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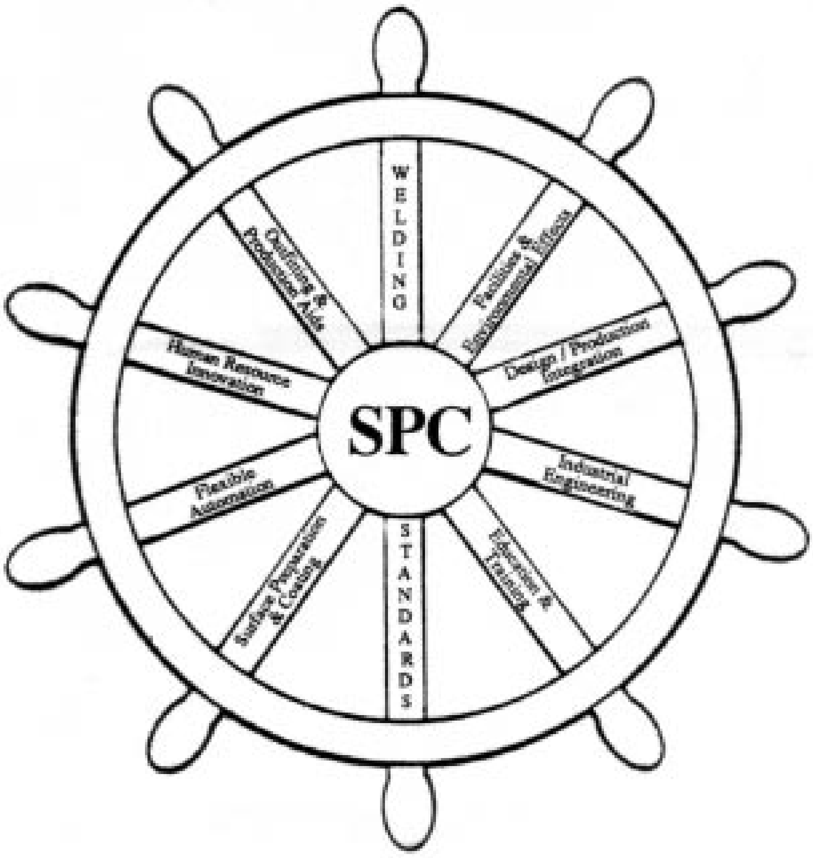

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What Can Adhesives Offer to Shipbuilding?

6A-1

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ABSTRACT

This paper presents an overview of recent research into the feasibility and advantages of using toughened structural adhesives to replace some conventional welding for primary structures in the shipbuilding and associated marine industries.

The concept is explored through its application to the stiffener/plate connections of thin plated grillage structures where a number of advantages can be identified. These include the potential for elimination of thermal distortion and residual stress with little cost or weight penalty. Data is becoming available on such longer term problems as durability in the marine environment, high temperature performance (including creep), fatigue and impact resistance. Research is continuing to improve understanding and increase confidence in application to large scale structures.

The paper concludes that the benefits to be gained from using adhesives to achieve novel structural configurations, possibly involving dissimilar materials, will provide continuing impetus to research and development in this area.

1. INTRODUCTION

The question in the title was first posed about six years ago when compiling the list of final year undergraduate student projects within the Department of Naval Architecture and Ocean Engineering at the University of Glasgow. At that time there had been a considerable amount of research and development effort expended in the civil engineering sector [1] advancing the use of structural adhesives as a means of adding additional stiffening members or extra flange material to the girders of bridge structures within the UK. As these applications appeared to be generally successful, it seemed that there was scope to apply similar technology within the construction of both ships and fixed or floating offshore structures.

An early potential application emerged in the grillage structure of frigates being built for the British Navy (MoD(N)). The shipyards involved have long experienced difficulty in controlling the distortion induced by the welding of the small section 'Admiralty Tees' to shell, deck and bulkhead plating. In general, the problem stems from the excessive size of the double fillet weld beads used for their attachment to relatively thin plating (typically Smm) where intermittent or staggered welding would have been sufficient for strength, but not acceptable to the MoD(N). Adhesive joints would appear to offer a practical solution to the shrinkage and distortion problems so often encountered in such light plated structures.

As a first step, a student project [2] investigated a number of possible adhesives and their application to bonding short sections of beam elements. typical of the warship structures referred to above, using 'I' beams in place of Tee sections. Although limited in its objectives, this project demonstrated both the smooth, unstressed nature of the bonded specimen and the feasibility of loading such beam elements in three point bending until the web of the stiffening member suffered plastic collapse without any signs of failure of the bond line between plate and stiffener. Figure 1 shows such an early museum piece, as it survives to this day in a heavily deformed state without showing any tendency to fail by creep or ageing.

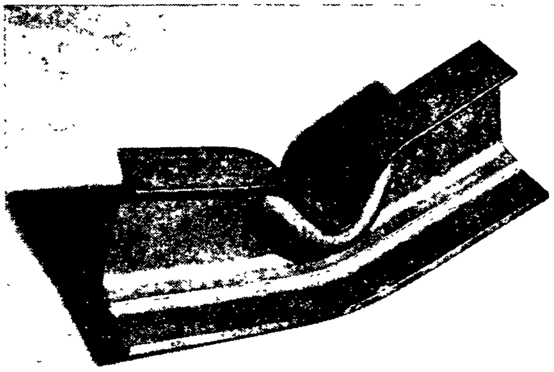


Figure 1 Early test specimen after six years

This early success inspired a two year programme of research to survey available adhesives, develop methods of fabrication and determine the material and structural properties of bonded stiffener to plate connections in lightweight ship grillages. The results of this programme [3] are summarised in Section 2. as the basis from which to introduce the findings of a number of more recent related projects, discussed in Section 3.

From these test programmes it is now clear that adhesives offer an alternative joining technology which may have important implications for significant parts of the structural design and fabrication of various ship and offshore structures. In particular this technology opens up the twin possibilities of lightweight sandwich construction and the combination of a wide variety of dissimilar materials to achieve specific design objectives. However, before this can be achieved the designer must understand the strengths and the weaknesses of both adhesives and bonding process, working to the former and eliminating the latter, so far as possible. A major objective of this paper is to contribute to this understanding.

1.1 Engineering Applications of Adhesives

At first sight the engineering properties of adhesives appear to offer little to the designer: viz. low strength, very dependent on temperature; low modulus; brittle. However, from modest beginnings in the 1940's. adhesives are now widely exploited in the aerospace industries and thereby provide a very important general basis for extrapolation into new fields through the availability of long term service performance. The successful bonding of aluminium alloys in this sector of industry also demonstrates some of the problems often considered to be inherent in the use of adhesives in general, i.e. the importance of careful surface preparation and the need for sophisticated jigs, fixtures and autoclaves to achieve a satisfactorily cured joint. It should be remembered, however, that the development of a range of toughened epoxy and acrylic adhesives in the 1970's has also catalysed a large number of applications in the automotive and general engineering sectors applied principally to the bonding of aluminium alloys as well as steel [4. 5, 6. 7, 8, 9]. An important stimulus to this trend seems to be that the fabrication and preparation requirements are in general far less stringent for steel than aluminium alloys (where careful growth and preparation of a stable oxide layer is required) while steel/steel bonding offers the highest potential for joint strength [IO].

It is not surprising therefore that several applications have already been found for adhesives in the marine industries. These range from the temporary repair of fatigue cracks in the superstructures of warships [11] to the longer term repair of damage to the tubular members of offshore jacket structures through the application of bonded sleeves [12]. Although many of these applications started as short term emergency measures, the benefits have proved so attractive that the owners of a well known passenger ship have modified the superstructure in way of structural openings by incorporating bonded doublers. In addition, several examples of the use of relatively low strength adhesives have appeared in Russia [13] involved in the manufacture of lightly loaded bulkheads, fire and watertight doors, instrument casings and ventilation ducts.

1.2 Adhesive Selection

Modem adhesives can be divided into two classes [14]:

thermosets - which set by chemical reaction

thermoplastics - which set as the result of physical changes such as solvent evaporation or solidification.

Both classes are important industrially but generally only the thermosets are able to withstand sustained loading. However, some recently developed hot melt thermoplastic resins such as polyetheretherketon (PEEK) could prove superior to the more widely used thermosets, they are extremely expensive at present and difficult to use when bonding large structural components [15, 16].

Among the therrnosets are two resin groups which stand out as having potential for bonding structural steel - epoxy and acrylic. Recent developments [17] have led to the introduction of toughened formulations in both these groups through the inclusion of a dispersed rigid or rubbery phase in the resin matrix which substantially increases resistance to crack propagation by absorption of energy at the crack tip. In consequence the onset of catastrophic adhesive failure is delayed and the resistance of a joint to cleavage and impact forces can be markedly improved. Toughening has not so far been successfully applied to other types of structural adhesives [18].

Toughened acrylic adhesives are generally rapid curing and give high cleavage and impact resistance. They are supplied in two parts (resin and catalyst) which usually require premixing in specialised dispensing equipment to achieve best results. They often contain volatile, flammable monomers and so vapour extraction is important for large structural applications. Acrylic adhesives are generally more suitable for joining plastics and have yet to be established as suitable for metals subject to high humidity and/or elevated temperature. In terms of both strength and stiffness, toughened epoxy adhesives are generally superior to acrylics for metal assemblies and also possess better heat, creep and environmental resistance.

Through their superior performance, toughened epoxies appear to offer the most suitable candidates for bonding structural steel. They are generally available in either one-part (hot cure) paste/film or two-part (cold/warm cure) paste. The hot cure varieties are essentially a premixed version of the two-part having exceptionally long cure times at room temperature. The hot (or warm) cure tends to improve the wetting of the adherend and encourage the development of strong molecular cross linking in these adhesives, thereby imparting better room temperature strength while allowing substantial time for adjustment of one or more joints prior to cure. Strength at, and resistance to, elevated temperature exposure is also improved through the higher glass transition temperature of the hot cured adhesives. This is likely to be important in any environment (such as shipyards) where the local damage effects of welding and gas cutting are to be expected.

