.

For most anisotropic composite sandwich materials the fatigue process is characterised by initiation and multiplication of cracks rather than propagation to fracture as seen in metals. The durability of these structures under cyclic loading is therefore determined by the intensity of damage accumulation (crack multiplication) which unlike in metals decelerates before final fracture. A comprehensive study of fatigue behaviour of MHI foam sandwich structure would require a large collection of test specimens evaluated over a prolonged period of time. In this study specimen failure point coincided with the onset of load reduction which is identified here as a crack initiation point. The fatigue results presented are considered indicative since only a limited collection of load/cycle data was obtained. Nevertheless, the results clearly show the trend and relationship between strength/stiffness reduction and fatigue life for a given specimen loading condition.

2. Experimental

The test specimens assigned for fatigue performance study were from the same batch as those used in the previous study concerned with static testing [2]. The GRP skins were laminated from 300 g/m^2 chopped strand mat (CSM), 600 g/m^2 woven rovings (WR) (ACI Fibreglass), using Dow Derakane® 411-C50 vinylester resin (Dow Chemicals (Aust) Ltd). The lay-up of glass reinforcement was CSM/WR/CSM that resulted in a nominal thickness of 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. Typical mechanical properties of the materials used in the test program are given in Table 1.

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

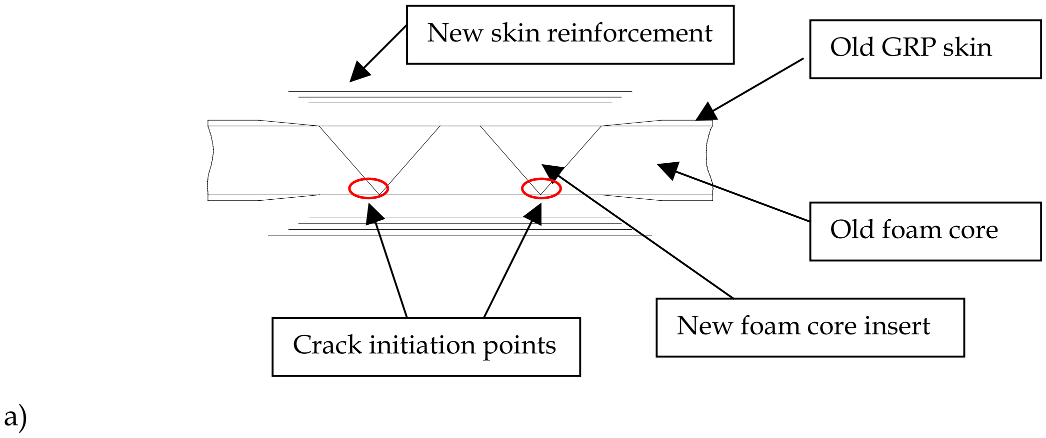
	Material	**Young's Modulus (MPa)**	**Shear Modulus (MPa)**	**Tensile Strength (MPa)**	**Shear Strength (MPa)**	**Density (kg/m³)**
Skins	GRP (CSM/WR/CSM with vinylester matrix)	12000	2600	n/a	n/a	n/a
Core	Divinycell HT90 PVC Foam	52	20	2.6	1.2	90
Adhesive	Divilette-600®	1000	380	10	3	600

The types of damage were designated as Type B and Type C. A Type B damage is limited to one skin and the core whereas Type C damage covers both skins and the core. In the repair of each type of damage, a standard technique and a modified technique were applied. A third batch of specimens in this study belonged to a reference batch, which had no damage.

The differences between the standard and modified repair techniques are shown in Figure 1 and and given in reference [2]. The standard repair method requires adhesive bonding between the existing core and the new replacement core material to be made at a 45° angle. This applies to both Type B and Type C repair, Figure 1(a). However, in practice the laboratory experiments showed that preparing the core at a 45° angle proved to be difficult. The second problem especially in Type B repair is that the entrapment of air between the replacement core and the existing skin can easily occur during the bonding process.

To overcome these problems the modified repair procedure was developed for Type B and Type C damage. This was achieved by replacing damaged core with the new, one-piece replacement material (whenever possible) and using 90° butt joints, Figure 1(b). Laboratory experiments also showed that the entrapment of air is avoided if holes are predrilled through the core at spacing between 50 mm and 100 mm. All entraped air between the core and the existing skin (Type B repair) is removed through the holes drilled in the replacement core when the repair is placed under vacuum bag. This technique proved to be considerably simpler, easier to perform and more economical than the standard repair method.

