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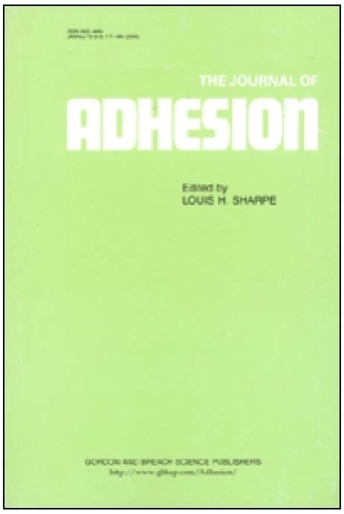

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ASPECTS OF JOINT DESIGN AND EVALUATION IN THICK-ADHEREND APPLICATIONS

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ASPECTS OF JOINT DESIGN AND EVALUATION IN THICK-ADHEREND APPLICATIONS

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Structural adhesives are gaining wide recognition by industry as they offer engineering designers greater flexibility to achieve economic and technical advantages. In the marine industry there are potential applications for adhesives in various types of construction, for example, thick steel and composite adherends, (typically 5–15 mm thick). The applications include panels and large pipes. This article is largely concerned with the use of two-part epoxy adhesives. The purpose of this article is to understand and evaluate the weaknesses of adhesives and adherends, in relation to specific applications and to use design and material selection to alleviate them. This understanding can be extended to other thick adherend applications. This article will also highlight the impact of structural epoxy adhesive technology on the design and fabrication of steel, composite, and hybrid constructions. The benefits and inherent limitations that can accrue are quantified through three case studies related to thick adherend connections.

Keywords: Joint design; Epoxy adhesives; Steel; Composite

INTRODUCTION

Structural epoxy adhesives show good potential in thick adherend applications [1, 2], and the choice of a suitable adhesive is important for good joint performance. Each study deals with a design aspect and with different materials combinations. The cases discussed below

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include the effect of tapering on the strength of steel and composite joints, adhesion characteristics of composites, and the effect of elevated temperature on hybrid steel/composite adhesive joints. In all of these studies, aspects of experimental and numerical techniques will be discussed and key conclusions will be drawn. Adhesive selection for the three cases is centred on design requirements and on an experimental programme based on test specimens modified from various BSI and ASTM standards. The choice of suitable standard test specimens to study adhesives for thick adherend applications should take into account the need to resist cleavage and shear modes of failure in stiff joints. These specimens can be modified to account for various materials combinations [3]. Figure 1 shows small shear, cleavage, and bulk adhesive test specimens that have no cracks. The fracture mechanics approach is not considered here. Data from the mechanical testing of bulk adhesives and bonded joint specimens can be used by designers to estimate structural joint strength using closed-form stress analyses.

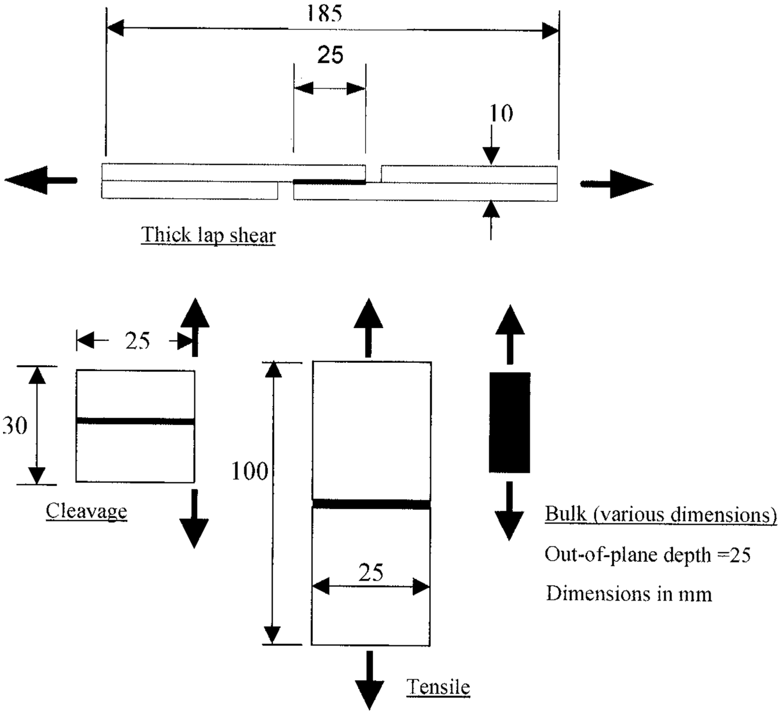


FIGURE 1 Small test specimens (various materials).