The formation of an adhesive bond may be explained in terms of the intermolecular forces which cross link the adhesive and adherends. The development of a durable bond depends on intimate contact. Intimate, continuous contact is difficult to achieve if either surface is contaminated with oil, dust, corrosion products or release agents; so efficient removal of these contaminants is generally essential. Such surface preparation usually requires solvent degreasing followed by abrasion or grit blasting and a final solvent wash to remove any remaining surface debris. However, one of the more notable features of the toughened adhesives is their good wetting properties which allow them to absorb thin oil films and dust particles. In general therefore, although *some* care is required, the surface preparation requirements for the structural epoxies used in the current programme are far less stringent than those applying to aluminium and its alloys as applied in the aerospace industries. In addition, the application of a water-based silane primer to both adherend surfaces should provide both a useful indicator of surface contamination and an ideal molecular link between steel and epoxy. The chemist argue that this should greatly improve the long-term durability of such joints in wet conditions.

Although film adhesives have worked well in small scale experiments they do not appear to offer sufficient initial thickness or viscosity to accommodate the inevitable variations in bond line thickness with stiff adherends. Paste adhesives, on the other hand, are easy to handle, being dispensed from hand or power operated guns as a uniform bead onto one of the adherend surfaces. Through the use of various modifying agents the viscosity of the adhesives can be adjusted by the manufacturers to cope with varying joint gaps (up to 2mm) as well as application to vertical surfaces without risk of loss of adhesive during cure. The structure must be clamped while the adhesive cures - with epoxy pastes only limited pressure is required for this process. . Any resulting spew fillet is best left undisturbed as it extends the bond area and reduces the stress concentration at the edge of the joint while improving the seal. Once cured the adhesive is generally assumed to retain its properties permanently.

1.3 Fabrication Procedure

At an early stage, a laboratory prototype system for heat curing stiffened panels had to be developed which would be capable of later development for full scale shipyard production. This is illustrated in Figures 2 and 3. Modelled on the stiffener injection and welding stages of a conventional automated or semi-automated panel line, the concept relies on sets of electrical resistance heating elements aligned with the joints on the underside of the plating. In full scale production it is anticipated that a number of rows of these elements could be supported on mobile. pressurised supports to be aligned with the joints, forming the base of the clamping jig which is necessary to support and align the stiffeners - in much the same manner as the one-side weld backing systems so common in the Japanese industry.

In normal conditions, the recommended cure cycle requires a steady rise in temperature to approximately 180°C over a period of about an hour. This peak temperature is held for about 30 minutes to effect the cure, before the assembly is allowed to cool naturally to room temperature. Temperature control is effected through a feedback controller with one or more thermocouples attached to the bond line. While it is appreciated that this is a time consuming process. it can be safely automated and requires no human intervention. Thus it is an ideal off-shift activity which could be scheduled at night without interfering with the rest of the production process.

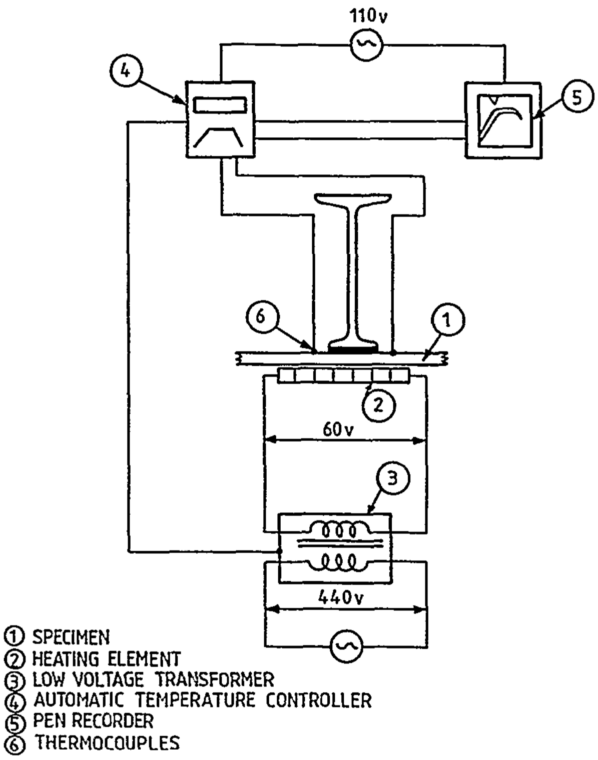


Figure 2 Schematic of heat curing process

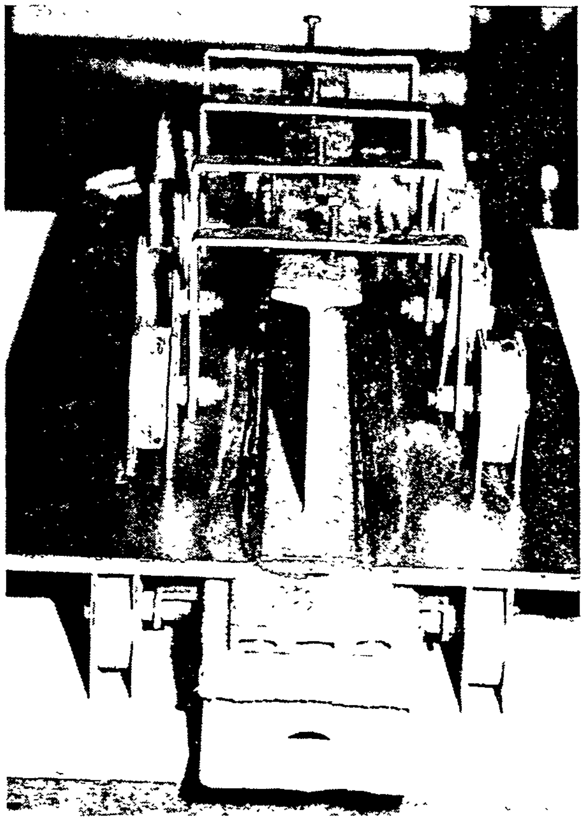


Figure 3 Layout of specimen during bonding

The minimum required preparation processes would consist of:

a. abrasion of the bond line surfaces to a surface roughness of 5-10um [19] using air powered flexible grinding equipment

b. brush or suction removal of debris

C. application of self-indicating silane primer to both surfaces

d. dispensing a uniform bead of adhesive paste to the stiffener flange

e. positioning and lightly clamping stiffeners to plate surface - simple magnetic bridges are adequate (see Figure 3). The use of adequate clamping is important to maintain a consistent minimum joint gap to avoid the formation of voids within the joint which are not easily rectified after curing.

It has yet to be determined whether an intermediate organic solvent degreasing stage is required between b. and c. for most large scale practical applications. In laboratory tests this stage has been retained to ensure optimum performance of test joints for comparison purposes. During these stages it is important that safety rules relating to skin protection, ventilation and flammability of solvents are observed.

2. EARLY EXPERIMENTAL PROGRAMME

The initial research programme concentrated on the problem of applying adhesives to the stiffener/plate connection of flat plate grillages as commonly found in the decks and bulkheads of ships. The choice of this joint was deliberate in that under bending load actions it is subjected primarily to bending shear along the line of the joint. However, as the joint is relatively close to the neutral axis of the plate/stiffener combination, the induced bending stresses are significantly less than the maximum stress in the stiffener flange. Thus the opportunity is available to use the adhesive in its strongest mode - that of shear - without exposing it to extreme loads.

Four aspects of the problem were apparent from the outset:

1. choice of adhesive through small scale standard tests
2. design of the joint to minimise risk of failure from end effects and secondary collapse mechanisms
3. verification of stages 1. and 2. through large scale panel bend tests
4. assessment of the impact performance of the joints

At the same time a number of longer term durability tests were established to allow this aspect of the problem to be monitored as the research programme developed. Details of these tests have already been published 120. 211 but are summarised below.

2.1 small Scale Standard Tests

One of the more important aspects of dealing with adhesives is coming to terms with the stress concentrations always present close to the boundaries of bonded joints [22]. These are illustrated in Figure 4 for the three basic modes of loading: tensile shear, symmetric axial tension and asymmetric axial tension (cleavage). It is evident that as these local stress concentrations determine the failure load. The nominal failure stresses (derived from load divided by area) are not therefore a reliable guide to the design strength of larger joints. In reality, most small scale standard tests are only useful for comparative rather than design purposes. It is also important to note from Figure 4b that the reliability of the tensile strength assumed for these adhesives is governed by the degree of cleavage which is present in the loading. The difficulty of eliminating this problem in small scale tests explains a measured variability of ±25 % among groups of three specimens in this type of test.

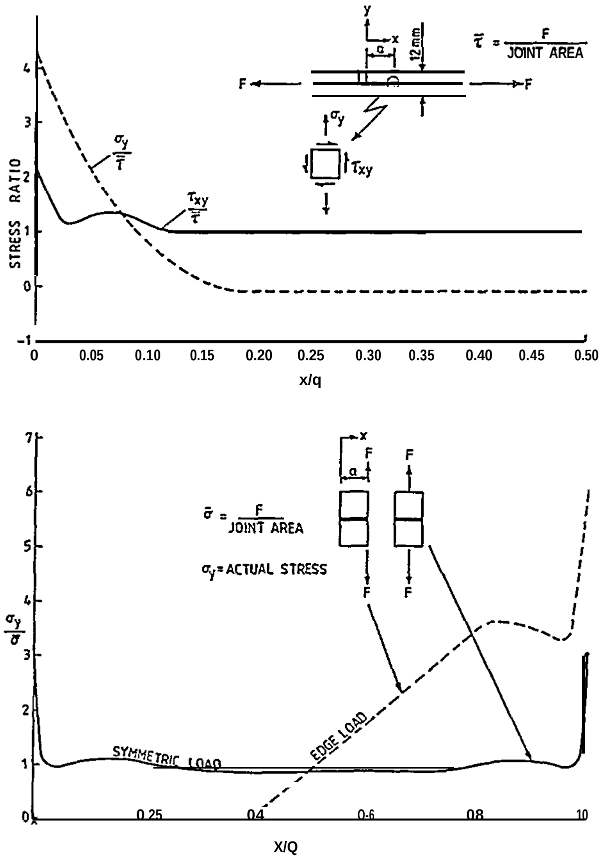


Figure 4 Typical stress distribution in adhesive joints

Figure 5 illustrates the range of ASTM and BS standard tests which were used to assess the relative merits of five paste and two film adhesives in a process of elimination to determine two candidate adhesives for larger scale testing and evaluation. The adherends were manufactured from mild steel stock (BS4360 Grade 43A) by milling and grinding to the dimensions indicated. Surfaces were prepared by solvent degreasing, grit blasting and further

