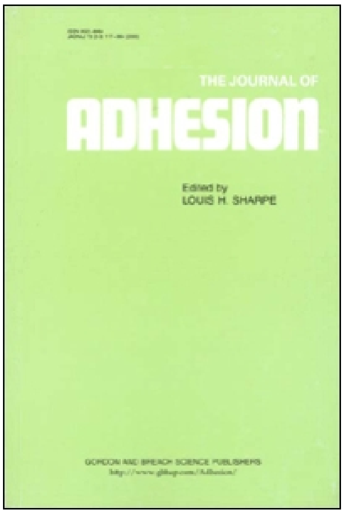

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Cleavage Strength of Steel/Composite Joints

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Cleavage Strength of Steel/Composite Joints*

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This paper presents the experimental results of an on-going study to examine cleavage strength, particularly at the interface regions of epoxy adhesive with steel and glass reinforced epoxy (GRE) composite. The adhesion is characterised by mechanical testing of cleavage specimens. A standard specimen was modified to allow testing of hybrid joints. The effects of adhesive thickness and various surface conditions of both adherends were examined. Among key conclusions, the study found that cleavage strength is not strongly dependent upon adhesive thickness and that polished composite gives better adhesion compared with polished steel. Test results were analysed and compared with aspects of numerical analyses. The study has also established a new methodology to test hybrid adhesive cleavage joints.

Keywords: Cleavage; Surface conditions; Adhesive; Epoxy composite; Steel

1. INTRODUCTION

Adhesive bonding of hybrid steel/composite structures is finding increasing applications in civil, marine, automotive and aerospace industries [1, 2]. The use of metal in conjunction with composite is more important where the structural stiffness is a design requirement. In a number of these applications, steel stiffeners are bonded to laminates to form panels. A difference in adherend stiffnesses may

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exist and cause significant cleavage stresses. These stresses can be detrimental to the integrity of load-bearing joints.

In a cleavage mode of loading, localised opening stresses are high on one side of the joint made of two rigid adherends. A similar behaviour occurs in the case of a peeling mode but this requires the joint to have at least one flexible adherend and to be able to fold during peeling. The two loading modes are illustrated in Figure 1. An example of cleavage failure in a load-bearing joint is shown in Figure 2

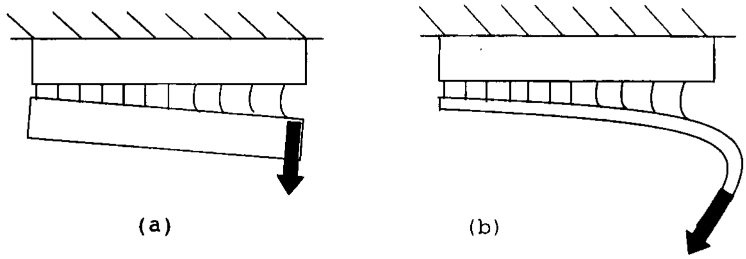


FIGURE 1 Modes of loading. (a) cleavage; (b) peel.

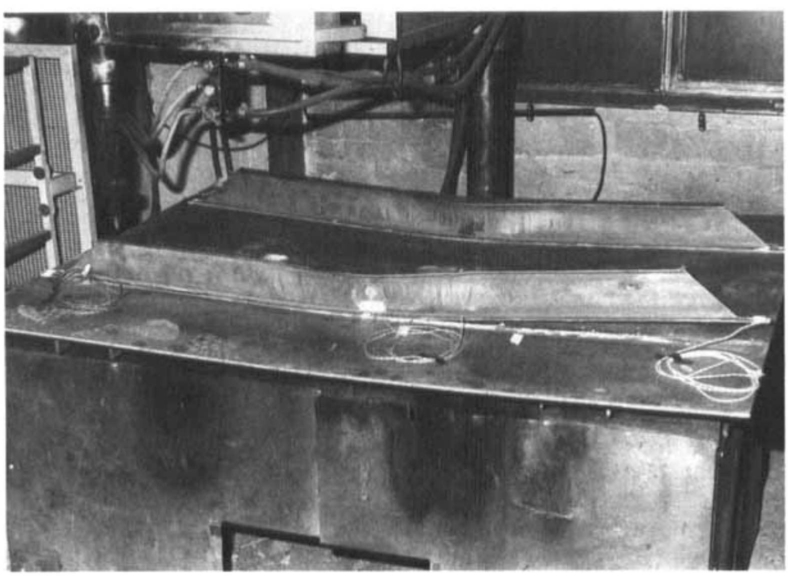


FIGURE 2 Cleavage failure in an adhesively-bonded panel (1.2 m × 1.2 m × 8 mm).

where, despite design measures having been taken to reduce cleavage stresses at the ends of the stiffeners, failure takes place there. Therefore, it is important to understand cleavage failure at the local level and a good starting point for this is to examine the behaviour of a small/standard joint specimen. However, in available references most of the data are generated for simple lap-shear joints and the cleavage strength is rarely quoted [3 – 5].