TABLE 1 Properties of Typical Two-part Epoxy Adhesives

Epoxy Adhesive	No. 1	No. 2
Cure temp. (°C)	20	20
ambient elevated	70	70
Cure time (min.)	2 day	1 day
ambient elevated	120	60
Gap filling (mm)	>0.5	>0.5
Max. service temp. (°C)	70	150
Young's modulus (GPa)	2	4
Poisson's ratio	0.35	0.35
Bulk tensile strength (MPa)	35	30
Av.* shear strength (MPa)	25	34
Av.*cleavage strength (MPa)	17	8

*Determined by dividing failure load by the bond area of steel joints (15 mm × 25 mm for shear & 25 mm × 25 mm for cleavage).

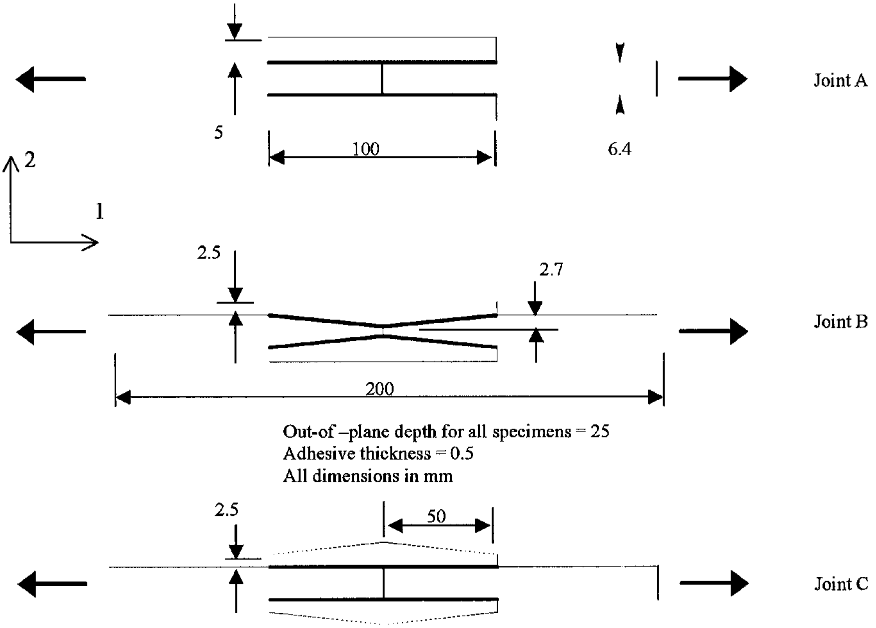
Table 1 shows the properties of two types of toughened two-part epoxy adhesives that have the ability to resist brittle failure to varying degrees and are used throughout the three cases in this article. These are suitable for bonding steel and polymeric composites and can be cold or warm curing. Adhesive No. 1 offers good cleavage strength while adhesive No. 2 has relatively high temperature resistance. Full curing of the adhesives may take days to achieve at ambient temperatures. They can also be warm cured, typically at 70°C for up to 2 h. Adhesive manufacturers are usually able to specify the curing schedule to give optimum adhesion.

The bonding process for steel or composite construction would typically require seven operations [4]. These are surface roughening, degreasing, marking, application of adhesive, positioning of clamps, curing, and removal of clamps. Silane primers can also be applied to steel surfaces to provide chemical and physical protection mechanisms to inhibit corrosion and promote adhesion. It is important that rules concerning safety precautions for working personnel are observed with reference to the COSHH regulations, particularly for skin protection and ventilation.

CASE STUDY 1: TAPERING JOINTS

The strength of a defect-free joint is largely governed by the stress concentrations at the edges of the joint [5]. The nature of these stress concentrations can generally be predicted by finite element analysis (FEA). Besides the properties of the adherends and the adhesive used in a joint, the design details of the joint are equally important for optimum performance. In thick adherend applications there is a benefit in making some simple changes to the joint geometry, such as stepping or tapering of adherends. This is impractical in thin adherend applications due to difficulties of machining thin adherends. The adhesive fillet has been shown to have a relatively small effect on the strength of thick-adherend joints, which is about 5% of the total strength for lap shear joints [4]. To investigate the influence of joint details on the design of thick-adherend joints, three steel double-lap shear joint designs were studied and are shown in Figure 2. The joints were bonded with adhesive No. 2 and tested under monotonic tensile loading to destruction at ambient temperature. The results are shown in Table 2. The loads at failure for joint B are 10% higher than those for joints A and C. Failure appeared to take place at the interface between the loaded steel adherend and adhesive line, initiating from one end of the joints' edges. This failure is typical for the three joints.