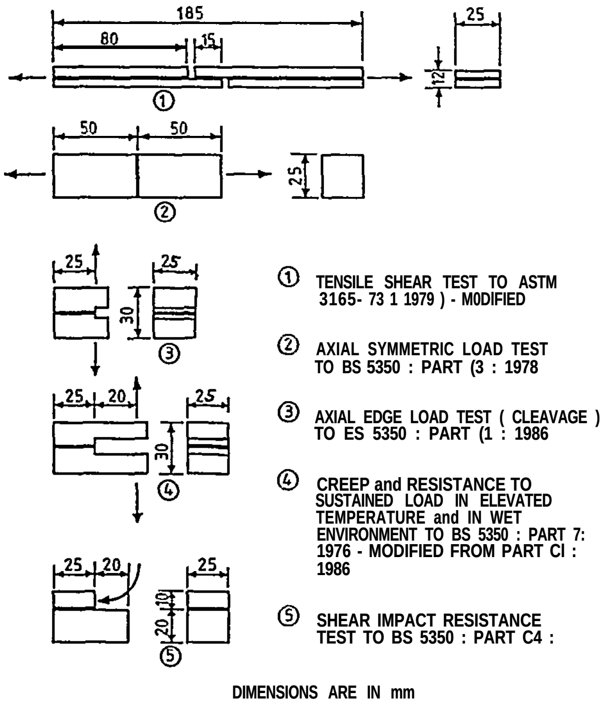


Figure 5 Standard test specimens

degreasing. The adhesives were all commercially available structural epoxies applied in nominal joint thicknesses of 0.15-0.2mm before curing to manufacturers recommendations. Progressive elimination based on the average results of three specimens for each test commenced with shear and cleavage tests followed by the tensile, shear impact and creep tests (under 50% ultimate load in salt water for 1000 hours). Three adhesives performed well in most of these tests, their results being summarised in Table I.

Both ESP110 (Permabond) and Araldite 2007 (Ciba Geigy) exhibit good all round static strength properties as well as shear impact and creep durability in sea water and therefore formed the basis of further testing. The significant difference between these adhesives is largely in their elastic modulus (manufacturers bulk figures) which has implications in the larger scale tests.

A range of further tests conducted using these two adhesives indicated that:

- joint thickness in the range 0.1-0.5 mm has no significant influence on joint strength except in the case of butt joints

- the presence of the a spew fillet can increase joint strength by up to 15% in many of these small specimens

- lightly contaminated surfaces have no short term effect on joint strength

- post cure cooling rate does not appear to affect joint strength

- prolonged post cure heating at 120°C for up to 20 hours does not affect joint strength.

2.2 Joint Design to Minimise Cleavage Effects

With the relative weakness of adhesive joints in cleavage it is important to give some considerations to the load actions which might produce this effect. One is the lateral instability of grillages under axial compression [22, 24] which can induce relative rotation between plate and stiffener about the axis of longitudinal joints. Resistance to this load action is provided by the width and stiffness of the lower stiffener flange (foot) which the designer would like to minimise. Another cleavage action is experienced at the free end of a stiffener joint - well known in the bonded stiffeners of large GRP hulls [25]. In this case it was thought that a tapered or shaped stiffener end might be beneficial through the introduction of a flexible toe to the stiffener to produce a gradual change in stiffness.

Figure 6 illustrates the general arrangement of this test series based on reduced 100mm deep ‘I’ sections bonded using Araldite 2007. Although these tests were somewhat qualitative in nature a number of important conclusions emerged:

- transversely loaded specimens of type 1 showed high resistance to cleavage with widths of 15 to 45 mm, all specimens failing by collapse of the stiffener web without bond failure. This indicates a potential for bonded structures to have bonded stiffener feet no larger in sectional area than the double fillet welds they replace

- variation of the thickness of the bonded flange between 2 and 6 mm did not affect the type 1 test results

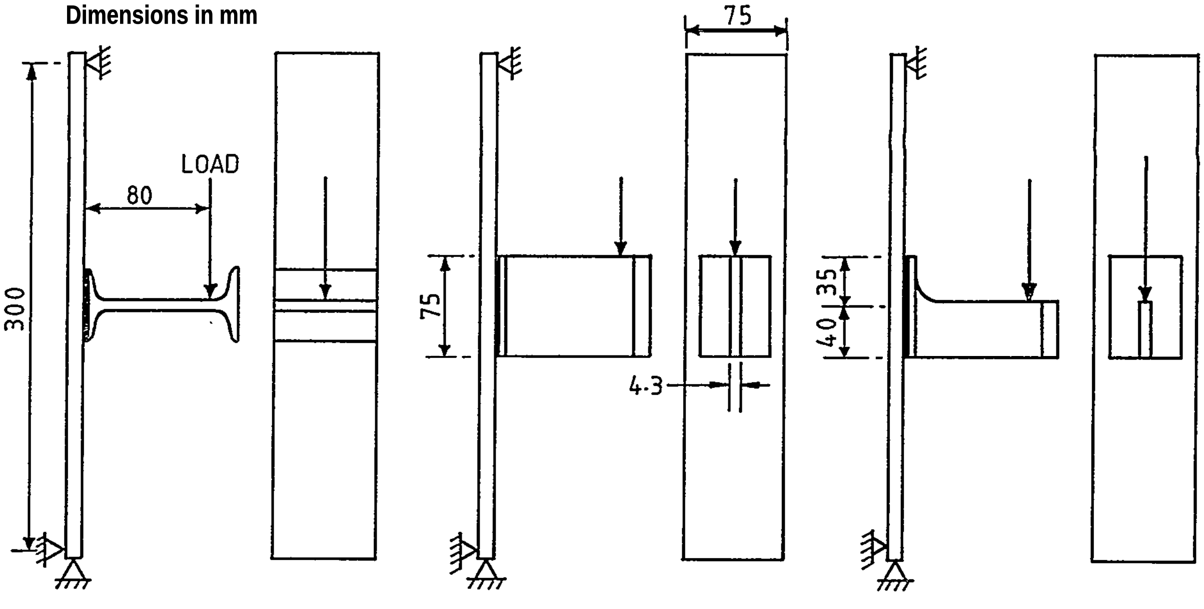
- shaped stiffener ends (type 3) are up to 50% stronger than their square cut (type 2) counterparts

- end cleavage strength is proportional to base plate stiffness - joints sustained twice the load on 10mm plates compared to 6mm.

Figures 7 and 8 illustrate typical specimens from these tests which did not fail in the adhesive.

Table I - Comparative Properties of Adhesives Tested

Adhesive	Form	Cure Temp	Cure Time		Strength		Elastic Modulus	Impact Resistance
				Shear	Tensile	Cleavage		
		°C	min	N/mm^2	N/mm^2	N/mm^2	N/mm^2	J/cm^2
E5238	paste	190	30	40.4	51.4	15.2	2010	6.7
ESP110	paste	180	40	44.8	82.3	16.1	11250	8.4
Araldite 2007	paste	180	30	48.5	86.3	18.8	5230	8.5



① SIDE LOADED (TRIPPING) SPECIMEN

② CLEAVAGE LOADING SPECIMEN (SQUARE END)

③ CLEAVAGE LOADING SPECIMEN (SHAPED END)

