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Polyurethane Sandwich Panel Systems for Ship Hull Reinforcement

Benjamin P Withy
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ABSTRACT

The Royal New Zealand Navy (RNZN) regularly patrol the waters of the Sub-Antarctic Islands and the Southern Ocean in support of the Department of Conservation and Ministry of Primary Industries. Operation in these waters includes the potential presence and threat from ice, and RNZN Offshore Patrol Vessels are protected against ice with a belt of thicker steel about the waterline. Excessive pitch and roll of vessels can however result in thinner and more vulnerable areas of the hull being exposed to sea ice.

Defence Technology Agency were tasked by the RNZN to evaluate whether there was potential to enhance the level of ice protection on vessels through the use of a polyurethane cored steel faced sandwich panel system that has recently been offered by commercial suppliers. This report summarises mechanical testing undertaken to explore the viability of this type of sandwich panel system. Testing included shear, flexure and impact testing across the likely temperatures that the system would be operationally exposed to, as well as fatigue and corrosion testing.

Results of the tests indicate that a polyurethane cored steel faced sandwich panel system is a viable solution for hull reinforcement, and raised a number of recommended questions that should be answered by any prospective supplier of a solution to the RNZN.

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EXECUTIVE SUMMARY

BACKGROUND

Ice belting on the RNZN Offshore Patrol Vessels (OPVs) meets Lloyd's Register requirements. Defence Technology Agency (DTA) were tasked to determine whether the ice belting could be upgraded through retrofitting polyurethane sandwich panels to the hull of a vessel. To determine validity of the concept and discern what questions remain of such a system DTA undertook the work summarised within this report.

AIM

Determine whether polyurethane core steel faced sandwich panels are a potential method by which the ice belt protection on the hulls of RNZN OPVs may be extended or upgraded.

RESULTS

Flexure and impact loads were determined to be the key service loads that the polyurethane sandwich panels would need to react, and as such, were the focus of this research. The properties of both full scale and scaled down polyurethane sandwich panels were determined at a range of temperatures expected to be met in operating the OPVs.

The resin core in the Intelligent Engineering system is not available for sale in New Zealand. A review of Lloyd's Registry rules and open literature provided details of resins that would be suitable for the core. Down selection of two potential resins from a local supplier identified a reasonable core material.

Flexure properties tested at low deformation rates were found to be highly temperature dependant, with greatest strength at specimen temperatures of -20°C, and weakest at 50°C. These changes are due to the variation of the core properties with temperature, as steel properties are constant over this temperature range. Even in the weakest instances the strength of the sandwich panel was ten times greater than that of the hull skin alone and twice as great as the equivalent mass of steel.

Impact strength of the sandwich panel system was evaluated through the use of Charpy impact testing. Un-notched specimens typically resulted in a disbond between the impact face and the underlying resin, whilst notched specimens essentially had no greater strength than a single steel skin. In no circumstances (notched or un-notched) did the rear face of the impact specimen fracture, indicating that even after an impact that caused delamination of the outer skin, the hull would remain water tight.

A brief series of flexure fatigue tests demonstrated that interfacial failures can occur as a result of cyclic loading and appropriate design will be required to ensure that loads in the hull are below the fatigue limit of the system.

DISCUSSION

Whilst testing was conducted over the temperature range of -20°C to 50°C, hull temperatures are only likely to range from -2°C to 30°C.

Failure within the resin was observed in flexure tests when samples were at maximum deflection, equivalent to 150 mm deflection between supports at 500 mm spacing (the spacing of the hull frames). Hull deflections of 150mm between individual frames would require drydock repairs, so resin failure in this instance is not a concern. At elevated temperatures (35°C and 50°C) resin failure occurred after an equivalent full scale deflection of 100 mm however as already stated opertional temperatures are only likely to reach 30.

Whilst Charpy testing indicated that if the outer skin is cracked through impact resistance is only equivalent to the resistance of the internal skin, this represents a long crack scenario. In reality a penetrating hull crack would not extend a long distance and the resin would transfer load to the non-cracked areas of the outer skin, giving improved impact performance over a single skin.

The effect of hull cracking and sea water penetration of the outer skin and resultant corrosion on the mechanical properties of the sandwich panels was investigated. Samples immersed in 3.5% NaCl solution for 1, 2 and 3 weeks showed no decrease in flexure, impact or fatigue properties.

Application of the sandwich panel system with an 8 mm thick steel outer skin would add approximately 85 kg/m^2 to the application area. This is equivalent to adding an extra 11 mm of steel to the hull thickness. The sandwich panel system would provide a minimum increase of yield strength twice that of the equivalent additional steel. Retrofit of the sandwich panel system would also be faster and involve less hot work than welding new thicker steel plates to the hull.

Whilst this work was conducted with the concept of ice hardening of a vessel it should be noted that ice strengthening is only a small part of ensuring a vessel meets ice class.

CONCLUSIONS

Results indicated that polyurethane core steel faced sandwich panels are an effective way to provide additional strength and stiffness to a platform. A benefit of the system is significantly less welding than a conventional repair or retrofit.

In addition to the potential to increase the stiffness and strength of a vessel hull, a sandwich panel system could also be used to strengthen vehicle decks or flight decks to accommodate additional loads beyond the original design.

Further, the results indicated potential weaknesses of this type of system, including increased maintenance complexity and temperature sensitivity.

RECOMMENDATIONS

Preference should always be given to manufacture/acquisition of the required ice class over retrofit where possible.

If retrofit of an existing hull is determined to be required, any supplier should be required to provide, at a minimum:

- Details about the mechanical properties of the sandwich panel system throughout the temperature range that is likely to be operationally experienced by the vessel.
- Evidence that at the design loads of the system the panels will not suffer fatigue failures within the expected design life of the vessel (as specified by NZDF).
- Evidence that impact with submerged containers in the tropics and bergy bits or growlers in the Southern Ocean will not result in penetration of the hull.
- Evidence of the level of stresses, both residual and in service, resultant from the thermal expansion coefficient differences between the steel skins and resin core.
- A maintenance plan for both the internal and external hull that takes into account the sandwich panel system.

SPONSOR

DNC CHRISTOPHER HOWARD

CONTENTS

1. Introduction

The RNZN regularly patrol the waters of the Sub-Antarctic Islands and the Southern Ocean in support of the Department of Conservation and Ministry of Primary Industries. Operation in these waters includes the potential presence and threat from sea ice, growlers (glacier ice protruding less than 1 m from sea surface and less than 5 m in length) and bergy bits (glacier ice protruding from 1 – 5 m above sea surface and 5-15 m in length) [1].

The RNZN offshore patrol vessels are constructed to Lloyd's Register rules for ice-class, which provides a belt of thicker steel around the nominal waterline of the vessel, increasing resistance to deformation and penetration from impacts with ice. The pitch and roll of the vessels in heavy seas can however result in thinner and more vulnerable areas of the hull being exposed to sea ice.

DTA were tasked by the RNZN to evaluate whether there was potential to enhance the level of ice protection on vessels in those areas not already protected by localised thickened hull plating.

The company Intelligent Engineering have commercialised a product, Sandwich Plate Systems, that might be suitable to retrofit reinforcing on RNZN hulls. The system has Lloyd's Register rules associated with it for use on ships. DTA were unable to source test material from Intelligent Engineering, but based upon information in open literature enough details were available to produce a reasonable facsimile in order to evaluate the potential of such a system for the RNZN.

DTA initiated a collaborative research project with AUT to determine the mechanical properties that could be achieved in a steel polyurethane sandwich structure. This investigation included research into possible core resins, appropriate surface preparation, bonding strength and mechanical properties of the steel polyurethane sandwich panels. The research work spanned two years and two student final year projects at AUT University. The first report [2], was completed by ENS Meyrick Pereira in 2014. The second report [3], was completed by Mr Daniel Tat in 2015. DTA technical memorandum C1308 [4] summarises Reference [2], whilst this report will summarise the work as a whole.

2. Materials selection and evaluation

2.1. Polyurethane

The material properties of the cured core resin were required to meet specified density, hardness, shear modulus, tensile stress, elongation and bond shear strength as determined by Lloyd's Register Provisional Rules for the Application of Sandwich Panel Construction to Ship Structure [5] as summarised in Table 1.

Test	Standard	Criteria
Density	ISO 845	≥ 1000 kg/m^3 at RT
Hardness	DIN 53505	Shore D ≥ 65 at RT
Shear Modulus	Torsion pendulum test -20°C to 80°C DIN EN ISO 6721-2	G ≥ 312 -2.4T °C
Tensile Stress	ISO 527 or ASTM D412	≥ 20 MPa at RT ≥ 5 MPa at 80°C
Elongation	ISO 527 or ASTM D412	Min. 10% at -20°C Min. 20% at RT
Bond Shear Strength	ASTM D429-81	≥ 2.7 MPa (shot blasted) ≥ 4 MPa (grit blasted)
		RT = room temperature in °C

Table 1. Required properties of the cured resin as per Lloyd's Register rules [5].

DTA entered discussion with local resin suppliers, and Era Polymers were able to provide two resins that broadly matched the requirements outlined in Table 1. Both resins were two part polyurethanes formed from polyol and isocyanate precursors. The two resins were Eracast TLS65D (henceforth TLS) and Eracast XPE12-1611(henceforth XPE). For both resins the primer Erabond Metal Red was recommended to improve bonding to the steel substrate.