To understand the failure and behaviour of joints A and B, a linear elastic FEA was used to determine adhesive stresses in these joints.



Out-of-plane depth for all specimens = 25
Adhesive thickness = 0.5
All dimensions in mm

FIGURE 2 Double-lap steel shear joints (showing local coordinate system).

TABLE 2 Failure Load of Double Lap Shear Joints (Figure 2), Using Adhesive No. 2

Specimen designation	A	B	C
Failure load [kN]*	40	44	40

*From one-off specimen with a typical COV = 4% for such specimens.

These were modelled in two-dimensional (2D) eight-noded reduced integration quadrilateral shell elements using PATRAN preprocessor and ABAQUS processor with five elements through the 0.5 mm adhesive thickness. As usual, fine-mesh elements were applied to the adhesive region at the edge to account for the high-stress gradient. Plane-strain conditions with elastic isotropic properties were considered for both steel and adhesive. The adhesive properties are based on the values in Table 1.

Figure 3 shows normalised shear and cleavage adhesive stress distributions along the normalised distance representing half of the adhesive line (50 mm) for joints A and B. The stresses are taken at the nodes nearer the surface of the loaded adherends (Figure 3). The normalisation is based on maximum shear stresses at joint failure of joint A. The maximum shear stress is reduced by about 7% in favour of tapered joint B, nearer the outer edge (distance ≈ 0). The maximum cleavage stresses are generally small for such joints, but their reduction is more substantial (75%). At the inner edge of the joint (distance ≈ 1) both cleavage and shear stresses are lower than at the outer edge. In addition, tapering results in a better stress distribution along the joint by utilising a larger portion of the joint. This could be important for a good fatigue performance of such joints.

The stress values for joint B relate to the global coordinate system shown in Figure 2. Coordinates parallel and perpendicular to the tapered surfaces were not considered due to the small tapering angle (approximately 2.8°).

Reducing the thickness of the tapered ends of the straps adherends in joint B down to approximately 1 mm, could increase joint shear strength; however, this requires further study. Besides the machining difficulties to achieve such geometries in panels, for example, this will not meet the minimum thickness recommended by Classification Societies (*e.g.*, Lloyds or DNV) for steel substrates to resist corrosion, typically a minimum of 3 mm. The thickness of the tapered ends of the loaded adherends in joint B is about 1 mm. This might be acceptable because the adhesive and straps encapsulate these ends, preventing them from corrosion.