Figure 6 Cleavage specimens

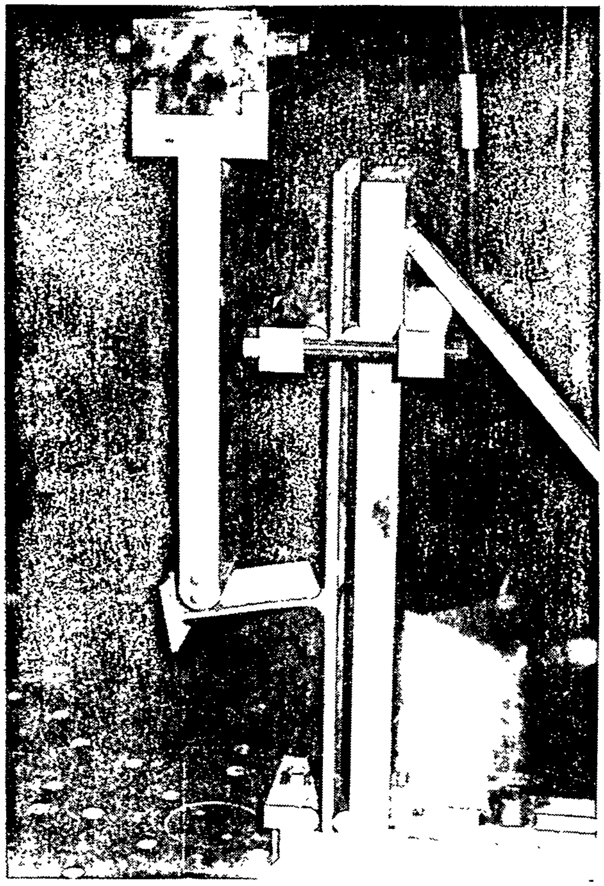


Figure 7 Side loading experiment

Figure 8 End cleavage experiment

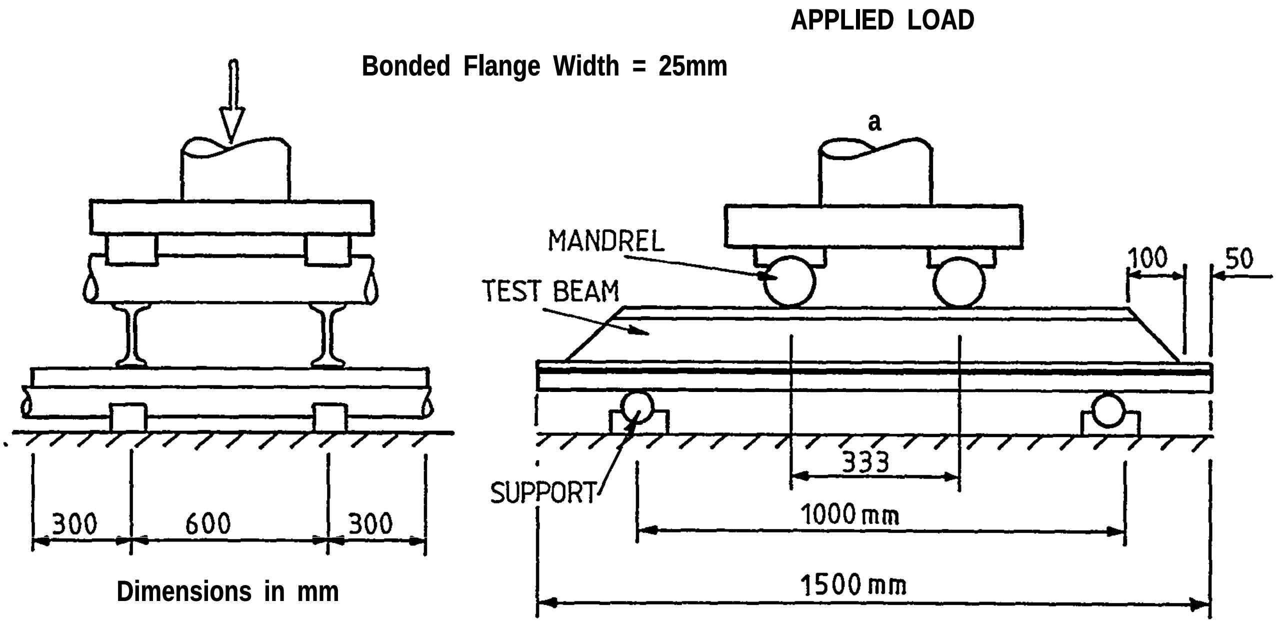


Figure 9 Four point bending test

2.3 Large Scale Panel Tests

To validate both the panel fabrication technique and the small scale tests outlined in 2.2 above, 1.5 x 1.2 m panels were fabricated, each carrying two 100 mm 'I' section stiffeners with reduced bonded flanges (25 x 2 mm) and tapered ends on 8mm plate, as shown in Figure 9. These were tested in four point bending over a span of 1.0 m, one from the stiffener side and the other from the plate side.

In each case central deflections of about 2.5% of span were achieved, by which time the stiffener web and flanges had collapsed as shown in Figure 10. At the elastic limit for these panels the maximum adhesive shear stress was estimated by composite beam theory to be about 28 N/mm^2.

2.4 Impact Tests

The behaviour of a bonded joint during impact loading is not only governed by the relative weakness of adhesives to cleavage/tensile stresses [26], but also by the fact that polymers, unlike metals. have properties which are relatively independent of strain rate [27. 28]. It was therefore suspected that one of the limiting criteria for the widespread application of adhesives would be poor impact resistance.

In order to gain some assessment of the parameters affecting impact resistance, a number of smaller beam elements were assembled using the same materials as in the large scale panels. Three different stiffener end conditions were applied (as shown in Figure 11) in conjunction with two adhesives of differing modulus and with adhesive thickness less than a nominal 0.5 mm. Two additional specimens were included with nominal adhesive thickness of 1.5-2-0 mm to examine the effects of adhesive thickness. The specimens were tested in a drop weight tower and the energy absorbed in dropping a round nosed steel projectile of variable mass up to 6.4 kg from heights up to

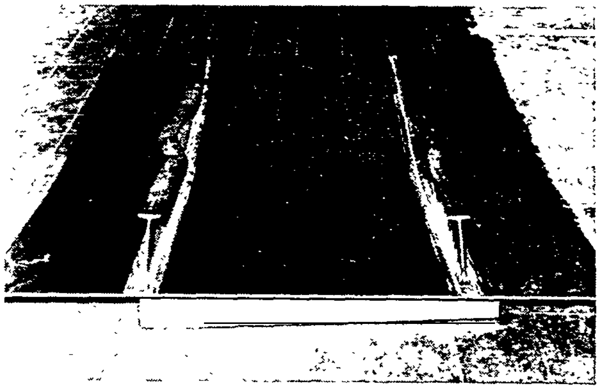


Figure 10 Large scale test panel showing buckled stiffeners

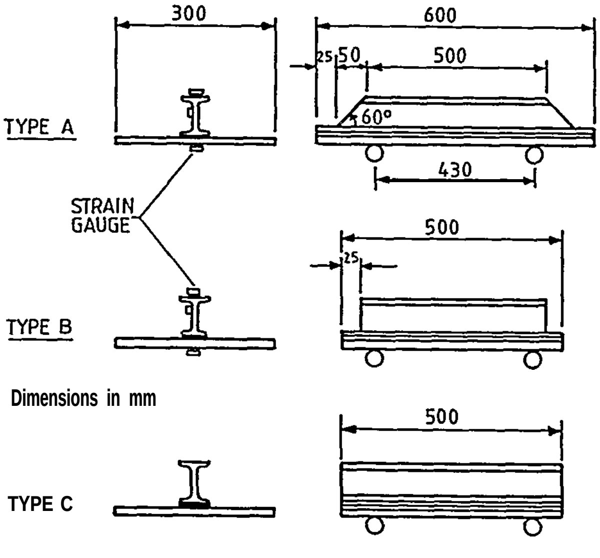


Figure 11 Impact test specimens

Table II - Summary of Impact Test Results

Adhesives:
A - Araldite 2007 Elastic Modulus 5 kN/mm2
B - ESP 110 Elastic Modulus 10 kN/mm^2

SPECIMEN	TOTAL ENERGY ABSORBED	DEFORMATION DEPTH	DEBOND %
	Joules	mm	
Impacts from stiffener side			
Type A / Adhesive A	565 x 3	7.0	60
Type A / Adhesive B	565 x 2	5.0	100
Type B / Adhesive A	565 x 3	7.0	0
Type C / Adhesive A	195 x 1	2.0	100
Type C / Adhesive A	195 x 3	4.0	100
Impacts from **plate** side - 0.5 mm nominal thickness			
Type A / Adhesive A	420 + 565	1.5	60
Type A / Adhesive B	420 x 1	1.0	5
Type B / Adhesive A	400x2	0.5	100
Impacts from **plate** side - 1.5 to 2.0mm nominal thickness			
Type A / Adhesive A	420 x 1	1.0	100
Type A / Adhesive A	420 x 1	1.0	100

12.5 m was determined. Most impacts were to the stiffener side, but impacts to the plate surface were included for comparison The experiments were repeated on each specimen until a failure occurred

The results of these tests are summarised in Table II in terms of specimen type, the total absorbed energy after repeat impacts (if applicable), depth of any local deformation in the impact zone and the extent of the debond at failure.

In the first three tests it was possible to deduce that the average impact load was about 250 kN and that this induced an adhesive shear stress under the point of impact of about 26N/mm^2. From these results it is possible to conclude that:

- the impact resistance is greatly improved by tapering the stiffener ends thereby reducing end cleavage (types A and B)
- the lower modulus adhesive appears to give better results although no significant difference is evident in small scale shear impact results (see Section 2.1)
- resistance to impact loading is better from the stiffener than the plate side, probably due the greater flexibility and energy absorption in local collapse of the stiffener
- the thinner the bond line the better the impact resistance.

To confirm the implications of these observations, a further series of small scale shear impact specimens were tested to BS 5350 part C4 as shown in Figure 5. In this case the adhesive thickness (Araldite 2007) was carefully controlled to vary from 0.05 to 1.5 mm. The results of these tests are shown in Figure 12. In these tests, the effect of thickness is clearly visible as a progressive decline in impact strength with increasing thickness, the impact strength reducing about 25% across the thickness range.

In itself, this finding does not appear to be all that significant, but the implications of the larger scale impact tests would suggest that the effect of thickness is far more significant in impacts which generate cleavage. In terms of long term structural integrity it therefore seems prudent to take all possible steps to minimise adhesive thickness during bonding processes within large structures, by careful attention to material preparation and clamping (without inducing large residual stresses).

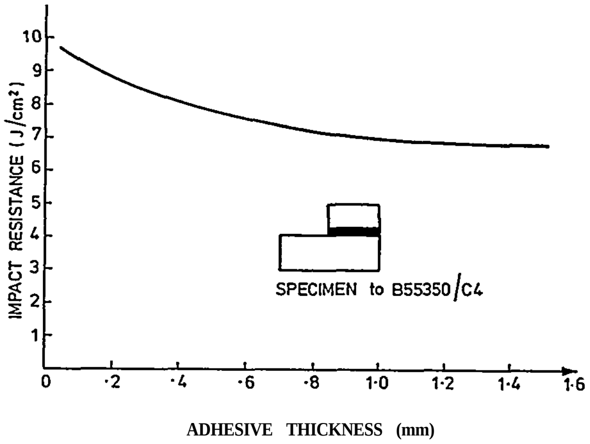


Figure 12 Effect of adhesive thickness on impact resistance (Araldite 2007)

3. SUBSEQUENT DEVELOPMENTS

Since the earlier programme of research outlined in Section 2 there have been a number of short and longer term projects which have enabled other factors to be tackled systematically. In particular, the behaviour of adhesives at elevated temperature, their fatigue strength and long term durability were all important areas of uncertainty which required systematic research. Attention has since been focused on research into steel sandwich structures which appear to offer possible cost effective alternatives to single plate, grillage structures and which would otherwise be difficult to manufacture by welding [29, 30]. In addition, since all the earlier work concentrated only on steel/steel bonding using hot cured epoxy adhesives, attention is now turning to the bonding of dissimilar materials for marine applications. In conjunction with a number of other UK universities, the Marine Technology Centre at Glasgow has therefore become involved in a collaborative research programme into the practical use of lightweight, fire resistant GRP structures for offshore applications. The bulk of this research at Glasgow is centred on the behaviour of GRP/steel and GRP/GRP joints bonded with two part, cold curing epoxy adhesives [31, 32] which directly complements the earlier studies. This work has been further complemented by a recent student study into the feasibility of bonding steel/timber/steel sandwich panels [33]. An overview of some of the more important findings from these studies is presented in this the rest of this section of the paper.