2.2. Steel

Typically naval vessels are constructed from D-grade steel. For the purpose of this research a generic low carbon mild steel was selected. This choice of alternative steel had no impact on bond strength or quality and significantly lowered the cost of the test program.

2.3. Methods of Evaluation

2.3.1. HARDNESS

The hardness of the cured polyurethane resin was determined through use of a Shore D durometer. These hardness measurements were also used to determine the time after which full cure of the polyurethane was achieved.

2.3.2. LAP SHEAR

Lap shear tests were conducted to evaluate the efficacy of the primer and the bond strength of the resin to the substrate. The mechanical properties of the polyurethane core will be affected by the temperature more so than the steel. The operational envelope of the OPVs includes a wide range of environmental conditions, from the Antarctic to the tropics, which the test conditions need to reflect. Southern Ocean air temperatures can be expected to be as low as -20°C. Conversely, in the tropics, sea and air temperatures can be in the high twenties, and deck temperatures can reach and exceed 50°C due to radiant heat absorption from the sun. Test temperatures of relevance to RNZN ships are summarised in Table 2.

Test Temperature	Description
-20°C	Lowest expected air temperature in the area that RNZN ships are expected to patrol.
-2°C	Typical sea temperature when sea ice is present.
20°C	Intermediate test temperature. Sea temperatures will often be between 10°C and 20°C around NZ.
35°C	Intermediate test temperature
50°C	A high test temperature. Superstructure temperatures over 60°C have been measured due to radiant heating from the sun. No hull temperatures were able to be sourced.

Table 2. Summary of test temperatures used and the reason for that temperature selection.

2.3.3. THREE POINT BEND TEST

Three point bend tests were conducted to evaluate the sandwich plate system in a similar situation to load on the external hull from sea ice or other in-water objects including semi-submerged containers and reefs.

Full scale test specimens were constructed from 8 mm steel (equivalent to the thickness of the OPV hull) and at a support spacing of 500 mm (equivalent to the OPV internal support spacing). Testing was conducted at the same temperature set as summarised in Table 2.

Scaled down test specimens were also used for some testing. These specimens were constructed from 2 mm steel with a 5 mm thick polyurethane core. Specimens and their dimensions are displayed in Figure 1 and Table 3 respectively.

2.3.4. CHARPY IMPACT TEST

Charpy impact tests were conducted to evaluate the resistance to impact of the sandwich panel system. The Charpy was deemed relevant as the impact velocity is similar to that of a ship operating in sea ice. Furthermore, it is an established technique where the results can be standardised and compared to literature results. As with the lap shear and three point bend testing, tests were conducted with specimens heated or cooled to the temperatures listed in Table 2.

2.3.5. FATIGUE TEST

Fatigue testing was conducted to determine whether cyclic loading was likely to cause failure of the system. As with other mechanical properties flexure was determined to be a key loading criteria so a three point bend fatigue test was conducted. Constant amplitude loading with a ratio of Minimum load/Maximum load of 0.1 was selected for simplicity of testing.

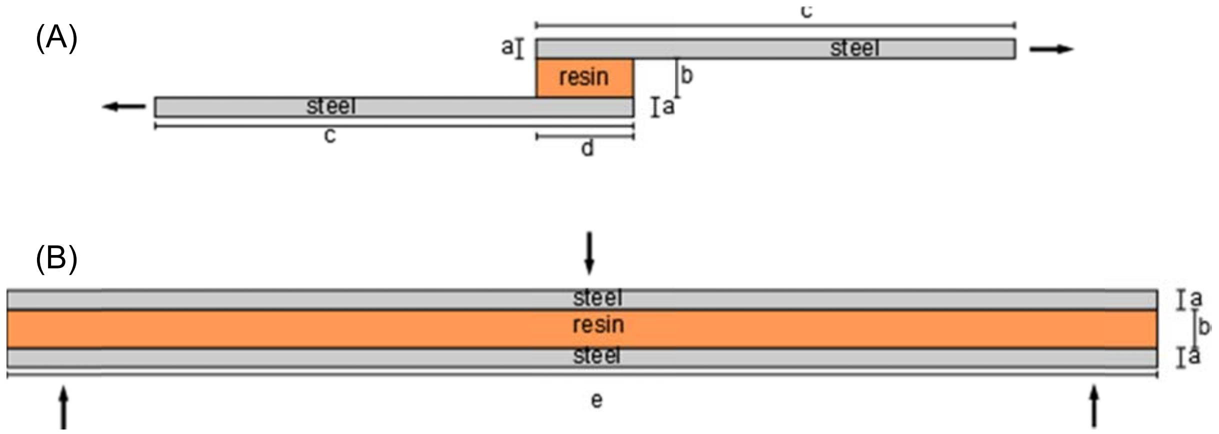

Figure 1. Lap shear (A) and three point bend (B) test specimen schematics.

Measurement	Full scale specimens (mm)	Scaled specimens (mm)
a	8	2
b	20	5
c	250	No scaled lap shear
d	50	No scaled lap shear
e	200	175

Table 3. Measurements of the test specimens as displayed in Figure 1.

3. Results

3.1. Surface preparation

The Lloyd's Register rules [5] required that the surface of the steel be grit blasted to achieve a minimum surface roughness of Rz = 60 µm and a minimum cleanliness of Swedish Standard Sa2.5.

In order to keep preparation as close to industrial reality as possible, the plates were grit blasted by the RNZN maintenance contractor Babcock NZ using standard practise. The surface roughness of the blasted specimens was evaluated using a surface profilometer. The results showed that surface roughness was consistently greater than the required level, and the roughness of the primed surface was nearly at the specified level (noting that the roughness of the primed surface was not required to exceed 60 µm).

The cleanliness of the surface was assessed visually and compared to pictorial guides and descriptors of the cleaned surface. The grit blasted surfaces were all determined to have a cleanliness of Swedish Standard Sa3.

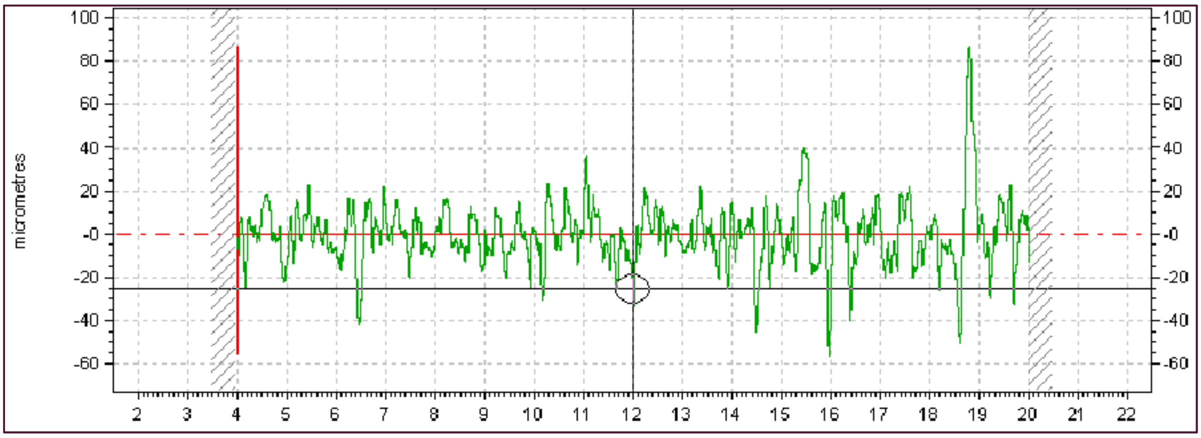

Figure 2. Representative surface profile of a grit blasted specimen

Measurement location	Sample 1	Sample 2	Sample 2 (after primer application)
	Rz (µm)	Rz (µm)	Rz (µm)
A	85.4	110.0	54.5
B	95.4	74.9	54.3
C	91.5	71.6	67.2
Average	90.8	85.5	58.7

Table 4. Surface roughness data from two separate samples, blasted on different occasions.

3.2. Resin selection

In order to determine which resin would be used for the sandwich panel core, a number of tests were conducted. The two resins were poured into moulds 20 mm deep, 50 mm wide and 300 mm long, casting long rectangular prisms of resin.

The hardness of these test blocks was measured over a period of 150 hours, both on an "as cast" face of the resin, and on a fresh cut face at each measurement point. The results are displayed in Figure 3 and show that the TLS resin cures to a stable homogenous hardness quickly. In comparison the XPE resin hardens slowly, and exhibits higher external hardness, with internal hardness stabilising at a low value of approximately 25 – 30 Shore D.

Literature suggested that preheating the substrate would result in a stronger bond. To evaluate, moulds equivalent to the full scale tests were heat soaked at 20°C, 40°C and 60°C. Shrinkage away from the mould was exhibited on the 20°C and 40°C specimens, but not at 60°C. As such 60°C preheating of the moulds was conducted for all further casting of full scale specimens.

In contrast, no shrinkage away from the steel was seen on the scaled down three point bend specimens. Strength of the specimens was evaluated for the three preheat temperatures of 20°C, 40°C and 60°C. The results of this testing (as shown in Figure 4) revealed no significant change in flexural strength of the specimens related to preheat temperature. As such, the scaled down specimens were cast at ambient temperature of 20°C.