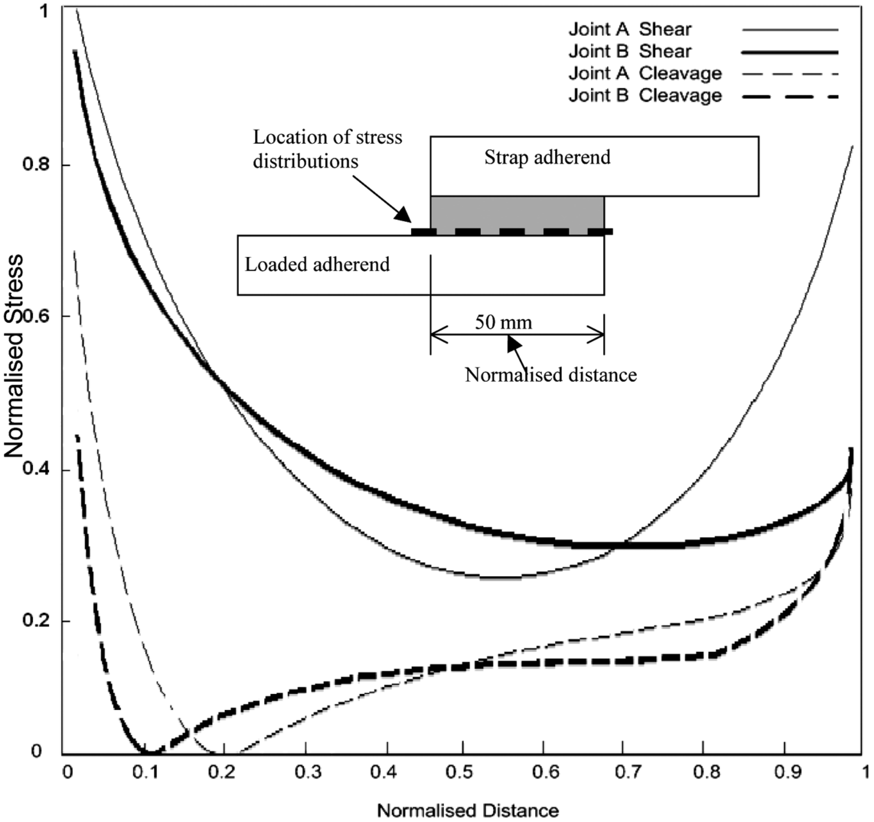


FIGURE 3 Effect of tapering on adhesive stresses in thick-adherend double-lap shear joint.

The reduction in shear and cleavage stresses by tapering is even more important in composite adherends due to their low through-thickness strength. Unlike metals, there is no minimum thickness limits to allow for corrosion. Adherends, tapering details similar to the above were found useful in bonding epoxy composite pipes used for offshore water-handling systems [6, 7]. Changing from a parallel pipe connection (quick-lock system) into a tapered equivalent was undertaken to achieve some design advantages. A double tapering of 2.5 degrees was achieved by using a manual turning shaving machine tool, which produced the 100 mm diameter pipe joint shown in Figure 4. The overall strength of this connection under tensile loading might not appear to be improved compared with the parallel equivalent [6]. The maximum adhesive shear stress near

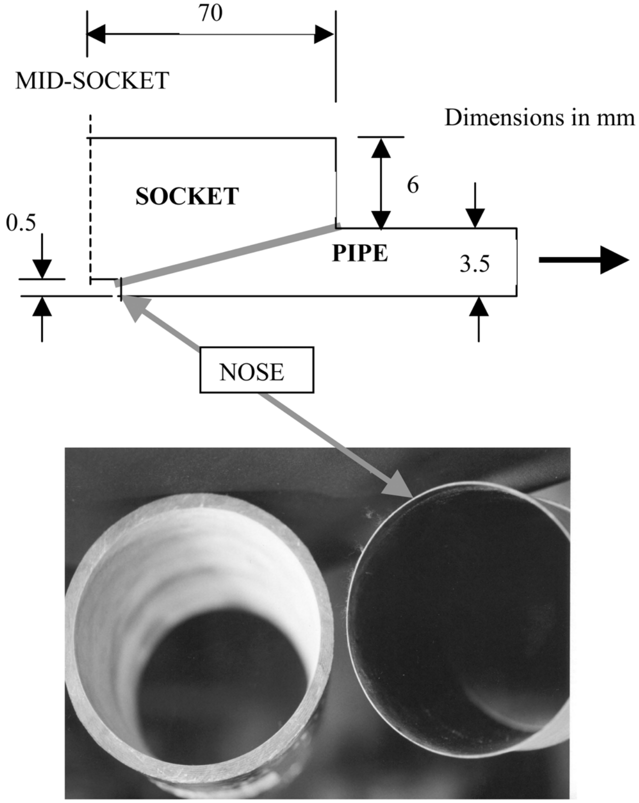


FIGURE 4 Details of shaved GRE pipe connection (100 mm diameter).

the socket edges for both configurations remains the same due to the limited tapering of the socket edge (6 mm thickness). However, the shear stress near the end of the tapered pipe (middle of the socket) is reduced due to the thin nose (0.5 mm thickness). Although the nose stresses are lower than at the edges, it is not possible to inspect the nose position visually (blind joint). Hence, any stress reduction increases confidence in the structural integrity of the connection. Besides the reduction in adhesive stresses, assembly of a tapered pipe joint gives a smaller clearance fit between the pipe and socket, and this could add further design advantages according to the manufacturer. Firstly, it reduces adhesive line thickness, which could improve joint strength, and secondly, tapered clearance helps to wedge the joint, which makes handling of the pipe prior to and during the curing process easier on site.

CASE STUDY 2: BONDING COMPOSITES

Adhesion in high stiffness composite joints is largely influenced by the resin system used and the moulding condition of a laminate/ component [8]. In stiffened panel connections, tensile loading modes result in failure due to cleavage stresses. To investigate the cleavage limitation, small cleavage specimens (Figure 1) were used to determine average strength. Three types of composite adherends were used, namely a pultruded (PU) laminate based on glass/polyester, hand lay-up glass-reinforced (GRP) laminate based on glass/polyester, and a glass-reinforced epoxy (GRE) laminate produced from glass/ epoxy prepregs. These were bonded to steel adherends using adhesive No. 1 to form hybrid steel/composite specimens [3]. In addition, steel/ steel joints were also tested for comparison.