Adhesion is a complex phenomenon and a number of factors affect adhesion. These include the type of adherends and adhesive, surface pre-treatment, adhesive thickness and bonding and testing conditions [2, 6 – 8]. Again, these parameters are often reported with reference to lap-shear and peel tests rather than cleavage ones.

The purpose of this study is to improve our understanding of the failure mechanism in cleavage joints between GRE composite and mild steel. Different surface pretreatments and conditions were considered. Surfaces were examined before and after fracture both visually and with an optical microscope. Prior to bonding, some surfaces were also examined with a Talysurf, a Michaelson's interferometer and atomic force microscopy (AFM) to measure their roughnesses. To obtain tangible results, a limited number of another two types of specimens were also tested. They were thick-adherend lap-shear specimens and hybrid cleavage specimens with glass reinforced polyester (GRP) composite. Their data were compared with those obtained from cleavage. Finally, cleavage joints were modelled numerically using finite element analysis to determine the cleavage stresses and to understand failure at macro levels.

2. EXPERIMENTAL PROGRAMME

Materials used in the fabrication of specimens were mild steel to BS4360 grade 43A, glass reinforced epoxy (GRE) composite and a structural epoxy adhesive, Araldite 420A/B (Redux 420A/B), from Ciba Speciality Chemicals (UK) Ltd.

Steel/steel cleavage specimens were made to British Standard BS5350 : C1 : 1986 [9] and the steel/composite/steel cleavage specimens were modified from the standard one. The adhesive bond between steel and composite adherends was produced by inserting a composite laminate between the steel adherends. An approximately 40 mm × 40 mm section of the composite laminate was extended beyond the re-entry of the joint to eliminate edge delamination in the composite. Configurations of standard and modified cleavage joints are shown in Figure 3. The bond area for the cleavage joint in both cases was 25 mm × 25 mm.

The 2 mm thick GRE laminates were largely produced from woven fabric prepregs (Fibredux 913G/37%/7781) by hot press moulding. The appropriate number of plies were cut into 125 mm × 125 mm pieces and stacked in the required sequence in a steel mould. To study the effect of unidirectional fabric, a prepreg type Fibredux 913G/30%/E5 layer was stacked on top of the woven fabrics to produce laminates with unidirectional surface ply. The mould was pre-spread with PTFE mould release agent. Applied pressure, temperature and curing time were 2 MPa, 150°C and 20 minutes, respectively. The composite adherends were then cut to dimensions from the moulded laminates.

Grit blasting of steel and composite, where applicable, was performed using 40/60 micron alumna grit at a pressure of approximately 550 kPa. Grit blasting was performed at right angles to the surface and at a distance of about 5 cm from the nozzle. Polishing was carried out using various abrasive papers and finishing with oil-wetted 1 micron diamond paste. After polishing, specimens were washed with soap and water, wiped with acetone and dried in hot air.

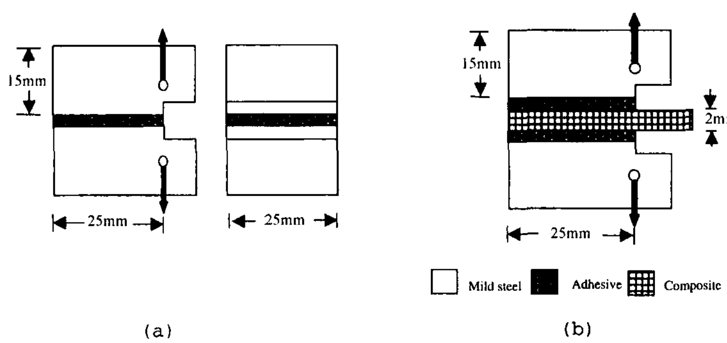


FIGURE 3 Cleavage test specimens. (a) standard; (b) modified.