Before a comparison of the shear strength of the XPE and TLS resins was performed, the effect of using the Erabond Metal Red primer was evaluated through the construction of lap shear specimens, as shown in Figure 1, with primed and bare steel substrates with the XPE resin. The use of the primer on the steel substrate increased the shear stress by about 45% as shown in Figure 5.

Comparison testing of the shear strength of the two resins was then conducted. This showed that the TLS resin was capable of a significantly higher shear stress of 10.5 MPa compared to only 2 MPa for the XPE resin. A three point bend test was then conducted with test specimens constructed as shown in Figure 1. These results (Figure 6) showed that the TLS specimen had greater stiffness and ultimate strength, and deformed as far as the test fixture would allow. In contrast the XPE specimen disbonded after a deflection of 134 mm and withstood a lower maximum load.

As a result of the testing summarised above, all further testing was conducted on the TLS resin.

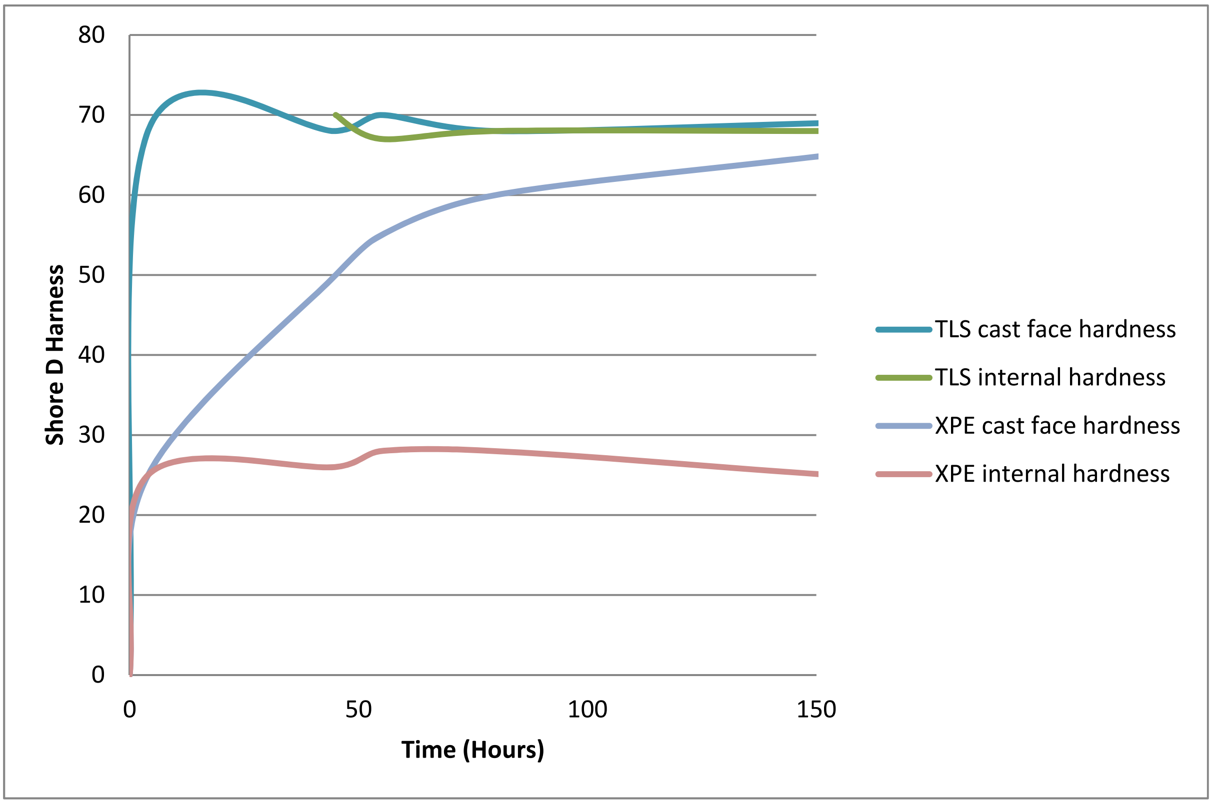

Figure 3. Core resin hardness over time for both the TLS and XPE resins. The XPE resin hardens slowly over time with the core not hardening appreciably after 150 hours.

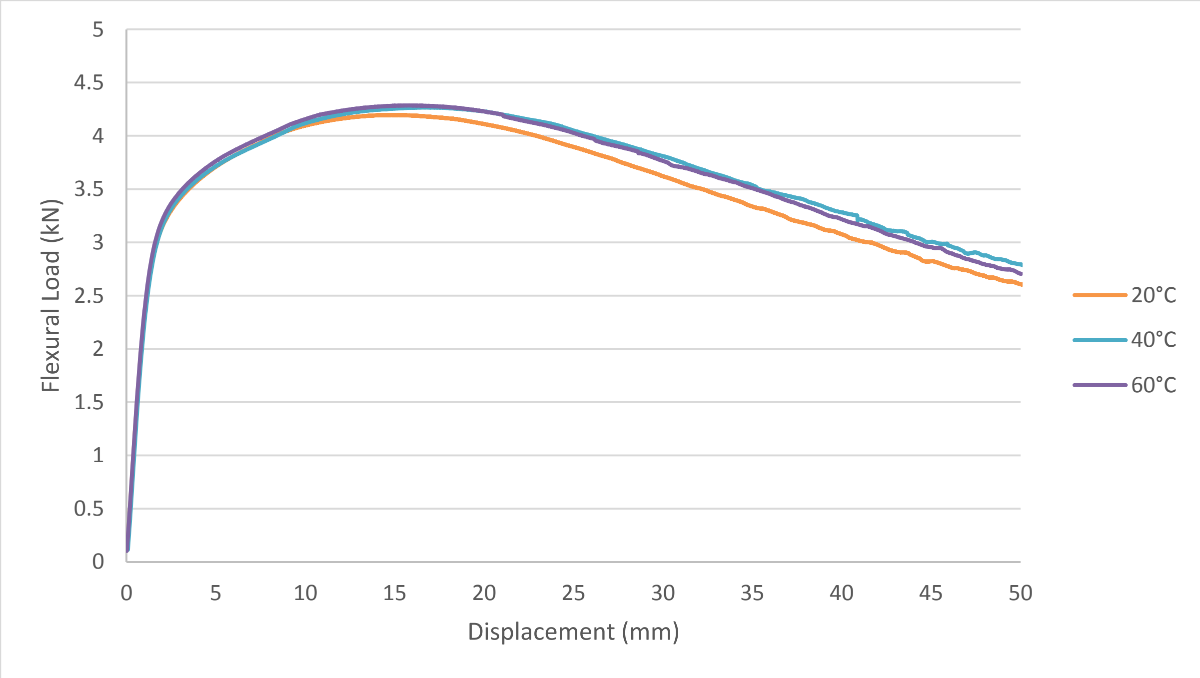

Figure 4. Three point bend test results (on scaled specimens using TLS resin) at different mould preheat temperatures. Results show that mould preheat had minimal effect on flexural strength.

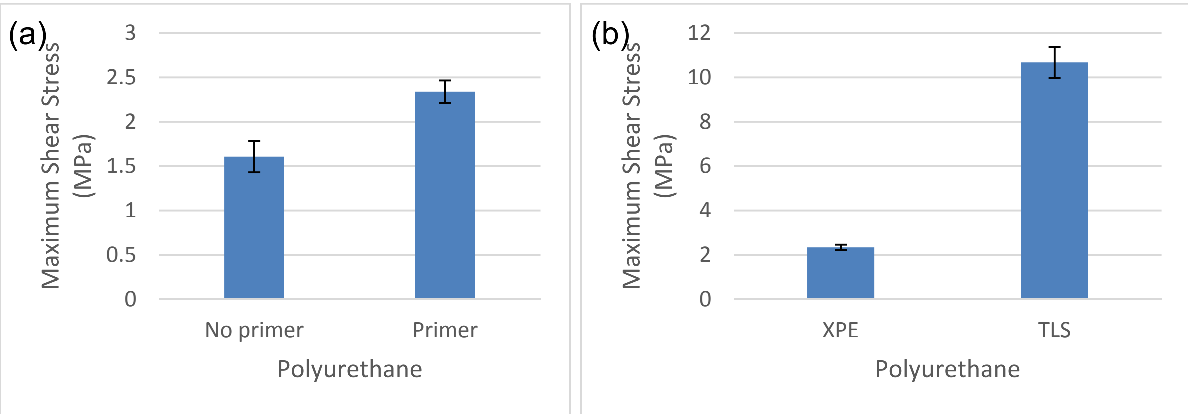

Figure 5. (a) The lap shear results when XPE resin specimens were assembled with and without the Erabond metal red primer. (b) The lap shear results when specimens were constructed from XPE and TLS resins as the core.