Prior to bonding, all the adherends were gritblasted and bonded with the adhesive and then tested under monotonic tensile load to failure. The average cleavage strength results, which clearly illustrate the weakness of the PU/steel combination, are shown in Table 3. Results show that the GRP/steel cleavage strength is 40% higher than for PU/steel, and the difference indicates a reasonable level of adhesion compatibility between the GRP and PU (due to similar materials properties, especially resins) in comparison with steel and GRE cleavage strength. All composite adherends failed in the resin matrix, which confirms the importance of the resin in determining the strength of thick adherend joints. On the other hand, the table shows that epoxy resin-based composite laminate (GRE) gives significantly higher cleavage strength that is comparable with steel joints.

The PU material has low adhesion and subsurface strength due to the nature of the moulding process, where a mould release agent is mixed with the matrix resin to prevent adhesion between the PU section and die. As a result, the adhesion is compromised, and any surface preparation and type of epoxy adhesive have little effect on shear strength [8]. However, in recent work [10] the lay up of the reinforcement fabrics was found to have some effect on shear strength, but these were relatively thin adherends (2 mm). These results give an indication of this weakness in tension. In lay-up moulding of

TABLE 3 Cleavage Strength Test Results for Materials Bonded to Steel, S (Figure 1)

Material combination	PU/S	GRP/S	GRE/S	S/S
Av.* cleavage strength [MPa]	5	7	14	17

*Average from three specimens with COV = 11%.

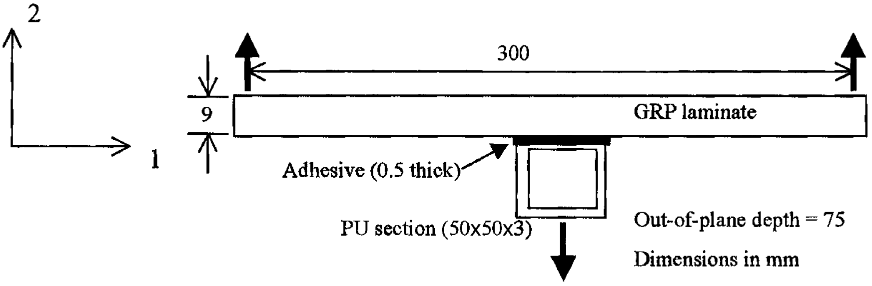


FIGURE 5 Laminate–stiffener test of panel joint.

laminates, the moulding release agent is normally applied to the surface of the mould, and the contamination on the moulded surface can be removed by abrasion or grit blasting prior to adhesive bonding.

To translate the practical issue of compatibility between GRP laminates and PU sections these can be used in bonded panels of both single-skin and sandwich constructions [8]. Such panels may be used for offshore and marine applications, where they could be subjected to transverse loading during service conditions, producing considerable cleavage stresses in the adhesive joints. The strength of PU/GRP-bonded joints was studied using both mechanical testing and linear elastic FEA. Figure 5 shows details for a stiffener/laminate tension joint that was tested in dynamic fatigue loading to simulate marine type wave loading. In this test the load R ratio was 0.2 and the frequency was 2 Hz. The test condition simulates extreme bending stress at the joint under high frequency as a form of an accelerated fatigue test. The results from these tests are shown in Figure 6 together with results of fatigue testing on the GRP laminate alone [8, 11]. These results indicate that, for a given load range, premature failure occurs in the PU material. In each case failure was taking place at the adhesive–PU interface as shown in Figure 7 where fibres and resin from the PU are left on the adhesive.

To understand the behaviour of the laminate–stiffener joint further, 2D FEA modelling was carried out to determine the level of critical stresses and their locations. This was again based on plane strain and elastic analyses where the GRP and PU properties are assumed to be linear elastic and modelled as orthotropic composite materials, using ABAQUS [8]. The PU section consists of random and unidirectional fabric, and the GRP laminate consists of woven roven plies. The modelling did not include the resin layers of the PU and GRP surfaces. However, the through thickness properties of these composites were given as that of the base resin materials.