3.1 Temperature and Creep Effects

In order to verify the reduction of shear strength with temperature for the hot cured epoxies used in the previous studies, a number of tensile lap shear specimens to ASTM 3165-73 (see Figure 5) were tested at a loading rate of 0.5 mm/min while contained within an oven at constant preset temperature. The results of these tests are shown in Figure 13 for Araldite 2007. These results indicate the dramatic overall reduction in strength that occurs as temperature increases towards the cure temperature. This reduction is particularly accentuated on either side of the Glass Transition Temperature (T_g) - about 120°C for these adhesives. In general. about 25% of the room temperature strength is lost by 80°C and 70% by the T_g. Beyond 160°C only marginal strength remains until the char temperature of about 25O°C is reached - at which point the adhesive starts to carbonise.

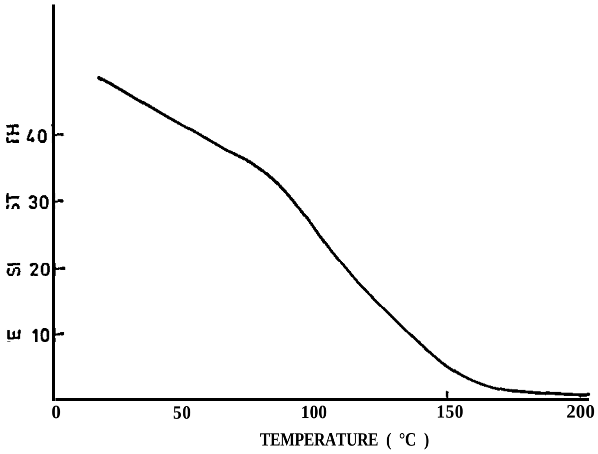


Figure 13 Strength-temperature profile of epoxy adhesive (Araldite 2007)

Not only does temperature affect the ultimate strength directly, but, in common with most plastic materials, it has a dramatic effect on the creep behaviour of the adhesive under sustained load. A continuing series of tests have been undertaken to try to evaluate this effect under a variety of load conditions, Figure 14 illustrates the creep deflection results for two different lap shear specimens maintained at constant temperatures and axial load. In each case the load was set as a percentage of the maximum failure load at room temperature. In the case of the specimen maintained at 130°C it is clear that even at very low stress levels failure will occur in a matter of hours. However, the 80°C specimen continues to creep at a slow, but predictable, rate without failure for many months. At any given temperature there is a small change in the stress regime which will cause the material to pass into a state of rapid tertiary creep resulting in failure.

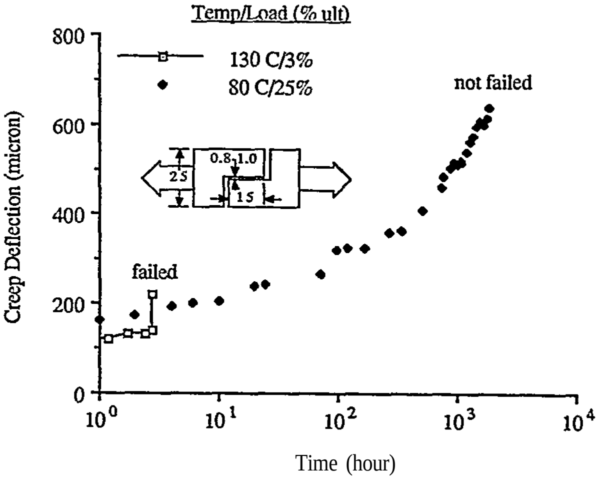


Figure 14 Thermal creep profile of epoxy adhesive (Araldite 2007)

The choice of factors of safety for steady or deadloads is therefore critically dependent on the operational temperature regime. Up to 80°C it seems that continuous stress levels of 15 to 20% of the ultimate can be tolerated, although some creep deflection may result. Above this temperature. creep effects become perhaps the major constraint on the use of this class of materials as only limited deadloads can be sustained for any length of time. These results have obvious implications for the behaviour of bonded steel structures in accidental fires and this particular adhesive property is likely to limit application in the first instance to areas where fire performance is unlikely to be critical unless protective insulation is applied. It is worth noting however that this aspect of adhesive performance has never adversely affected their take-up in the aerospace industries.

3.2 Fatigue Strength

There is already a wealth of standard fatigue data available relating to the performance of welded joints. The objective of a range of fatigue studies has been to compare the performance of adhesively bonded joints to this data. In line with the research programme outlined in Section 2.1, interest focussed initially on comparisons with Class F, non-penetrating. fillet welded connections. Test specimens were bonded as shown in Figure 15 to

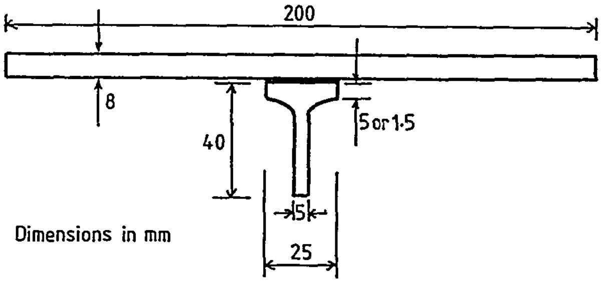


Figure 15 Fatigue endurance testpiece

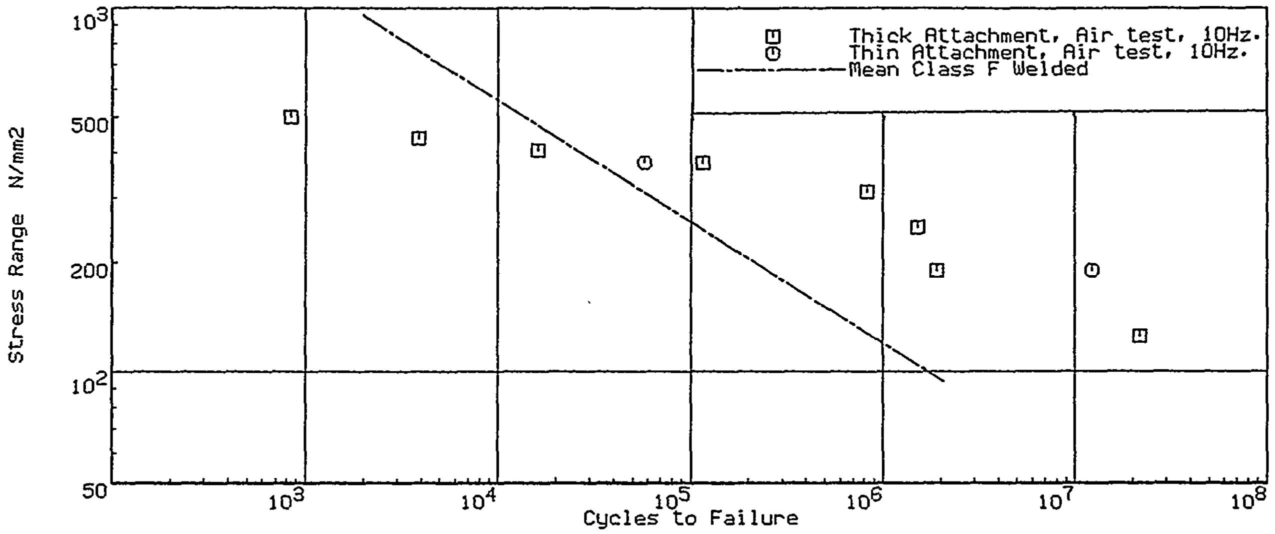


Figure 16 S-N data for adhesive joints compared to mean Class F welded

provide a joint with an unloaded bonded attachment. Constant amplitude fatigue loading with R ratios from 0.17 to 0.5 and a loading frequency of 10 Hz were applied transversely to the line of the stiffener.

The resulting fatigue endurance has been plotted together with the standard mean Class F welded S-N curve to give Figure 16. It can be seen that bonded specimens with both thick and thin attachments perform consistently better than the fillet welded equivalents. This can be explained in terms of the lower stress concentration and lack of residual stress between the low modulus adhesive and the lower stressed skin of the plate. In several examples the plate was observed to suffer fatigue cracking before failure of the joint which suggests that the the adhesive joint fatigue performance is at least as good as the plate material in this class of joint. A complementary series of thick plate (35 mm) bonded fatigue specimens will be tested in the near future.

Other classes of fatigue tests are also under way to compare the performance of bonded sandwich structures (see 3.4 below) with similar structural sections manufactured using through-thickness, laser welding techniques as proposed by the Teesdale et al [34]. Only limited results are currently available from these tests which are somewhat inconclusive. However, a number of small bonded butt joints conforming to the configuration of BS 5447 have indicated a high threshold of fatigue resistance when loaded to about 40% of their static load capacity while carrying an artificial crack-like defect (a sharp saw cut). They have so far sustained more than 5×10^7 cycles without failure or crack growth.