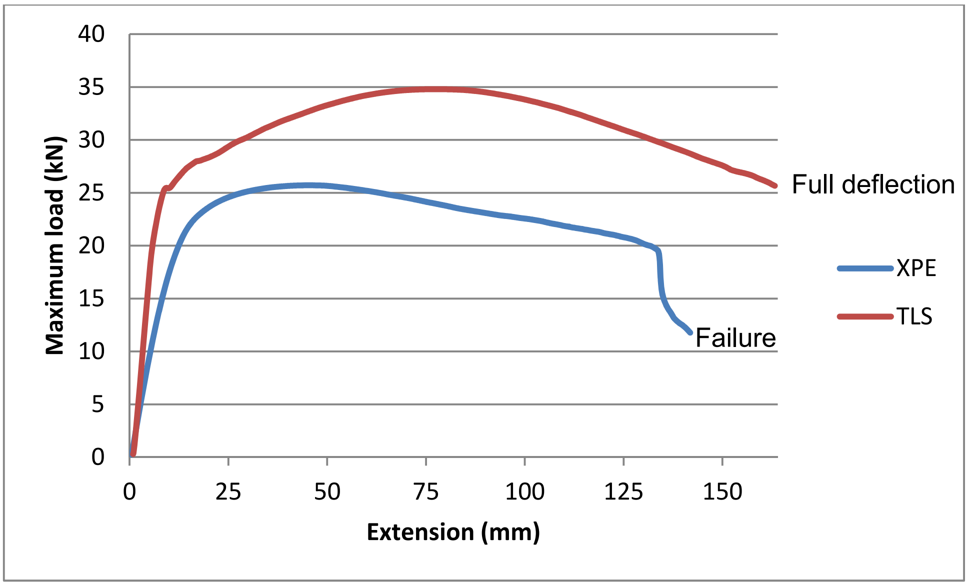

Figure 6. Load extension plot for three point bend comparison of XPE and TLS cores. Of note the XPE disbonded after 134 mm deflection, whilst the TLS absorbed the full deflection the test rig allowed.

3.3. Shear Strength of Bond

Lap shear testing was primarily conducted to optimise the resin selection and surface preparation as summarised in section 3.2, and then to quantify the bond strength in shear and assess the effect of temperature on bond strength.

Full scale single lap shear tests were conducted at -20°C, -2°C, 20°C and 50°C with the results shown in Figure 7. This set of four single specimen tests revealed a spread in strengths. The strength results on their own do not provide significant information as each is only a single data point. Examination of the fracture faces provides additional information to interpret these results.

The fracture faces of the four specimens are displayed in Figure 8. The failure mode of the fracture clearly changes as the temperature increased. At -20°C the failure was predominantly an adhesion failure between the primer and the TLS resin. With the temperature increased to -2°C the failure mechanism was now approximately 60% adhesion between the primer and the resin, and 40% adhesion between the primer and the steel. At 20°C, the failure mechanism changes again, with about 40% adhesion failure steel to primer, and about 60% cohesion failure within the resin. Finally, at 50°C, failure was about 80% adhesion between the primer and steel and 20% cohesion failure within the resin.

These results indicate that the measured differences in lap shear strength were real and that the steel – primer – resin bond interfaces are highly influenced by temperature. Also of note is that no specimens failed within the polyurethane resin but all failures occurred at or adjacent to an interface.

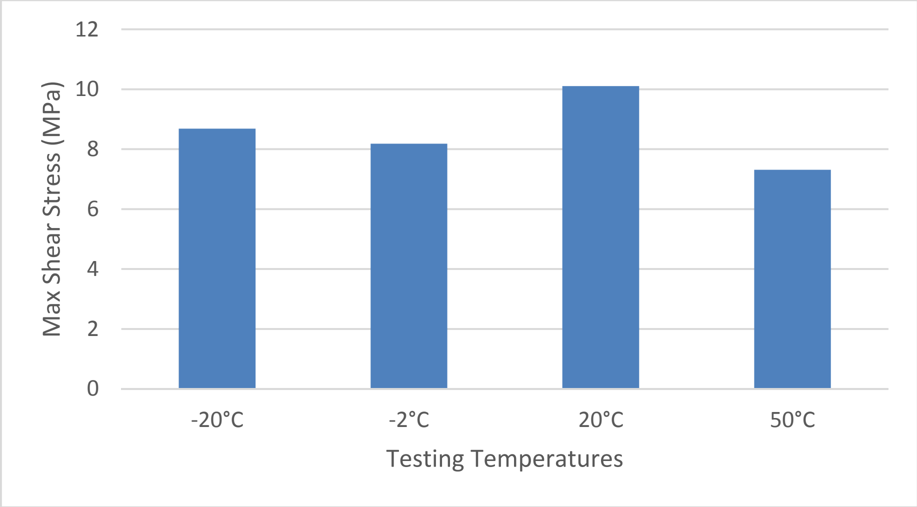

Figure 7. Maximum shear stress from full scale specimens across a range of potential operating temperatures.

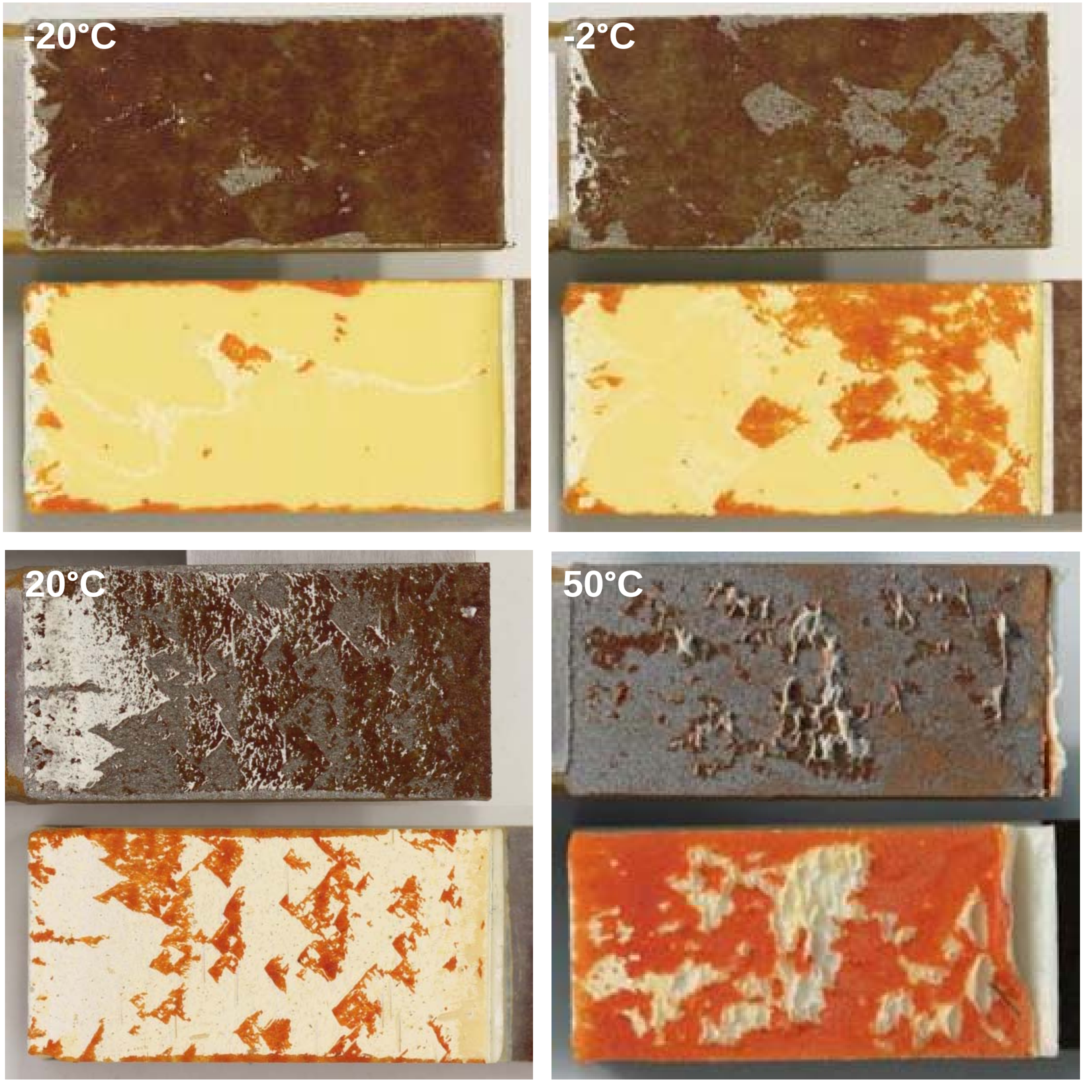

Figure 8. TLS Lap shear specimen fracture faces at the four test temperatures (as annotated)

3.4. Flexural Strength of Sandwich Panels

The service loads that the hull panels will most likely be required to react in the southern ocean are flexural in nature. As a result flexural testing was conducted to evaluate the efficacy of the proposed polyurethane core sandwich panel system.

Tensile and flexure testing was conducted on the steel used for the construction of the scaled test specimens. In tension the steel had a 0.2% proof stress of 198 MPa, with an ultimate tensile stress of 300 MPa. The flexural 0.2% proof stress was 375 MPa with an ultimate flexural stress of 432 MPa (specimen 25 mm wide, 2 mm thick with a 125 mm support span, as for the sandwich panels) .