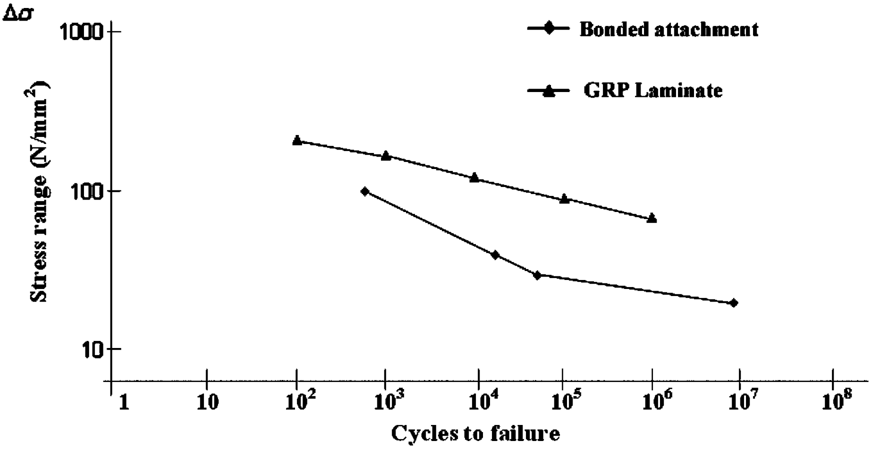


FIGURE 6 Fatigue test result of stiffener–laminate joints in ambient conditions.

Figure 8 shows the results from the analyses where the predominant stress to cause failure is the transverse/cleavage stress, S_{22}, based on the material local coordinate system (Figure 5) at the edge of the PU material. Although adhesive stresses near the surface of GRP laminate are higher than nearer the PU surface, failure (from experiment) was initiated at the latter. This is at the interface

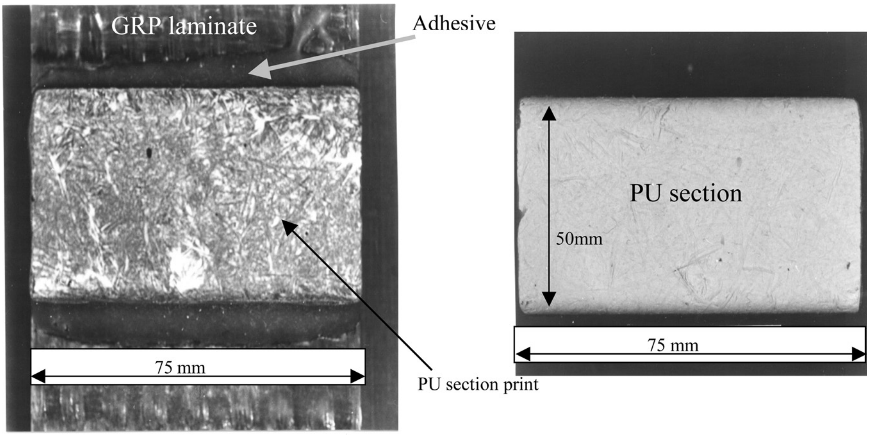


FIGURE 7 PU surface/subsurface failure of laminate–stiffener joint (see Figure 5).

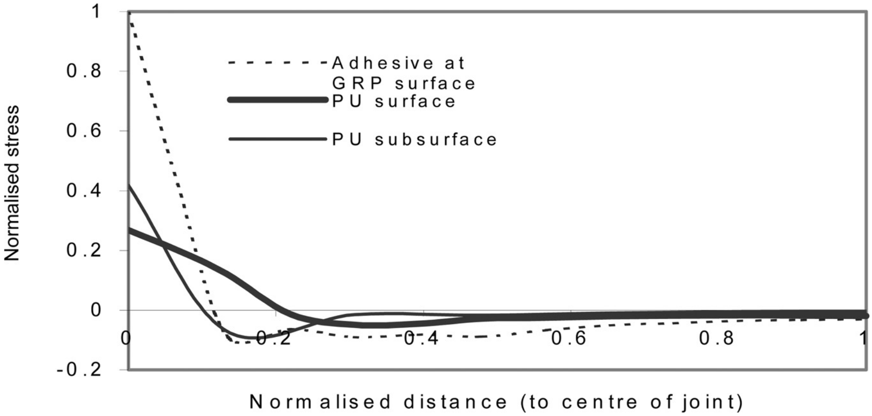


FIGURE 8 Stress distribution in adhesive and PU along half the bondline (Figure 5).

between the outer resin layer and the first layer of reinforcement, i.e., composite rather than adhesive failure. This confirms the PU material's inherent weakness. However, despite this there is a level of adhesion compatibility between the GRP and PU, as both are based on polyester resins.