3.3 Durability in the Marine Environment

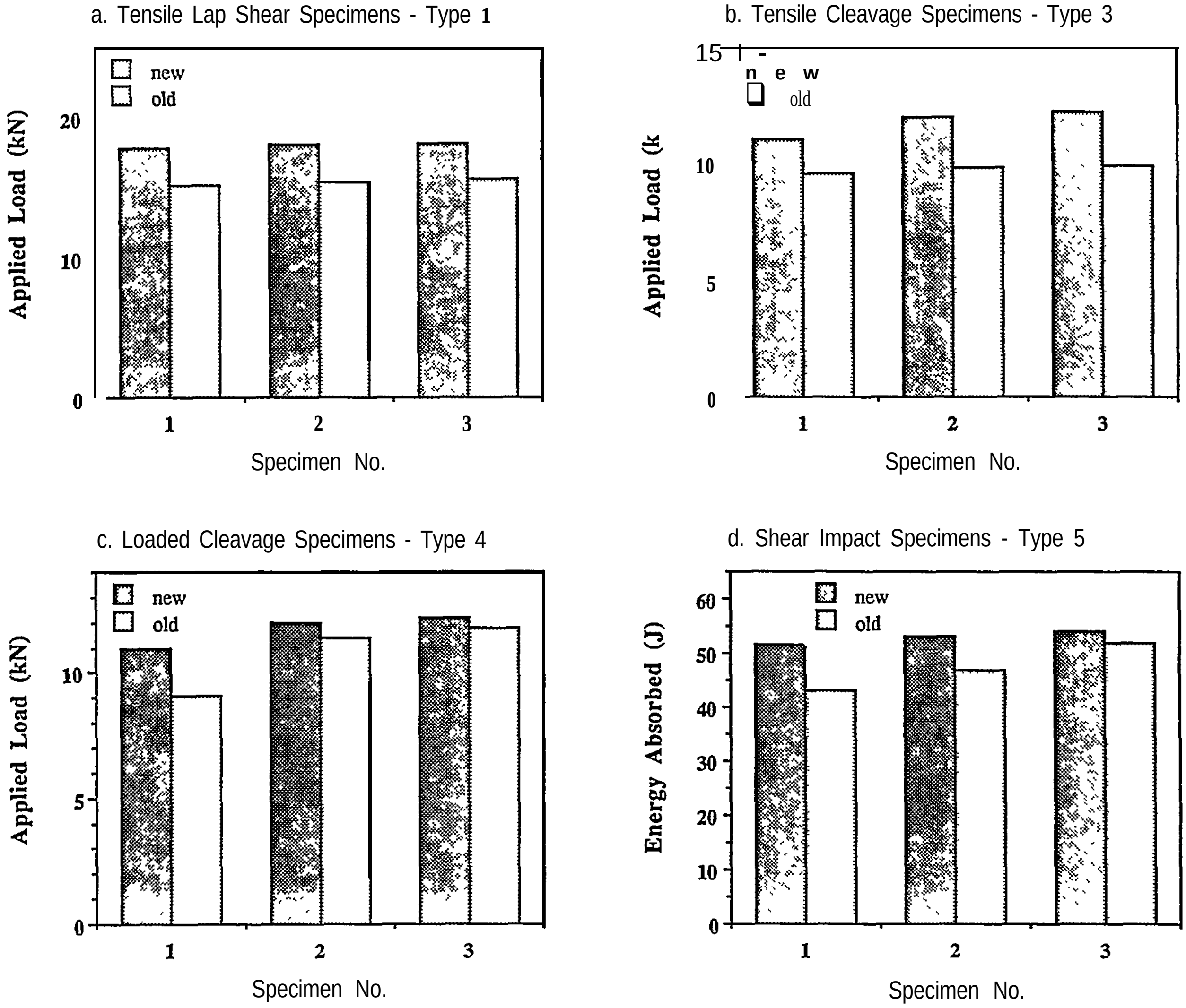
One of the early objectives of the initial programme of research outlined in Section 2 was to start the process of assessment of durability of steel/steel joints bonded with hot cured epoxy adhesive when exposed to a marine environment. Epoxy materials are naturally inert to hydrocarbon fuels, but can suffer weakening through the effects of plasticisation in contact with water. Furthermore, the possibility of the migration of water molecules to the steel/adhesive interface offers a real threat of degradation through the preferential displacement of the large molecular links formed between the adhesive and steel by those of the smaller, more chemically active. water molecules. Together with the possibilities of corrosion at the interface, there are a number of worries over the durability which are being addressed through two forms of long term experiment.

3.3.1 Unprotected specimens in abiotic sea water

The first study consisted of preparing a large number of standard test specimens of the types illustrated in Figure 5 having their bond surfaces initially primed with a silane. In all cases the spew fillets were left in place. These specimens were then immersed without any further protection in a bath of synthetic sea water to be withdrawn for testing at intervals. After a period of 28 months the first batch of 12 specimens has been tested to destruction in the same manner as the earlier batch of dry specimens discussed in Section 2.1. In this case, however, all specimens were tested in the fully plasticised. wet condition.

The results of each group of three specimens tests are compared in Figure 17 with those of the three original dry specimens for each type of loading. In all cases a small loss of strength can be observed. Losses of 15 to 17% were found for the tensile lap shear and unloaded cleavage specimens, while only 8 to 10% losses were observed in the preloaded cleavage and shear impact specimens. Considering that the latest results were all for fully plasticised specimens these are very encouraging results. Examination of the fractured bond surfaces showed no evidence of any corrosion at the interfaces despite the complete lack of corrosion protection to both the joints and specimens which were otherwise heavily corroded.

The effect of creep in the preloaded cleavage specimens was evident from the reduction in load at the locking screw from 45% of maximum failure load to about 20%.



a. Tensile Lap Shear Specimens - Type 1

b. Tensile Cleavage Specimens - Type 3

c. Loaded Cleavage Specimens - Type 4

d. Shear Impact Specimens - Type 5

Figure 17 Durability in abiotic sea water after 28 months

3.3.2 Painted lap shear specimens at sea under load

In August 1989 a number of tensile lap shear specimens were modified so that they could be strung together with stainless steel shackles to form a chain tensioned by a heavy weight to approximately 10% of failure load - see Figures 18 and 19. This chain is designed so that failure of any one bonded ‘link’ will not influence the remainder. The individual specimens have been bonded either with, or without, silane primers and all were fully coated on top of any spew fillet with an epoxy paint system similar to that used as the primary corrosion barrier in ships. The chain has been suspended from a pier in the intertidal range of the lower Clyde estuary where it is subject to the additional loads of waves and currents. Unless links are observed to fail in situ, it is planned to recover them at intervals in the future for testing to determine the ultimate effects of realistic continuous ‘marine’ exposure.

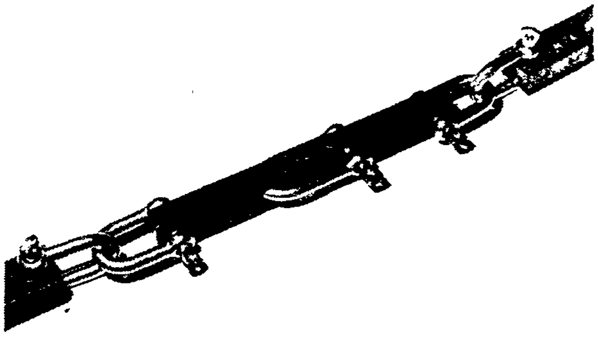


Figure 18 Lap shear joint (modified Figure 5)

3.4 Steel Sandwich Structures

Naval architects have always recognised the theoretical virtue of sandwich structures applied to panels of plating under axial compression or bending. Structural symmetry assures more efficient use of the continuous plate members and allows for the possibility of reduced weight for increased structural stiffness. However, to date such structures are only found in cofferdam bulkhead and side shell structures where the spacing between plates is sufficient to allow for access by welders. In

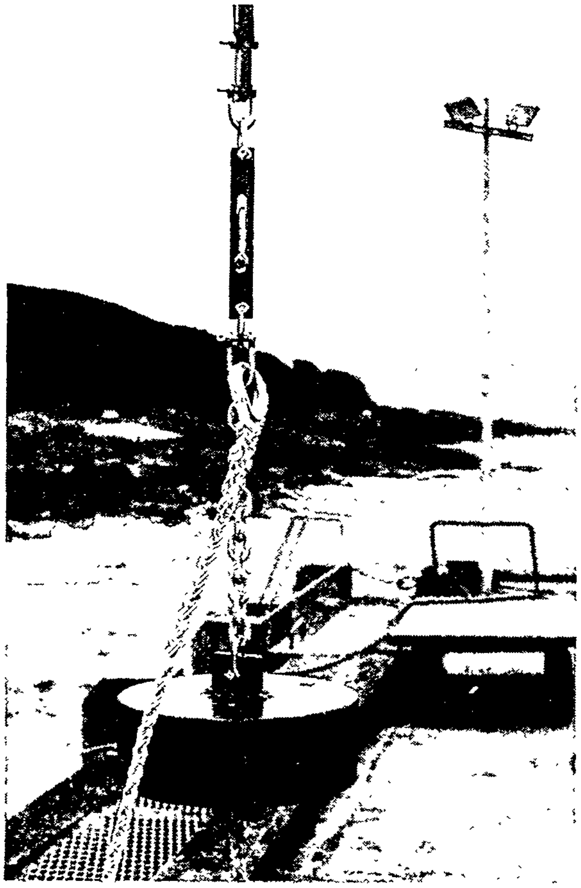
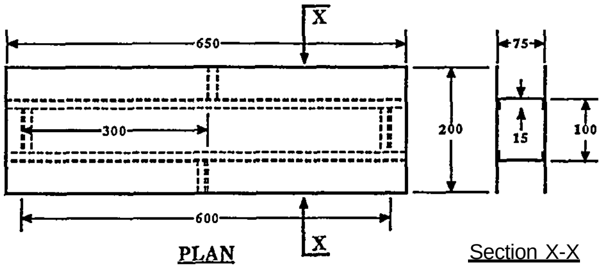


Figure **19** Weighted specimen chain at test site

such situations, the minimum thickness rules adopted for corrosion and abrasion resistance generally cancel out any benefits which might be obtained from increased stiffness and cost and weight increase. It has been recognised [34] that if methods can be found to join the materials reliably, stiff, lightweight, steel sandwich structures could offer advantages in some applications. To date. through-thickness, laser welding has been seriously researched to this end. and although possible, it is rather a long way from being practical. Adhesives, on the other hand, appear to offer a practical alternative if they can be shown to perform well in the stress regimes that are likely to apply.