Surface roughnesses of various adherends were measured using a Taylor and Hobson's Form Talysurf Series 2 surface profiler. Surface roughnesses were also measured (where possible) with a Michelson's interferometer and atomic force microscopy. Average values of surface roughness measurements of various surface finishes are shown in Table I. Measured values of surface roughness of various substrates were found to be in line with those measured by Gilibert and Verchery [10]. A typical profile of polished surfaces is given in Figure 4.

Just before bonding, all adherends were again degreased with acetone and dried in hot air. Wire spacers were used to control

TABLE I Surface roughnesses

	Average roughness (μm)	
Surface finish	*Ra**	R_{ymax}**
Grit-blasted surface	2.67	18.67
Polished surface	0.095	0.903

*Ra – Centre Line Average (CLA).
**R_{ymax} – max. roughness between peak and valley.

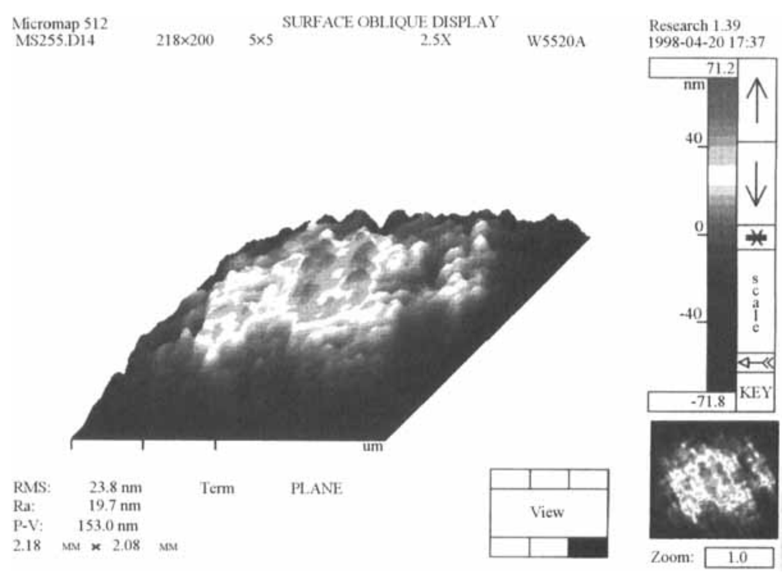


FIGURE 4 Surface profile of polished steel. (See Color Plate I).

adhesive thicknesses. Two wire spacers were attached to the metallic adherend near the front and rear ends (see Figs. 10 and 11). A manual dispensing/mixing gun was used and the adhesive was applied and spread onto the bonding surfaces with a spatula. The specimens were then bonded and clamped using a jig that allows bonding of cleavage specimens with composite inserts at controlled adhesive thicknesses. All specimens were cured for 2 hours at 70°C. Cured specimens were removed from the jig and adhesive fillets were removed by scraping away manually with a razor blade.

Cleavage specimens were tested on a Llyod tensile testing machine using standard clamps and fixture (Fig. 5). All tests were carried out under monotonic loading at room temperature with a cross head speed of 0.5 mm/min. With the exception of rusted specimens, a minimum of five specimens of each type were tested to achieve an average result. Three specimens, however, were used in case of the rusted specimens due to production limitations. After each test, the failure load was recorded and the fractured surfaces were examined to determine whether the failure was adhesive, cohesive or within the adherends. In some cases, the failure is referred to as adhesive/cohesive, especially

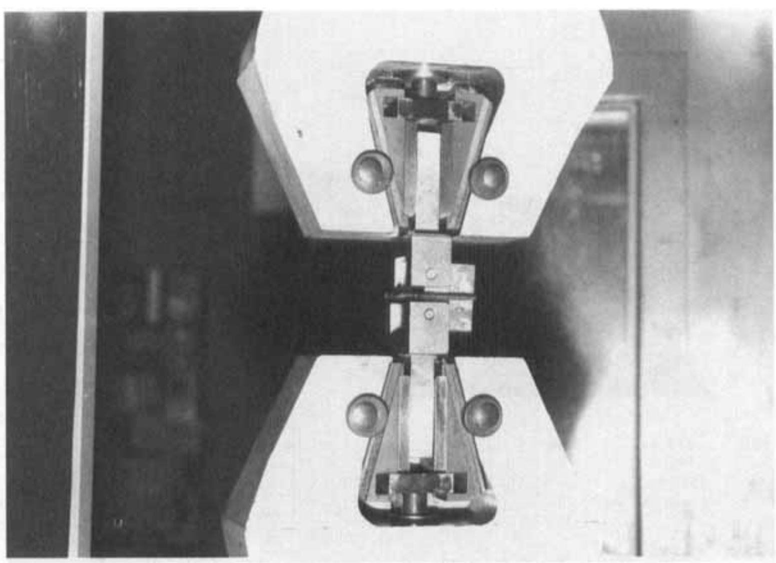


FIGURE 5 Testing of cleavage specimen.