CASE STUDY 3: HIGH TEMPERATURE

Although organic matrix resins are intrinsically combustible, it became apparent that thick composite adherends possessed desirable properties in fire; especially as they have low thermal conductivity [12]. A key to utilising this benefit is to avoid the use of metallic fasteners to reduce any bridging of heat and this can be achieved by using adhesives. Utilising the good thermal, structural, and blast properties of composite materials, steel-stiffened GRP panels could form the boundary of modules for offshore platforms to provide a structural panel and to contain possible fire sources on the GRP side. The structural integrity was evaluated and found adequate to resist design loading [1]. Reflecting the need to maintain low temperatures at the GRP outer surface (including the GRP/steel bond line), thermal insulation must be considered regardless of the type of structural materials used for panels.

A series of experiments was aimed at the development of a practical-scale fire panel capable of withstanding a hydrocarbon fire [12]. Following an extensive small-scale development programme the

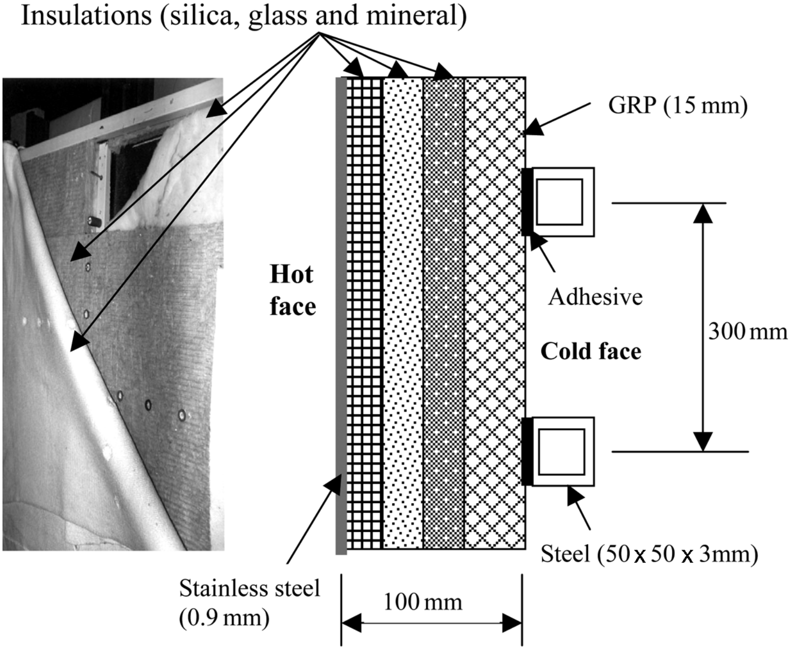


FIGURE 9 Design of fire-resistant panel (not to scale).

multimaterial fire/blast panel was constructed as shown in Figure 9. The general structure of a 1.2 m × 1.2 m and 100 mm thick panel was fabricated by incorporating layers of structural and thermal insulating materials faced with a thin stainless steel sheet.

The 15 mm GRP panel was bonded with steel stiffeners (50 × 50 × 3 mm HSS) using high glass transition temperature (T_g) epoxy adhesive No. 2. The panel was tested under hydrocarbon fire conditions. Figure 10 shows the results of temperature/time performance of the panel. The maximum temperature inside the testing furnace and the hot face was above 1150°C. The difference between the hot and cold faces shows the effectiveness of the insulation. The rise in cold face temperature passed the H60 rating for firewall design to the Norwegian Petroleum Directorate (NPD) code rating for hydrocarbon fire conditions. The temperature at the adhesive line was over 150°C and slightly lower than for the GRPS cold surface. The adhesive joints between steel stiffeners and GRP rear (cold face) retained adequate structural integrity during and after the experiment as shown in Figure 11 (photo along the adhesive joint). There

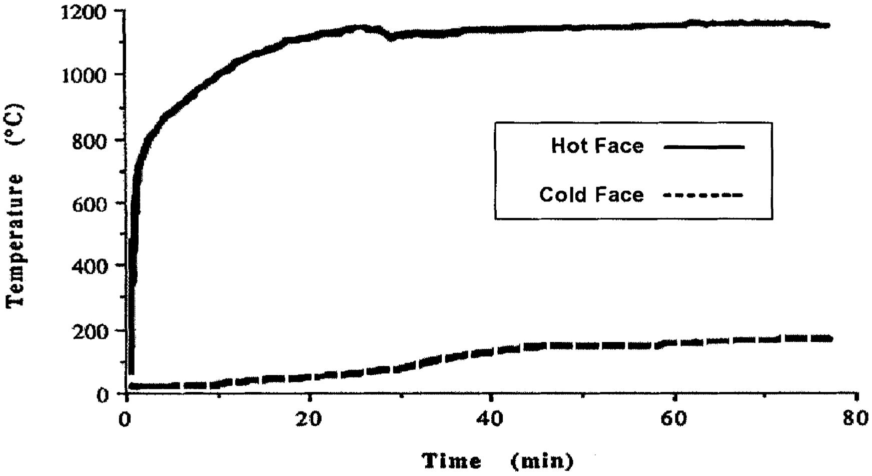


FIGURE 10 Temperature/time profile of fire test panel (Figure 9).