Scaled sandwich panel specimens were loaded in three point bending to a maximum displacement of 50 mm. At each temperature of interest five specimens were tested. Characteristic load displacement curves are displayed in Figure 9. These curves and the chart of flexural results in Figure 10 show a distinct trend of decreasing yield and ultimate strength with increasing specimen temperature. Figure 9 clearly shows that the specimens at 35 and 50°C behaved differently to those at lower temperatures. At 35°C, the polyurethane core failed at ~36 mm displacement and again at ~45 mm. At 50°C, the core just kept stretching up to the maximum 50 mm displacement of the test.

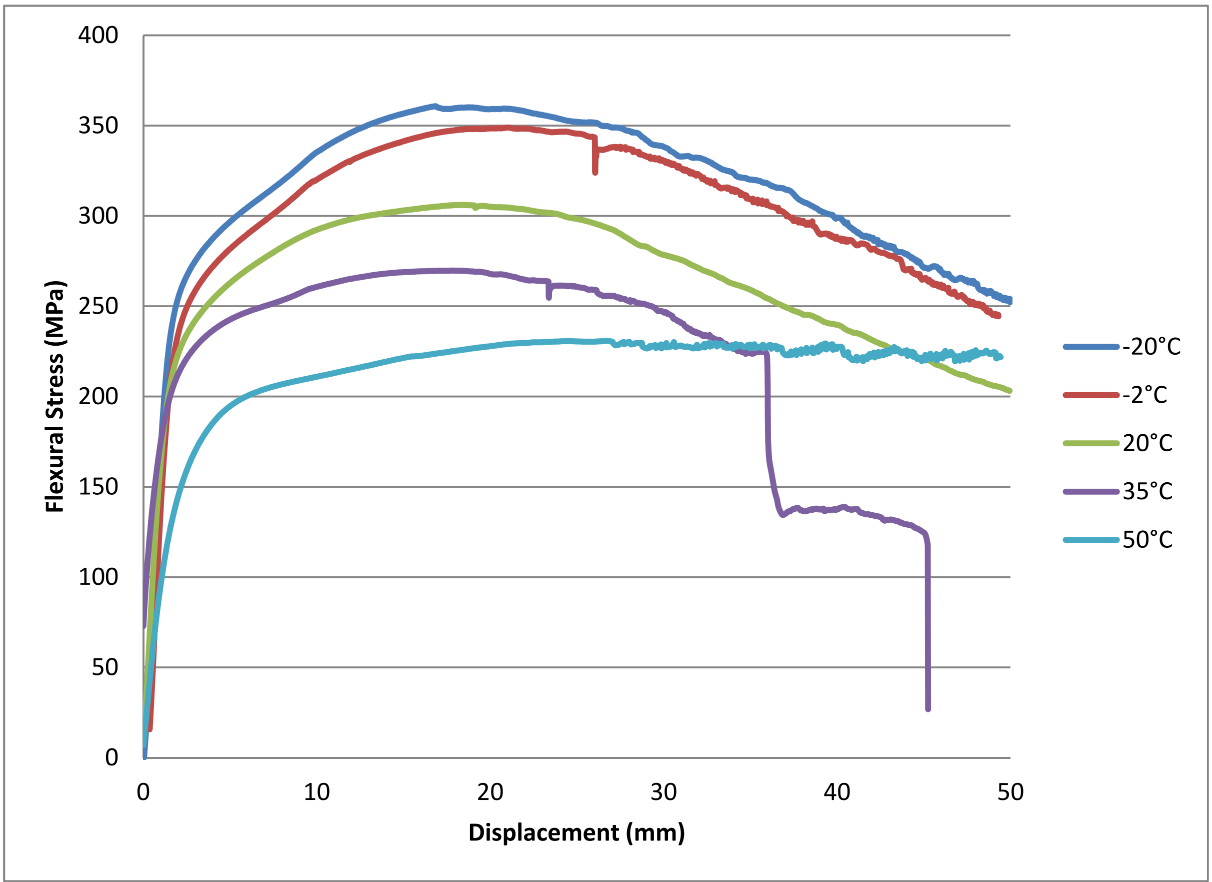

Figure 9. Representative stress – displacement curves obtained from the flexural tests at the temperatures of interest.

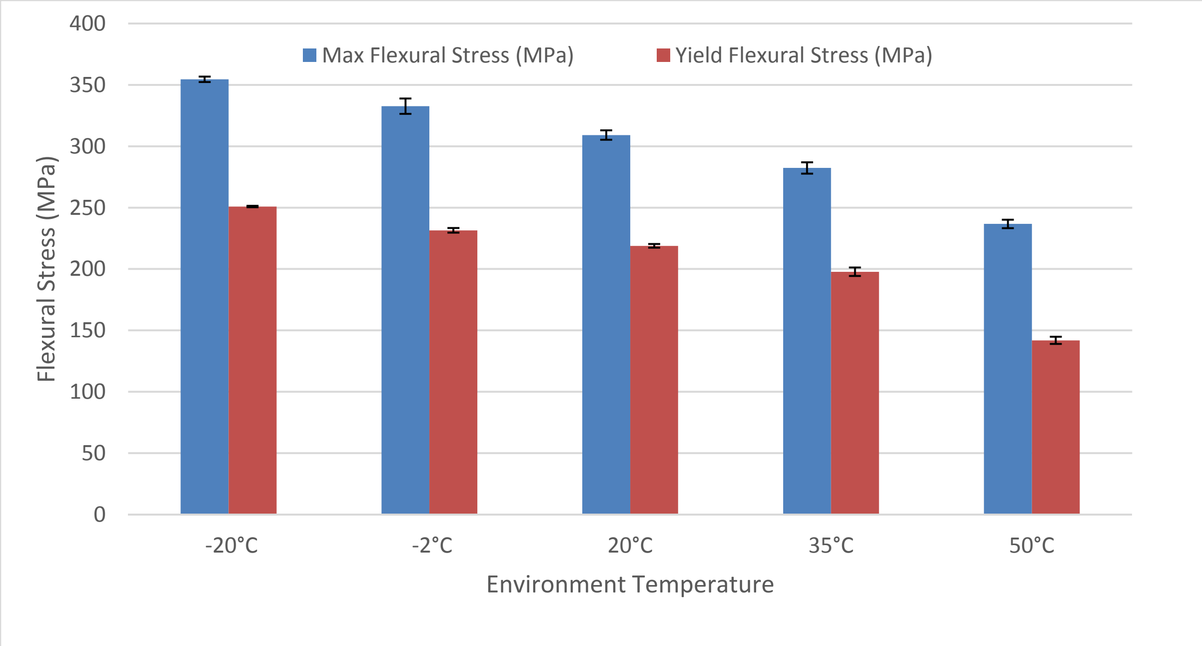

Figure 10. Yield stress (0.2% proof stress) and ultimate strength of the scaled three point bend specimens at the five temperatures of interest.

Digital image correlation viewing of the full field strain was conducted on a single specimen at each temperature of interest to provide a quantitative guide to the strains developed and the strain transfer between the upper and lower skins of the sandwich panels.

As can be seen from the images in the left hand column of Figure 11, under low displacement the strain is essentially uniform across the core, with the exception of beneath the loading nose of the three point bend test jig. As displacement (and thus load and strain) is increased, as shown in the second and third columns, the strain increases and becomes more localised adjacent to the loading nose. At specimen temperatures of 20°C and below, the maximum strain is on the lower surface of the sandwich panel specimens. At maximum displacement minor cracks occur in the core adjacent to the loading nose at -20°C and -2°C as can be seen in Figure 12. For specimens at 35°C and 50°C, the maximum strain is no longer adjacent to the lower skin but moves up to approximately mid-plane of the core and near maximum displacement typically results in shear failure of the core or disbond of the lower skin from the core, as demonstrated in Figure 12.

In an effort to understand the effect of salt water on the sandwich panel system, three point bend specimens were immersed in a 3.5% sodium chloride solution (as a rough approximation of sea water) for one, two and three weeks and then tested. These tests were conducted in an effort to determine what effect a breach of the outer skin may have on the mechanical property of the system. Test results are presented in Figure 13 and show that the salt water immersion resulted in no significant change in either the maximum flexural strength or the yield strength of the sandwich panel specimens.