when no clear pattern is apparent. Composite adherend failure includes surface resin fracture and fibre "plucking". Delamination was not considered for the GRE laminates. Delamination failure, however, was expected in the case of GRP laminates due to weak polyester resin. Steel adherend failure includes pulling of corrosion scale.

A limited number of thick steel adherend lap-shear specimens, modified from ASTM D5656, were also tested. Dimensions of modified specimen are shown in Figure 6. The bond area of these specimens was 15 mm × 25 mm. Furthermore, cleavage specimens using GRP adherends were also bonded and tested for comparison.

The experiments considered the effects of the following parameters on joint strength:

1. Adhesive thickness of 0.1 mm and 0.5 mm on cleavage and lap-shear strengths of mild steel adherends.
2. Roughness of polished and grit-blasted surfaces.
3. Rusting of mild steel specimens for 17 days in natural environment (average temperature 6°C and R.H. 85%) before bonding. Adherend surfaces were either grit-blasted or polished before exposure. This was aimed at producing accelerated results from the effect of corrosion.
4. Pre-treatment conditions of composite surfaces, including grit-blasting and polishing.
5. Fibre direction of the surface ply of the composite including woven, 0°UD and 90°UD. The UD surface plies were moulded on top of the woven plies.

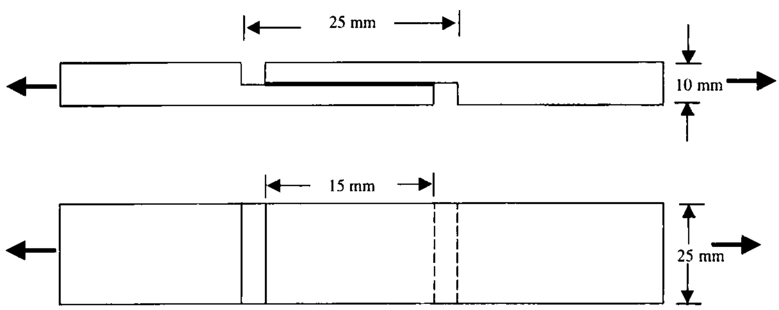


FIGURE 6 Thick-adherend lap-shear specimen.

3. NUMERICAL MODELLING

Limited finite element (FE) analyses were used to support the mechanical testing in order to interpret failure in the cleavage joints with woven fabric laminates. The analytical macro model, based on the modified cleavage joint (Fig. 3a), was made using PATRAN preprocessor and solved using ABAQUS [11]. It was modelled in 2-D using eight-noded, 2-D, solid quadrilateral plane stress elements. An adhesive thickness of 0.5 mm was considered and modelled with 3 elements through the thickness. A finer mesh of elements was applied to the adhesive region at the loaded edge to account for the high stress gradients. Figure 7 shows details of the numerical model. Adherend surfaces were considered to be polished and, therefore, surface roughness was not modelled at this stage. Elastic isotropic material properties were considered for adhesive and steel. Properties

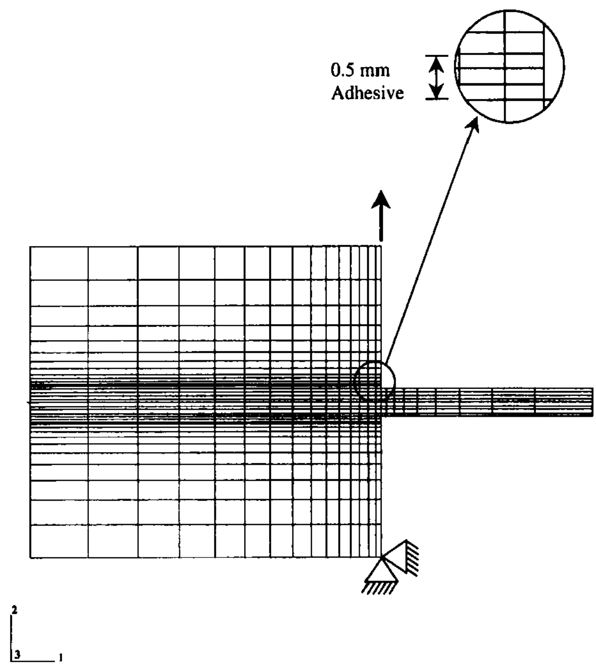


FIGURE 7 Numerical model.