To shed some light on this problem a short term project [29] compared the performance of fillet welded double skinned, double beam elements (shown in Figure 20) to bonded alternatives. In both cases the specimens were made throughout from 1.5 mm cold rolled steel plate, cut and flanged to form continuous longitudinal channels (75 mm x 15 mm) stabilised by short transverse channels at the loading points. Both ESP 110 and Araldite 2007 adhesives were used in accordance with the techniques indicated in Section 1. All specimens were gradually loaded and unloaded to the point of ultimate structural collapse in three point bending over a span of 600 mm as illustrated in Figure 21. The lack of any distortion due to welding stresses was noticeable in the bonded specimens and may have important implications for the fabrication of very lightweight structures.



All dimensions In mm
All material 1.5 mm thickness

All channel stiffeners formed 75 X 15 mm

Figure 20 Double skinned. double beam element

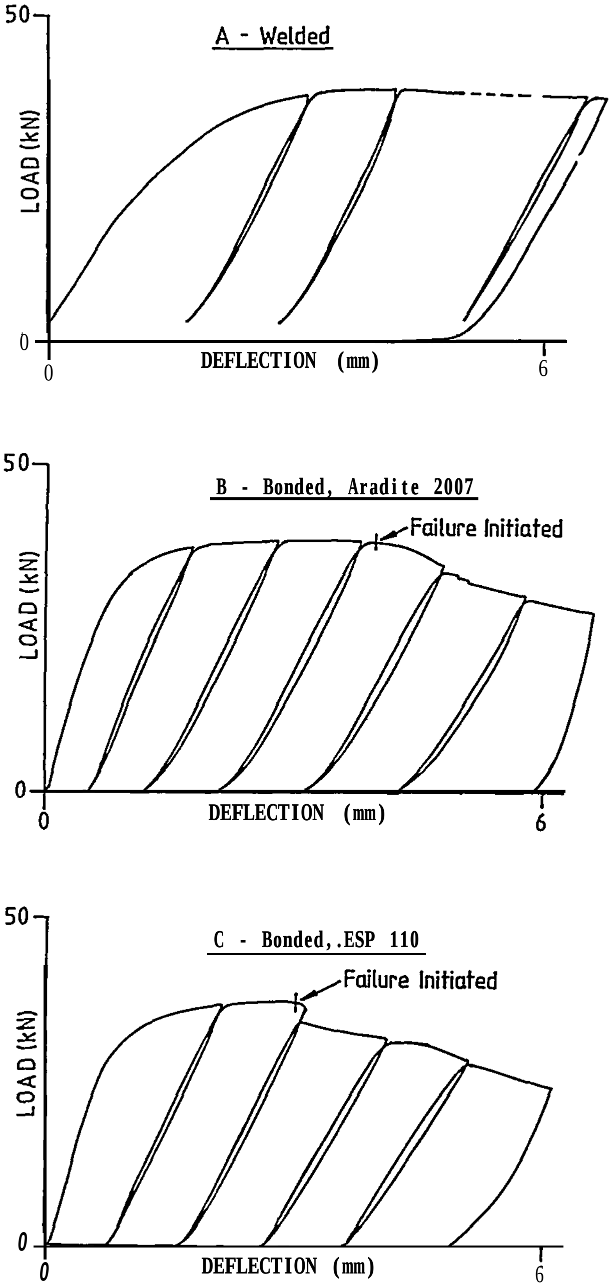


Figure 21 Load-deflection curves for double beam elements in three point bending

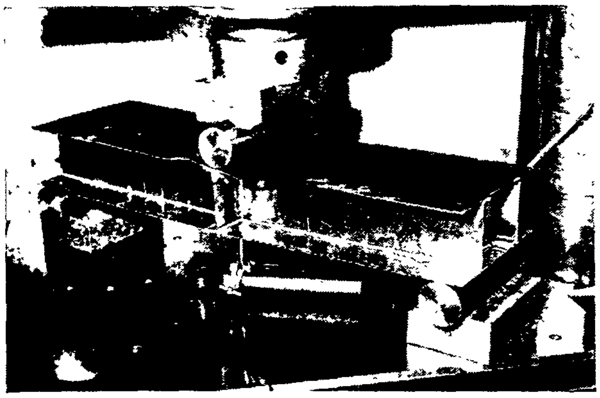


Figure 22 Bonded double beam element at ultimate failure

The load - deflection curves resulting from three of the specimens are shown as Figure 21(a, b and c). All specimens achieved approximately the same ultimate load of 37.5 kN. In doing so. however, the two bonded specimens (Figure 21b and c) displayed much greater stiffness in the elastic region than the welded specimen. This was initially somewhat surprising as the presence of a low modulus material between the flange and web of a composite beam should lead to slightly larger deflections and apparently lower stiffness. On closer examination of the welded specimen it was realised that the fillet weld lines were inducing longitudinal shrinkage of the top of the web which was evident from a rippled surface in the panels of plating between the webs. The bulk of the plating in the flange was therefore relatively ineffective in elastic bending until the specimen had been loaded to its plastic limit. At this point, plastic 'shake-down' results in all the material of the section becoming fully effective again as can be seen in the increased gradient following unloading, which is almost identical to that of the bonded beams. The ultimate failure mechanism of the bonded beams is similar to that of the welded specimen in that the compression flange buckles around the central load point. In the bonded beam elements the upward buckling half wave causes local cleavage/tension failure in the bonded joint - see Figure 22. Continued loading results in a progressive 'unzipping' of this joint, ensuring that considerable plastic load capacity is retained without catastrophic failure.

A more substantial programme of research is now in hand to investigate the structural efficiency, behaviour and feasibility of bonding steel sandwich structures using a variety of internal steel cores, including standard structural sections, and varied forms of corrugations.

3.5 Bonding Steel to Other Materials

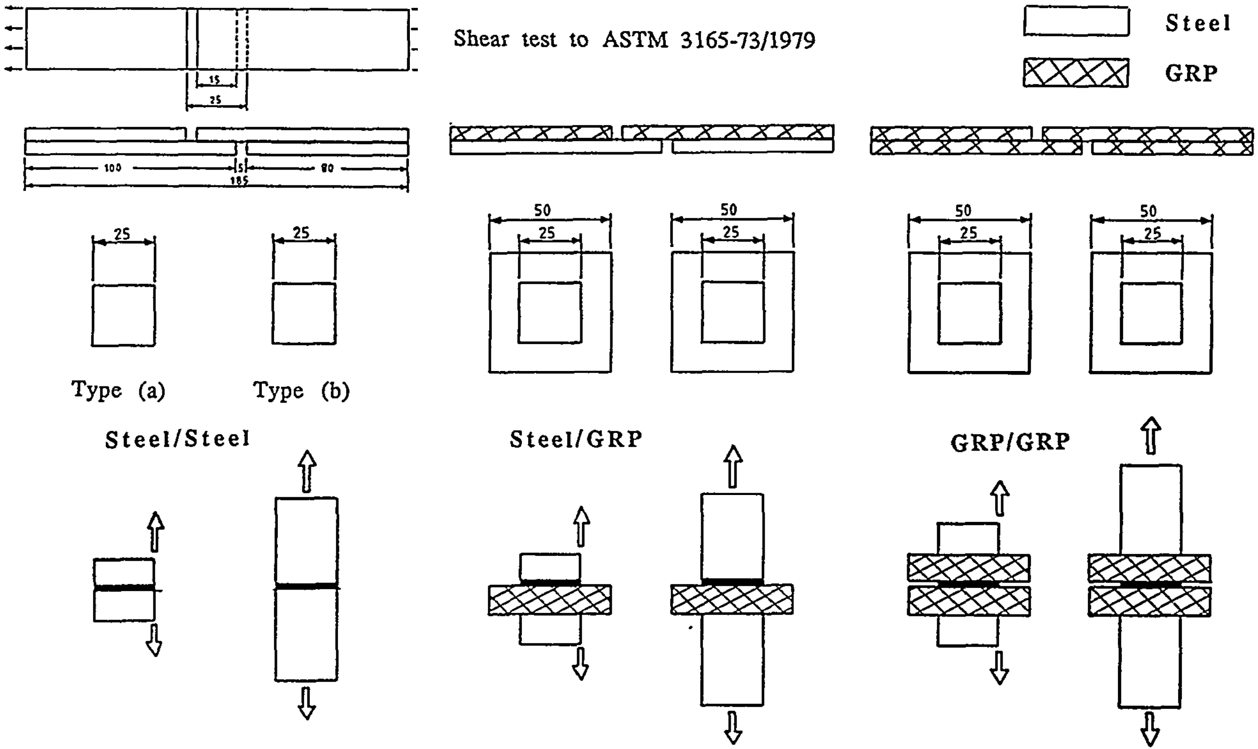
Adhesives have obvious potential for the joining of dissimilar material where the only competitive methods are bolting or rivetting. As both these alternatives cause significant damage through local stress concentration and fretting, the use of adhesives offers a means of spreading loads efficiently without localised damage. However if this is to be done efficiently then the performance of suitable structural adhesives must be assessed in much the same way as has been indicated for steel/steel joints.

Many applications are being proposed for GRP and similar composite materials in the topsides of ships and offshore structures [25, 35, 36]. Apart from minimal maintenance, the benefits are a combination of low modulus (enabling the structural disconnection of superstructures and hull girder) and weight. In addition, such properties as good ballistic resistance and poor thermal conductivity which enable these materials to be considered as major components of fire and blast walls. After the considerable experience gained through the development and production of a long series of GRP mine counter measures vessels (MCMV), it is now possible to manufacture large structural components in such materials with a high degree of confidence in their performance and durability.

Most earlier structures relied on the forming of GRP 'top hat' stiffening members on panel components using the same polyester resins to bond the components as were used in the layup. Modifications of this process now employ flexible acrylic resins at the flange comers to minimise the effect of stress concentrations in this joint [36]. However in topside applications, there are clear advantages in being able to attach such panels to steel stiffening sections which form structural ring frames [25]. In addition. pultruded GRP sections are now available which, together with mass produced flat GRP panels and filament wound tubes, now form the building blocks for a wide range of fabricated GRP structures. Adhesion has a major part to play in all these applications.