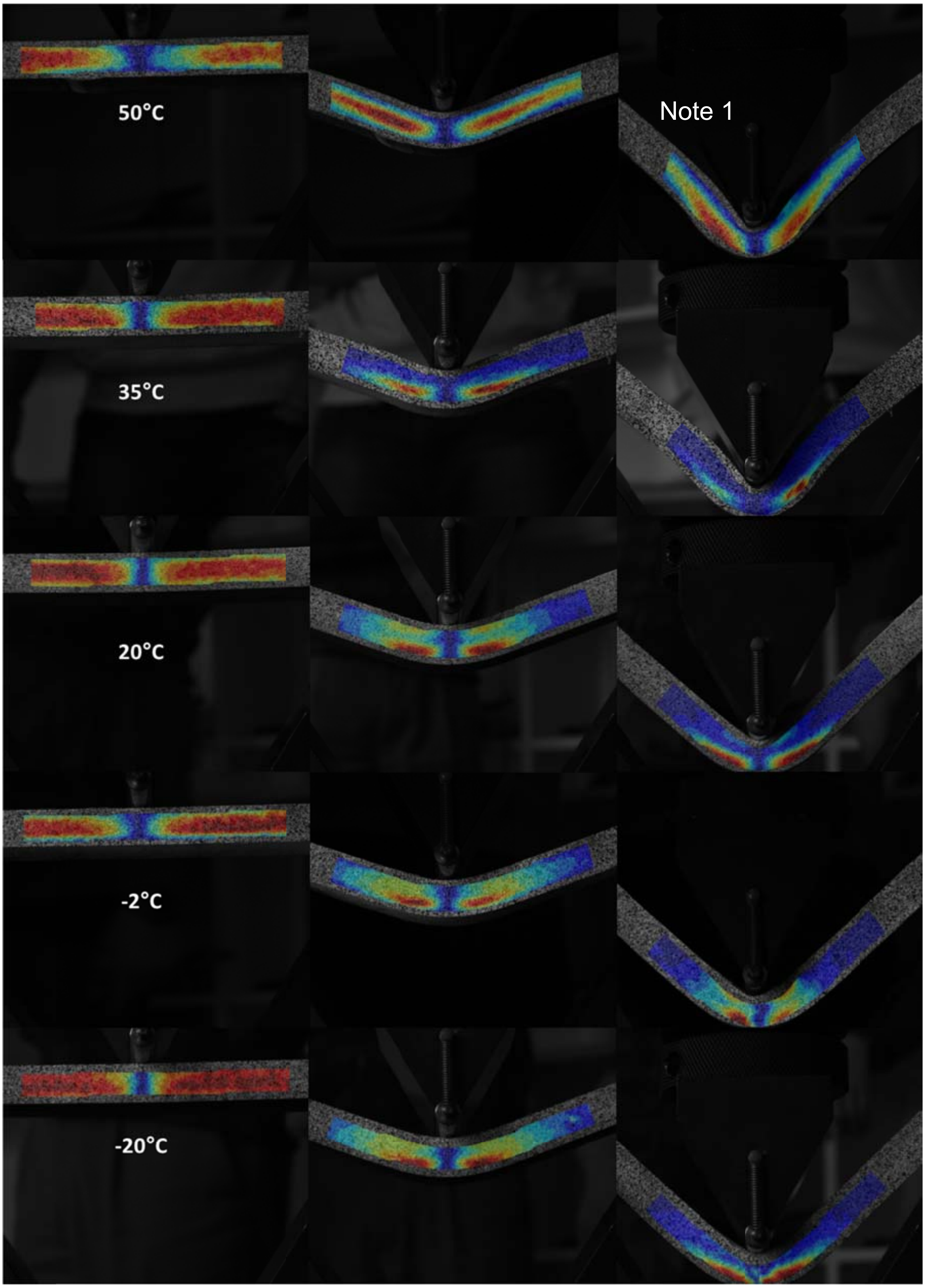

Figure 11. Digital image correlation results for three point bend testing. Red equates to maximum strain, blue to minimum strain. The absolute strain values are unique to each image and these images are provided purely for visualisation of the strain distribution. 1. Gross plasticity is seen in the core at 50°C. At 35°C and below only localised plasticity in the core is seen either side of the loading nose.

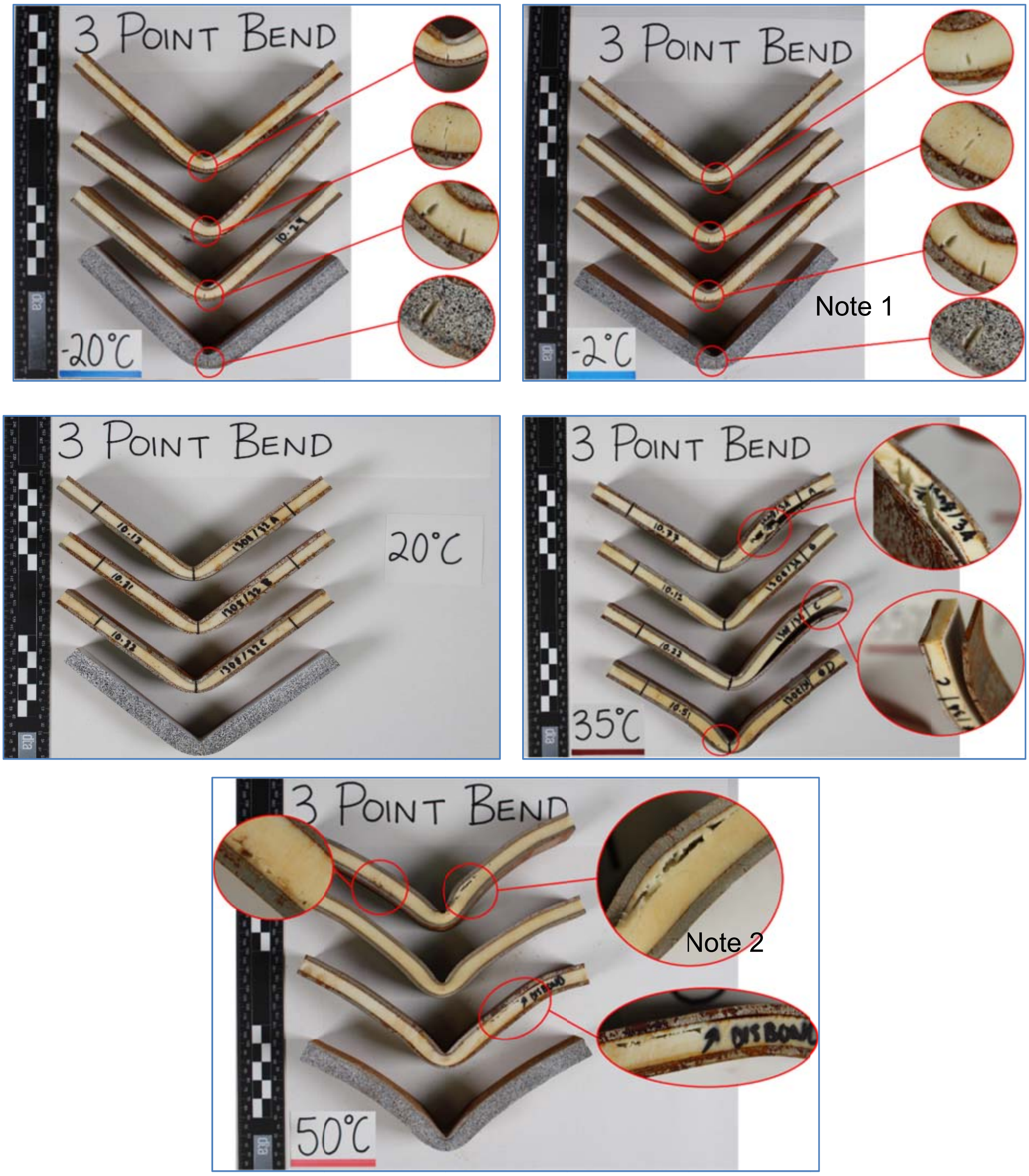

Figure 12. Three point bend specimens after testing to maximum displacement. 1. At temperatures below 0°C small tears occurred in the polyurethane resin just before maximum displacement was reached. 2. Specimens at 35°C and 50°C suffered failures either at the core/skin interface or in the core after ~35 mm displacement of the specimens.

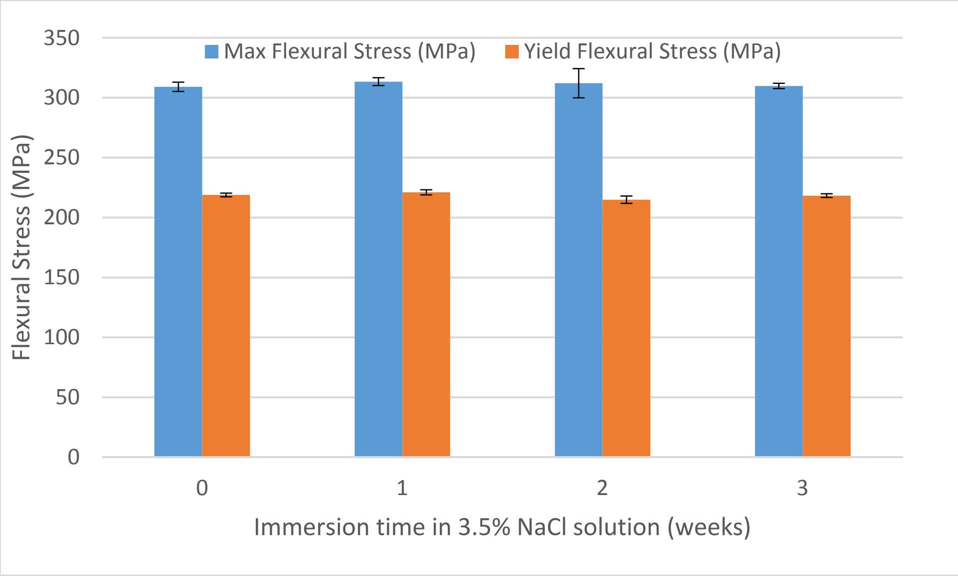

Figure 13. Flexural strength after immersion in 3.5% NaCl solution as determined by three point bend test at 20°C.