High-cycle fatigue (>10^3) was carried out at the frequency of 0.4 Hz using a sinusoidal waveform. A stress cycle, N=1, constitutes a single application and removal of a load followed by another cycle in the opposite direction. Specimen load application was carried out through a preset specimen deflection parameter (ie. constant amplitude) which corresponded to a specific load magnitude. This load/deflection relationship (linear range) for undamaged specimens was evaluated separately as part of static 4-point bend test procedure. Therefore, a fatigue strength (S_f) level of 55 N/mm relates to the load applied to a 40mm wide specimen (2.2kN) which in turn corresponds to specimen deflection of 10mm (The 250kN dynamic load cell, used for these tests, lacks adequate sensitivity in the load ranges characteristic of the test specimens).



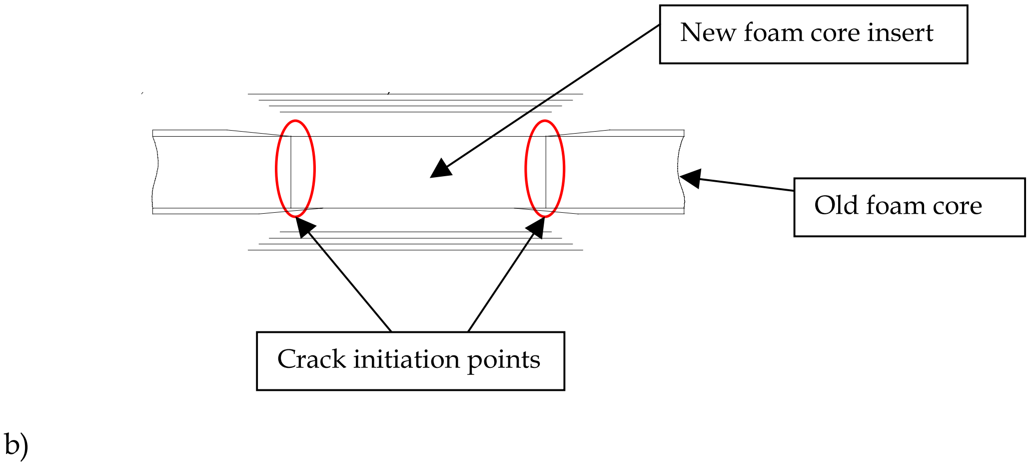


Figure 1. Fatigue crack initiation points for the two Type C repair procedures:

a) standard repair method
b) modified repair method

3. Results and Discussion

This report covers the flexural fatigue work on foam sandwich composites with damage types designated as Type B and Type C. In specimens from the reference batch, complete fatigue fracture occurred immediately following crack initiation and therefore, fatigue life results represent cycles-to-total failure. The fatigue life results from tests on the standard repair and the modified repair specimens belonging to Type B and Type C batches represent cycles-to-crack initiation

- ***Type "C" repair***

A graphical presentation of fatigue results for all three classes of specimens, ie. reference, standard repair and modified repaired specimens are given in Figure 2.

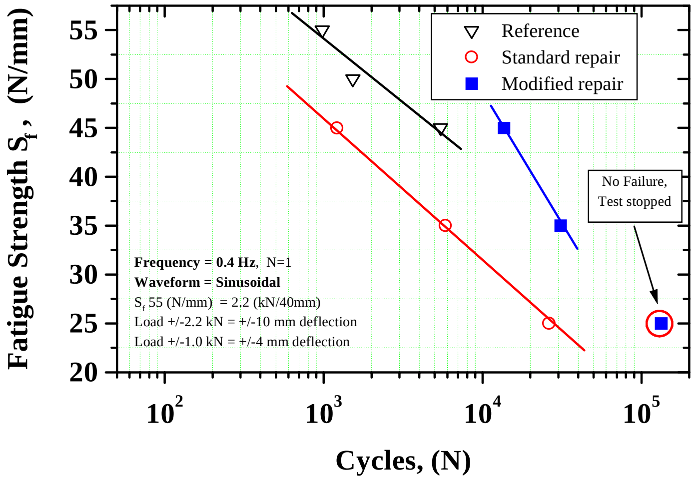


Figure 2. Fatigue cycles-to-crack initiation for GRP/Foam sandwich specimens, Type "C" repair.