As part of a wider collaborative research programme with other UK universities, the properties of a range of two part, cold curing, structural epoxies are being investigated, for application to steel/GRP and GRP/GRP joints. Epoxies are in general quite compatible with, if generally stronger than, the polyester resins used in the relatively low cost polyester, 'E' Glass (woven roving) GRP which has so far been widely used for marine applications. In these studies, it has been particularly important to find adhesives which perform well both in potential fire conditions as well as a marine environment. This has generally been at the sacrifice of other strength properties. In the first instance a comparative study was undertaken into the relative strengths of a range of adhesives using adaptations of the small scale standard tests outlined in Figure 5. In this way the number of candidate adhesives for further testing was reduced to two. To complete the study, a number of steel/steel joints were included to form a reference point for the strength of the other material combinations and to provide a comparison with the hot cured adhesives discussed above.

The results of a range of small scale tests, indicated in Figure 23, are given in Table III, show how the strength of a joint is a function, not so much of the adhesive used, but more of the relative stiffness of the joint and surface energy of the adherends. With metal adherends, joint failure can be adhesive, cohesive or by yield of the adherend itself. With GRP adherends. the failure is generally tensile interlaminar or transverse, either within the resin or at the fibre/resin interface. Surface preparation is a particularly important feature in assuring joint strength. With GRP, some of the best results have been obtained through the use of an



(a) Cleavage test to BS5350-Cl/1986

(b) Tensile test to BS5350-C3/1978

Figure 23 Small test specimens varied adherend combinations

outer peel ply layer, which after removal and degreasing leaves a thin roughened resin layer which requires no further preparation for a reliable bond. The use of peel plies seems to be the most practical way of assuring good preparation in a large fabrication environment through the added protection offered to joint surfaces prior to bonding. The best alternative to the use of peel plies has been found to be shot blasting which provides a good key for the adhesive, but tends to damage the outer fibre layers and leave embedded dust particles.

A small project has recently been completed [33] which considered the viability of combining structural components of timber (birch plywood) with steel. In this case a series of sandwich beams were constructed, similar to those discussed in Section 3.4, in which timber was used as the core material. After some difficulty it was realised that hot cured adhesives were unusable in this configuration because, when hot, the adhesive is drawn off the surface of the joint into the fibres of the timber. Two cold cured adhesives were therefore used - E32A (Permabond) and SP120 (SP Systems). Small scale tests indicated good bending shear stresses performance for cold rolled steel plate bonded to a machine cut cross-section of plywood with outer grain parallel to the joint. In the case of E32A the failure was invariably initiated in the fibres of the parallel grain timber. Replacing the cold formed channel sections shown in Figure 20 with 75 x 24 mm birch ply sections and increasing the plating thickness of the flanges to 2.0 mm, it was possible to obtain ultimate loads of about 48 kN at the mid point of a 550 mm span in three point bending. In all cases failure occurred

Table III - Bond Properties of Araldite 2004 Epoxy Adhesive

(τ and σ = F/Bond Area)

Combination	Specimen No.	Shear Strength		Tensile Strength		Cleavage Strength	
		F (kN)	τ (N/mm^2)	F (kN)	σ (N/mm^2)	F (kN)	σ (N/mm^2)
Steel/Steel	1	13.0	35.0	21.3	34.0	5.2	8.3
	2	12.5	33.0	20.0	32.0	5.1	8.2
	3	12.6	34.0	20.0	32.0	5.2	8.3
Steel/GRP	1	4.9	13.0	9.6	15.4	2.9	4.7
	2	4.8	12.8	10.0	16.0	2.5	4.0
	3	5.0	13.3	8.9	14.3	2.4	3.9
GRP/GRP	1	3.5	9.3	4.9	7.8	2.0	3.4
	2	3.6	9.6	5.0	8.0	2.3	3.7
	3	3.5	9.6	5.2	8.3	2.1	3.4

close to the plastic limit load in the upper (compressive) joint, propagating fairly rapidly to the free edge through failure of the timber as in the small scale tests. In the case of E32A there appeared to be more arrest stages during final failure than with SP120, probably due to the toughened nature of the former adhesive. Throughout the elastic region the stiffness of these composite beams was very close to that predicted by composite beam theory. The joints appeared to be unaffected by the tendency of the timber to creep (most of which is recoverable) under high load.

Although limited, the results of the steel/timber beam study support the more general composites research in suggesting that adhesives offer the possibility of employing a wide range of material combinations in heavily loaded composite structures. A lot remains to be done, however, in establishing the practical limits for such applications.

4. DISCUSSION

Despite the low strength, low modulus and generally brittle nature of most adhesives in their bulk state, it is possible to design joints of high load bearing capacity in a range of adherends that can be applied a wide variety of marine structures. Furthermore, such joints appear able to resist substantial impact and survive plastic deformation of their adherends without catastrophic failure. In particular, the lack of stress concentrations resulting from bonding offer real advantages through the limitation of structural distortion and/or improved fatigue performance. In general it appears that in many configurations the fatigue performance is limited only by that of the adherends themselves.

Durability in the marine environment is still uncertain, as experience can only be gained slowly. The degree of care with which joints are prepared is an important factor in this respect, but given certain minimum standards of preparation and protection. there is little to suggest any long term problem in this respect. Already there is eight years of experience [12] to suggest that the general class of epoxy adhesives appears to suffer little long term degradation in sea water, while experience in the aerospace environment suggests that so far as the durability of this class of adhesive is concerned there are no significant long term problems over periods of 20 years or so.

There are some concerns over the limiting performance of most adhesives with temperature, but this is not a problem so far as day to day operation is concerned for many marine applications. Since most fixed and floating structures must be insulated against the risk of serious fire there are ways in which this weakness, once recognised, can be minimised or eliminated.

The strength of bonded joints depends to a large extent on the stiffness of the adherends and a joint design which avoids the possibilities of significant cleavage stress. Since cleavage is often the by-product of tensile and/or bending stress. this implies the avoidance of such environments and the placing of joints in compression and shear if high loads are to be carried. The designer should therefore refrain from duplicating welded design in detailed design and location of joints and try instead to optimise the advantages of adhesives.

The limiting strength of a bonded joint is largely a function of the stress concentrations at the edges of the joint. Average stress values are useful for comparative assessment, but may be misleading when applied to a design. Great care must therefore be taken in attempting to extrapolate large scale performance from small scale tests. Modification of the spew fillet and local stiffness of the adherends can also have a marked effect on the local stress concentrations and therefore on the performance of the joint itself. The nature of these stress concentrations is generally predicted by detailed Finite Element (FE) analysis, but the fracture/failure process is still poorly understood.

FE analysis can be useful in correlating failure stresses within large joints with those predicted from small scale tests. Figure 24 illustrates the non linear stress distribution predicted from elastic FE stress analysis at the failure load of 20 kN in a tensile lap shear specimen. Although such analysis probably overpredicts the maximum stresses (which are beyond the elastic range of the bulk adhesive). such results are very useful in attempting to quantify stress levels when assessing the failure mechanisms of larger joints Accuracy and reliability are dependent however on careful modelling of the boundary conditions and the various material properties. Accurate modelling of the failure mechanism in particular, and FE analysis in general, is made more difficult by the difficulty of assessing the bulk properties of the adhesive materials themselves and by the many proposed, but still rather uncertain, failure criteria.

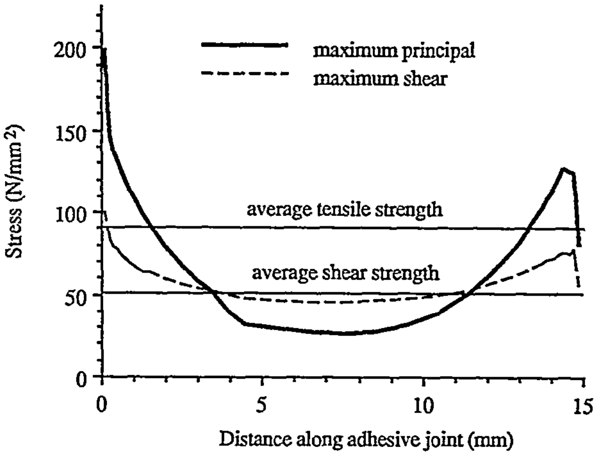


Figure 24 Stress distribution of a lap shear joint at failure

At present it has to be acknowledged that quality assurance is a practical problem associated with assembly of most adherends as the joint, once made, is generally difficult to inspect. Continuity of exposed bond line surface is often a good guide to the continuity of the joint as a whole. but there is no straightforward way of inspecting the degree of bonding once the assembly process is completed. However, under most forms of loading, the edge of the joint is the most highly stressed, and hence the most critical region. Large voids and other defects may be detectable by tap tests [37], but the detection and significance of small voids is not yet well understood [38]. It should always be remembered that similar quality assurance problems exists with the fleets of composite MCMV's and yet they have not hindered their deployment.

5. CONCLUSIONS

Adhesives are part of a technology slowly coming of age. Welding took more than 20 years to be generally accepted in shipbuilding, but is now dominant. A similar time scale is needed for adhesives to gain general acceptance and for their complementary nature to welding to become fully appreciated. In that time a great deal of research and development is required - but why bother?

- There are new designs that can perhaps only be successfully accomplished with their use.
- Their use in conjunction with welding may result in more cost effective structures.
- Engineers would like to exploit the potential of new materials or combinations of materials to the full in cost effective designs.

As mankind moves inexorably from the surface into subsea environments in the next century innumerable applications for lightweight, reliable structures will emerge, many of which will require the use of sophisticated adhesives. As the applications develop, the adhesives themselves will improve so that many of the problems identified at present will be overcome. Adhesives, and the possibilities they offer for new material combinations, are being launched on a new user community - it is up to that community to determine whether they will float!

6. ACKNOWLEDGEMENTS

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Metric Conversion Table

1 m = 3.28 ft
1 cm = 0.394 in
1 mm = 0.039 in
1 N = 0.225 Ibf
1 kN = 224.8 Ibf
1 J = 0.7376 ft-lbf
1 N/mm2 = 145 Ibf/in^2
$^{\circ}C = (^{\circ} F - 32) \times {}^{5}/_{9}$

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