3.5. Impact Strength / Fracture Toughness

To evaluate the fracture toughness of the sandwich panels, Charpy fracture toughness specimens were manufactured, both with and without the traditional notch. The notch on the notched specimens fully penetrated the outer skin, representing a through crack in a weld in the outer skin of a vessel. The un-notched specimens represented an undamaged section of sandwich panel.

The un-notched specimens, as shown in Figure 14, had a large degree of scatter in their results, and showed no clear trend as to energy absorbed on impact in comparison to specimen temperature. Failure mechanisms of individual specimens varied, with some disbonding on the front face, some on the rear face, and some fracturing the resin core (Figure 15(a)).

In contrast to the variation in un-notched specimens, the notched specimens all fractured in the same manner, and at a significantly lower energy than the un-notched specimens, as shown in Figure 14 and Figure 15. The lower energies were due to the significantly lower fracture toughness of the polyurethane core and the full penetration of the steel skin by the notch. Of note is that the two sets of specimens tested below 0°C exhibited higher energy absorption than the specimens tested at temperatures above 0°C.

Test results from un-notched specimens immersed in 3.5% sodium chloride (NaCl) solution for zero to three weeks revealed no significant decrease over time as shown in Figure 16. Similarly, results from notched specimens immersed in salt water were consistent with notched specimens that had not been immersed.

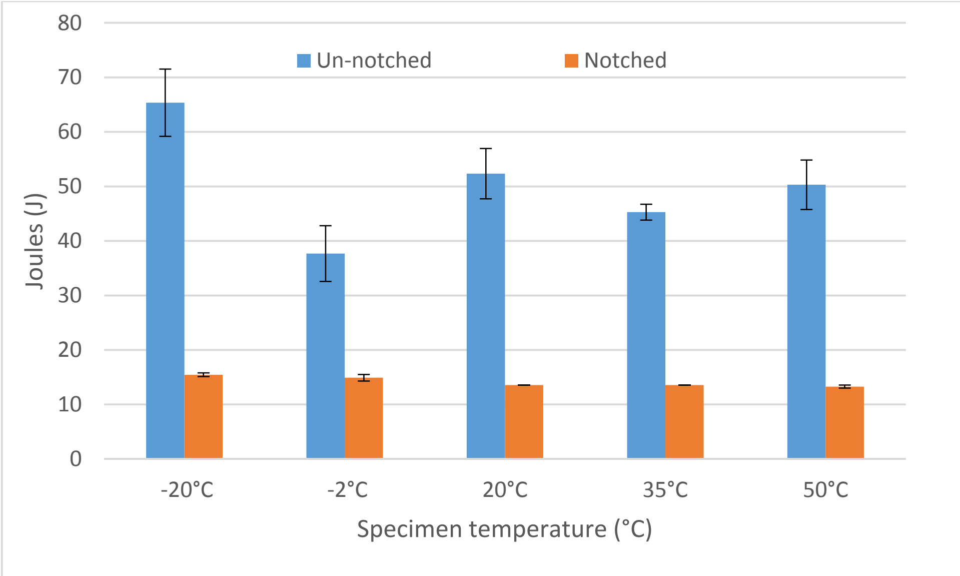

Figure 14. Average Charpy impact energy of notched and un-notched sandwich panel specimens at different specimen test temperatures.

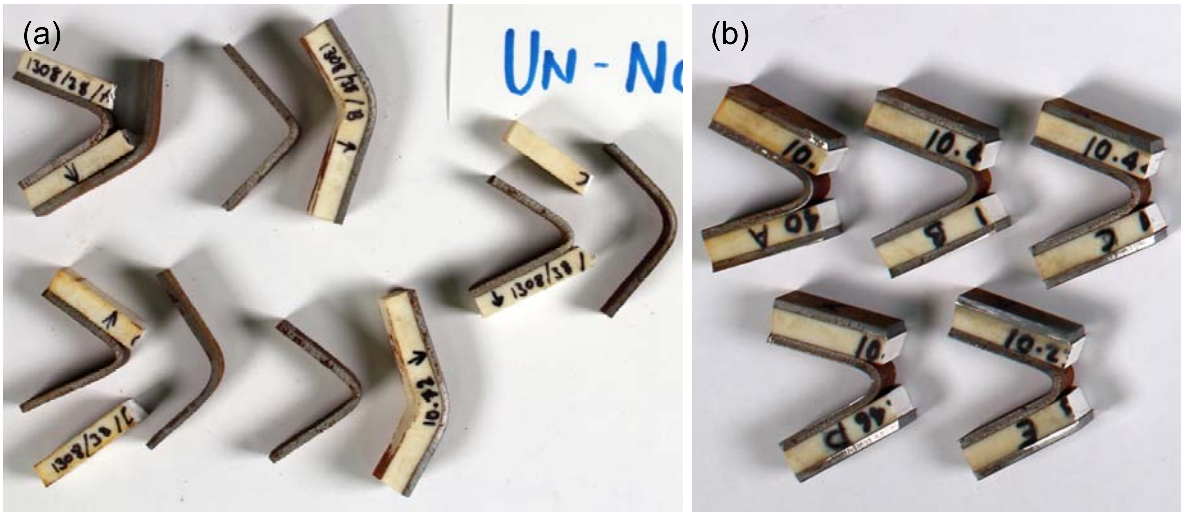

Figure 15. Some of the typical failure mechanisms of (a) un-notched and (b) notched Charpy specimens. The different failure mechanisms of the un-notched specimens are thought to contribute to the scatter of the data.

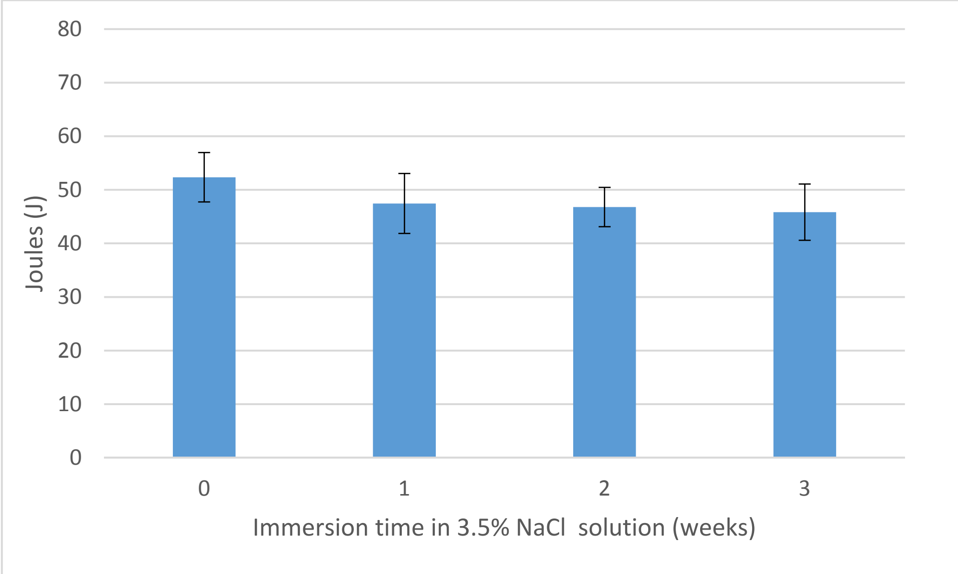

Figure 16. Average Charpy impact energy of un-notched sandwich panel specimens at 20°C after immersion in 3.5% NaCl solution for zero to three weeks.

3.6. Flexural Fatigue

A very brief set of fatigue tests were conducted on sandwich panels, loading the specimens in three point bending as in the flexural tests. Testing was conducted at constant amplitude with a load ratio of R=0.1. Maximum test loads were equivalent to 60%, 80% and 100% of the 0.2% proof load yield of the specimens, with two specimens at each loading condition. The results are presented in Figure 17. One specimen loaded at 1.8 kN (60% of yield) remained intact after 1 million load cycles. A determination of a safe design load at which fatigue does not occur within the expected load cycles the panels will endure could not be achieved from these results.

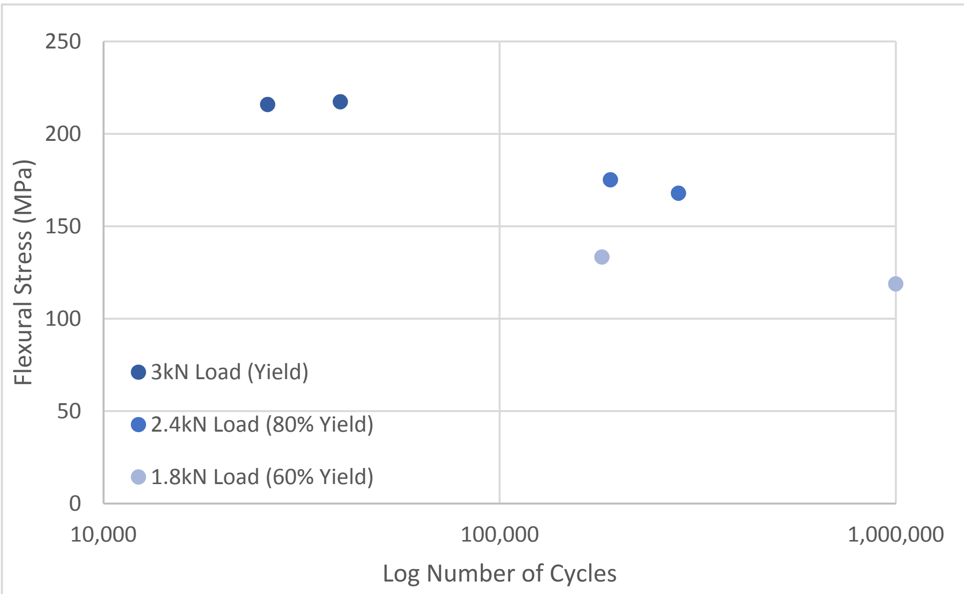

Figure 17. Fatigue test results of three point bend specimens, R=0.1

4. Discussion

Shear testing revealed that for temperatures of 20°C and below, a shear strength of at least 8 MPa was achieved. Failure of the specimens was repeatedly at or adjacent to the substrate. However, the precise nature of the failure location differed, including at the metal - primer interface, primer - polyurethane interface or cohesively within the polyurethane resin adjacent to the primer.