The fatigue results, shown in Figure 1, clearly indicate approximately an order of magnitude higher fatigue resistance (number of cycles, N) for specimens repaired as per the modified repair method in relation to those repaired by the standard procedure. The selected fatigue strength range, S_f = 25 - 45 N/mm, produced crack initiation, (ie. specimen failure point) in all repaired specimen except for one modified repair specimen tested at 25 N/mm which resulted in "run-out", ie. did not develop fatigue failure. The results for the reference specimens relate to the fatigue strength obtained at higher loads and are not directly comparable to those for the repaired samples. Although, at one point, S_f = 45 N/mm, the data lies between the two points for the repaired specimens, additional data points tested at the 35 and 25 N/mm level will inevitably cause the "run-out effect" for the reference specimens and thus produce unquantifiable results. Insufficient data exist to correlate fatigue cycles to failure (N) determined at different fatigue strengths (S_f), however, it is reasonable to assume that the order of fatigue performance of specimens restored by different repair methods is as follows: modified repair > standard repair. In addition, as the data at 45 N/mm indicates, the modified repair performance exceeded even that of the reference.

All repaired specimens failed by crack initiation within the adhesive bondline as indicated in Figure 1(a) and 1(b). The specimen reconstructed as per standard repair tends to initiate adhesive bondline cracking at the roots of "V" profile (foam core inserts), Figure 2 a). Similarly, modified repair specimens also developed crack initiation in the adhesive bondline, between the old and new foam core material, Figure 1(b).

- ***Type "B" repair***

The fatigue results showed that the modified repaired specimens, when compared with standard repaired specimens, had significantly higher fatigue life both in terms of cycles-to-crack initiation and cycles-to-total failure, see Figure 3. Unlike the difficulty of comapring the reference data with the Type C repair data, the reference data along with the Type B repairs data falls within the range of the standard and the modified repair data and hence provide easy comparison. In both batches, the crack initiation was in the adhesive bondline.

As evident from the above results, the nature of the fatigue test often produces considerable scatter of results. The observed scatter of results is especially true for the foam sandwich structures, which have, in a sense, a physical arrangement of a number of elements all with different mechanical properties. In fatigue testing, the weakest link in such a structure will cause premature failure, which is often further exacerbated by imperfections in material quality and manufacturing defects. The results obtained for the Type B and Type C repaired specimens certainly suggest that the presence of such factors had a varied degree of effect on specimen failure and the scatter of results. By increasing the sample population, the scatter and the standard deviation can be reduced, but the observed trend is not expected to change significantly over several orders of magnitude in cycle life.

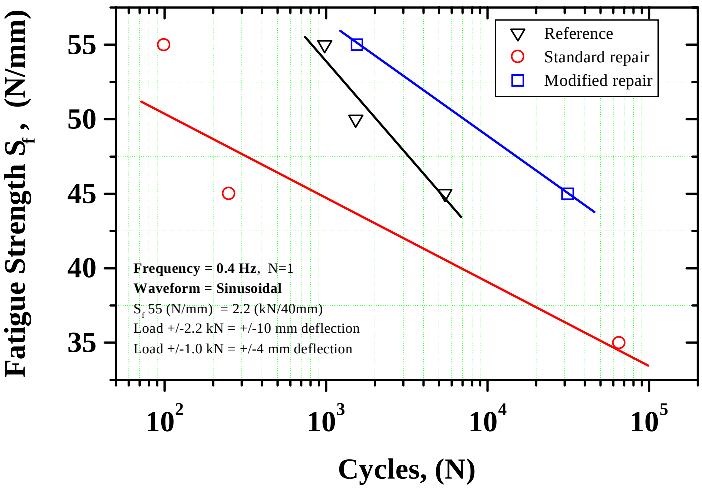


Figure 3. Fatigue cycles-to-crack initiation for GRP/Foam sandwich specimens, Type "B" repair.

4. Conclusion

The results from this study clearly indicate that the modified repaired foam sandwich composite specimens, irrespective of the type (B or C), have far superior fatigue resistance than the standard repaired specimens. Because of this, the modified repair technique should be endorsed as an improvement over the standard repair technique for the foam cored sandwich GRP naval structural material.

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19. ABSTRACT

Sandwich construction panels, comprising glass reinforced polymer (GRP) composite skins and PVC foam core, are in use in the current generation of naval vessels of the minehunting class. Such structures will inevitably be subjected to damage and any repair techniques need to ensure that the strength, stiffness and resistance to fatigue crack initiation of the structure are restored. In a previous study the recommended techniques, outlined in Defence Instruction (Navy) ABR 5803 for the repair of sandwich structures, have been evaluated under static four-point bending and deficiences in the repair techniques which affected sandwich strength and stiffness were identified. A modified repair technique was proposed to simplify the repair procedure for GRP sandwich panels and to overcome the problems associated with the RAN repair technique. In this study the repair techniques were scrutinised by measuring the cracking resistance of repaired sandwich panels under fatigue loading. The modified repair technique, in comparison with the RAN repair technique, was found to fully restore the fatigue cracking resistance of sandwich construction panels to the level observed for the undamaged panels.