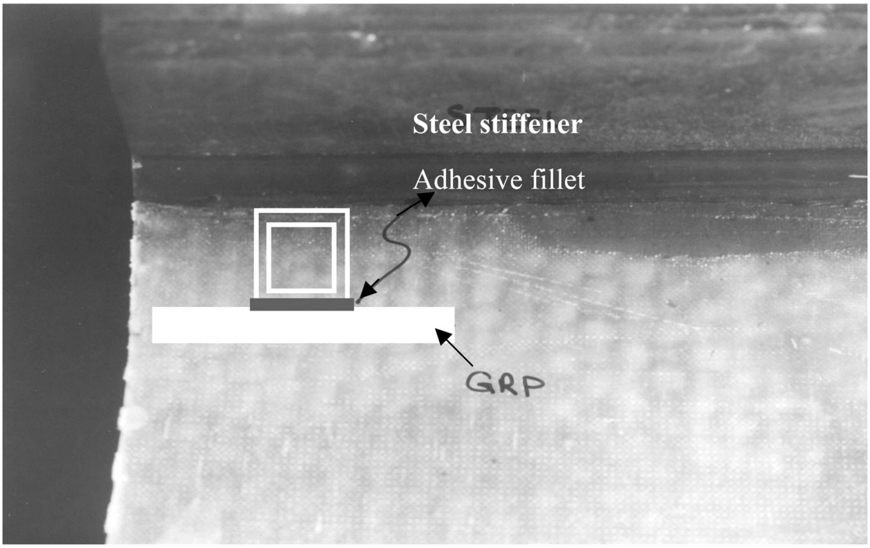


FIGURE 11 Top GRP surface (cold face) and adhesive joint after fire test (Figure 9).

TABLE 4 Creep Resistance of GRP/Steel Shear Joint (Figure 1)

Av *. shear stress (MPa)	0.9	0.5	0.5	0.3	0.3
Temp (°C)	100	150	155	200	203
Time to fail (h)	>2000	3	1.5	330	200

*One-off specimen.

was no visible sign of distortion in the adhesive or slipping of the 5 kg steel stiffeners. The GRP laminate also retained considerable strength.

In order to investigate the creep resistance of the adhesive during fire conditions, experiments were carried out using thick adherend steel/GRP lap shear joints (Figure 1). These were bonded with the same adhesive (No. 2). The specimens were subjected to small sustained stresses at elevated temperatures, reflecting the minimum design loading and elevated temperatures in fire conditions. In this test the joint was heated in oven enclosures to the required temperature, and sustained loadings were applied on each specimen, and the time at failure was recorded. In some cases the load and temperature did not lead to a failure, and the test was discontinued after a certain duration. The results of the tests, which demonstrate adequate creep resistance, exceeding a minimum design stress, and temperature and time requirements, are shown in Table 4. The rateability of these data is virtually impossible because the test temperatures were well above the T_g of the adhesive (90°C). However, the results give a good indication of the validity of the fire test result of the panel.

In the absence of sufficient thermal insulation materials, bonded joints may be designed so that the adhesive is placed under compression, which can produce a fail-safe design. This concept may be applied to deck or flooring constructions.

CONCLUDING REMARKS

It was demonstrated through the three cases that adhesives are helping to accomplish new design applications. It is also true to say here that the above cases have demonstrated that design could be more important than materials. Several limitations appear to worry designers when dealing with adhesives and understanding properties and joint behaviours. Relevant design tools could overcome these difficulties. The specific technical conclusions from this study are:

- Modifying joint geometry within the practical limits of a thick adherend improves the strength of bonded joints.
- Understanding the moulding process and properties for composite materials is important for optimising adhesion.
- Adhesives can be used for heat-resistant applications, including the design of fire-resistant composite panels.
- Evaluation and validation of bonded joints relies heavily on experimental techniques. These are often nonstandard experiments.

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