Flexural strength of the sandwich panel specimens was determined through three point bend testing of both scaled down and full scale specimens. At specimen temperatures of 20°C and below it was shown that resin tearing only occurred at maximum displacement, equivalent to 150 mm of penetration or deflection between support frames on a hull. Specimens at 35°C and above did suffer core and adhesion failures, but only after the equivalent of over 100 mm of penetration or deflection between support frames on a hull. Operationally even if hull penetration or deflection resulted in local failure of the polyurethane core the steel skins would remain watertight, although in need of dry docking for repairs.

Increased temperature reduced both the ultimate and yield flexural stress of the test specimens. However, even when the sandwich panels were weakest (at 50°C) the load required to yield the specimens was ten times greater than that which would yield a single steel skin. This indicates that even at its weakest the sandwich panel system would be ten times stronger than the existing hull strength of a naval vessel.

Charpy fracture toughness tests were conducted on scaled specimens both with and without notches. The notches were 2 mm deep and fully penetrated the outer skin of the specimens. Results showed high variability for un-notched specimens due to variance in failure mechanism, at fracture energies of approximately 50 J. Temperature had no discernible effect on the un-notched specimens, possibly due to the high variability. Notched specimens showed much lower fracture energies due to the notch completely penetrating the outer skin of the sandwich panels. Temperature also showed an appreciable effect on notched specimens tested at -2°C and -20°C providing results of approximately 15 J, compared to 13 J for specimens tested at 20°C and higher.

The performance of sandwich panel specimens at different temperatures clearly demonstrates a link between the bonding and mechanical properties of the polyurethane core and temperature. In all instances an increase in specimen test temperature resulted in degradation of mechanical properties.

Immersion of both three point bend and Charpy impact specimens in 3.5% NaCl solution to simulate sea water had no adverse effect on the mechanical properties of the bonds over the three week immersion period.

A brief fatigue investigation did not determine the fatigue limit of the system. The test results whilst not exhaustive do indicate that fatigue properties will not be a barrier to implementation on a vessel.

Applying a polyurethane sandwich panel system to a ship hull would naturally result in increased mass of the vessel. For the system tested by DTA the mass gain would be approximately 85 kg/m^2 of application area, with the polyurethane core contributing 22 kg/m^2 and the steel skin 63 kg/m^2 (based upon a core of 20 mm thick and a skin of 8 mm thick). This mass is the equivalent to an additional 11 mm thickness of steel plate. The load required to yield the sandwich panel system is at a minimum twice that required to yield the equivalent mass of steel (a 19 mm thick plate). In addition to the additional strength, installation of a sandwich panel system would be faster and cheaper than retrofit of thicker steel plating.

Application of a sandwich panel system to a hull to increase ice protection appears to be a feasible approach based upon these test results. The system would provide increased stiffness of the hull, increased resistance to penetration, and increased thermal insulation from the sea. The thermal insulation from the sea would be a benefit in the Southern Ocean, but would increase the load on environmental control when operating in tropical waters. Another consideration is that maintenance to the hull would increase in complexity. Weld repairs would be significantly more difficult, and inspection of the hull through traditional non-destructive techniques would be complicated and/or impossible.

The testing that has been conducted has been on a system devised by DTA to be similar to that offered by Intelligent Engineering. It is important to recognise that none of these results are from specimens supplied by Intelligent Engineering. This work was not intended to be used as a test of an alternate system, but to understand the challenges associated with steel – polyurethane sandwich panels and what questions should be asked of a supplier if the results were favourable. Information that should be sought from any sandwich panel system supplier should include (but not be limited to):

- Mechanical properties throughout the temperature range of interest (consideration should be given to both sea temperatures and air temperatures for panels in and out of the water).
- Whether a primer is used, and justification of the answer.
- Fatigue test results at ship design loads.
- Impact test results from sub-component (or component) level specimens.
- Data on internal stresses resultant from thermal coefficient mismatch between the polyurethane resin and steel.
- A maintenance plan of the hull (both internal and external).

This work program was undertaken with the concept of reinforcing a hull by retrofitting increased ice belt protection. It should be noted that increasing the ice class of a ship extends far beyond the ice loading on a hull and due consideration needs to be given to all aspects of increasing the ice class of a ship before this sort of work should be undertaken.

Furthermore, sandwich panel systems could also potentially be used to increase the stiffness and strength of flight decks or cargo bays should the service loads increase beyond the original design for example due to the acquisition of heavier helicopters or army vehicles.

5. Conclusions

Polyurethane core steel faced sandwich panels proved to have excellent static mechanical properties. The adhesion between the steel and the polyurethane core was excellent when a primer was used and failure at the interface during mechanical testing only occurred on some specimens at temperatures of 35°C and above.

A brief fatigue program indicated that cyclic loading did lead to failures at loads significantly below the yield load of the specimens. A supplier should be required to provide evidence that at service loads fatigue will not lead to failure within the predicted operational life of a vessel. Exposure of specimens to salt water to test corrosion resistance had no significant effect on the flexure or impact properties of the specimens.

The test program has proved that polyurethane core steel face sandwich panels can effectively carry significant loads. The results highlight that mechanical property data is highly temperature dependant due to variation in resin properties with temperature. However, despite the weakening of the sandwich panels with increased temperature, a system manufactured from 8 mm steel skins and a 20 mm thick polyurethane core at its weakest can carry a bending load at least ten times greater than the existing 8 mm hull plating on the RNZN OPVs. However, these results cannot be directly used to validate any other polyurethane – steel system.

The primary benefits of application of the type of sandwich panel system discussed, using the existing hull of a ship as one of the sandwich panel skins, are cost and ease of installation. The time and cost of removing the existing hull plate and welding thicker hull plates on is significant. Welding the second skin panels to the hull for the sandwich panel system (and subsequent bonding with the polyurethane core) can in contrast be done simply, without concern for systems internal to the hull, and cheaply.

Polyurethane core steel faced sandwich panels could be used to retrofit increased ice protection to the hull of an RNZN OPV (or other vessel). However, such an endeavour should only be undertaken upon specific mechanical data about the system being provided by the system manufacturer as summarised in the recommendations, and taking into account the significant additional requirements beyond hull protection to increase the ice class of a vessel. Manufacture from new to a specific ice class should be the preferred option, if it is available, so that ship systems from propulsion, through communication and ships boats can be adequately specified and designed to cope with the hostile Southern Ocean conditions.

6. Recommendations

This report was written based on the requirement to retrofit increased ice protection of an existing hull. Preference should always be given to manufacture/acquisition to the required ice class when possible.

If a retrofit to an existing hull is determined to be the preferred solution, any supplier of a sandwich panel system, such as that investigated in this work, should be requested to provide at a minimum:

- Details about the mechanical properties of the sandwich panel system throughout the temperature range that is likely to be operationally experienced by the vessel.
- Evidence that at the design loads of the system the panels will not suffer fatigue failures within the expected design life of the vessel (as specified by NZDF).
- Evidence that impact with submerged containers in the tropics and bergy bits or growlers in the Southern Ocean will not result in penetration of the hull.
- Evidence of the level of stresses, both residual and in service, resultant from the thermal expansion coefficient differences between the steel skins and resin core.
- A maintenance plan for both the internal and external hull that takes into account the sandwich panel system.

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13. ABSTRACT

The Royal New Zealand Navy (RNZN) regularly patrol the waters of the Sub-Antarctic Islands and the Southern Ocean in support of the Department of Conservation and Ministry of Primary Industries. Operation in these waters includes the potential presence and threat from ice, and RNZN Offshore Patrol Vessels are protected against ice with a belt of thicker steel about the waterline. Excessive pitch and roll of vessels can however result in thinner and more vulnerable areas of the hull being exposed to sea ice.

Defence Technology Agency were tasked by the RNZN to evaluate whether there was potential to enhance the level of ice protection on vessels through the use of a polyurethane cored steel faced sandwich panel system that has recently been offered by commercial suppliers. This report summarises mechanical testing undertaken to explore the viability of this type of sandwich panel system. Testing included shear, flexure and impact testing across the likely temperatures that the system would be operationally exposed to, as well as fatigue and corrosion testing.

Results of the tests indicate that a polyurethane cored steel faced sandwich panel system is a viable solution for hull reinforcement, and raised a number of recommended questions that should be answered by any prospective supplier of a solution to the RNZN.

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