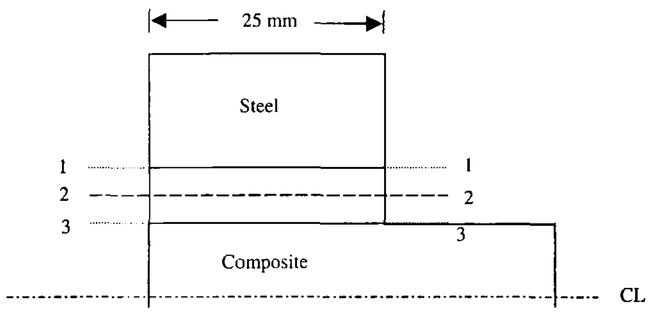


FIGURE 8 Possible failure sites in bond line.

for the woven fabric laminate in two directions were used in the modelling, without considering the details of the layer and resin at the surface at this stage of the work. A load of 10 kN was applied and the experimental boundary conditions were simulated.

Three possible failure sites within the bond line were considered as shown in Figure 8. These were adhesive interfaces with the steel (Site 1 - 1), the composite (Site 3 – 3) and the centre of the adhesive line (Site 2 – 2). Although there is a possibility that failure can take place within the composite adherend, stresses through the GRE laminate thickness were not considered to be the critical, especially when the possibility of delamination was largely reduced due to laminate extension. However, should a GRP laminate be considered for the modelling, then the through-thickness stresses would be more important [12]. The assessment of the failure was considered with reference to the critical value of the maximum principal stresses at the joint edge. To avoid mathematical singularity problems at the free tension edge of the joint, stresses at the edge nodes were ignored.

4. RESULTS AND DISCUSSION

Results from the mechanical testing are given in Tables II – VI. Average cleavage strength values are presented for comparison. The strength was calculated by dividing failure load by the bond area. Results from F.E. analysis are also given and discussed.

TABLE II Effect of surface roughness and adhesive thickness on cleavage strength of steel specimens

Surface finish	*Adhesive thickness [mm]*	*Average strength [N/mm²]*	*Coeff. of variation [%]*	*Possible failure initiation*
Polished	0.1	14.0	18.2	Adhesion
	0.5	15.8	2.9	Adhesion
Grit-blasted	0.1	17.7	9.0	Adhesion/Cohesion
	0.5	17.0	3.2	Adhesion/Cohesion

TABLE III Effect of adhesive thickness on lap-shear strength

Surface finish	*Adhesive thickness [mm]*	*Average strength [N/mm²]*	*Coeff. of variation [%]*	*Possible failure initiation*
Grit-blasted	0.1	23.2	10.6	Adhesion/Cohesion
	0.5	18.2	5.9	Adhesion/Cohesion

TABLE IV Effect of corrosion on cleavage strength of steel specimens

Surface finish	*Adhesive thickness [mm]*	*Average strength [N/mm²]*	*Coeff. of variation [%]*	*Possible failure initiation*
Rusted after	0.1	2.3	29.1	Adherend (oxide)
polishing	0.5	2.6	12.4	Adherend (oxide)
Rusted after	0.1	6.5	3.8	Adherend (oxide)
grit-blasting	0.5	6.0	30.2	Adherend (oxide)

TABLE V Effect of surface treatment of GRE laminate on cleavage strength of hybrid specimens

Surface treatment of composite	*Average strength [N/mm²]*	*Coeff. of variation [%]*	*Possible failure initiation*
Peel ply [Woven fabric]	9.8	8.1	Adhesion (from composite)
Grit-blasted [Woven fabric]	13.9	11.8	Adherend (composite) resin
Grit-blasted Unidirectional 0°	14.5	1.5	Adherend (composite)
Grit-blasted Unidirectional 90°	13.1	10.7	Adherend (composite)
Polished [Woven fabric]	17.0	3.4	Adhesion/Cohesion (from steel)

TABLE VI Cleavage strength of hybrid specimens with GRP laminate

Composite	*Average strength* [N/mm^2]	*Coeff. of variation* [%]	*Possible failure initiation*
GRP laminate	5.6	13.0	Adherend (composite resin)

4.1. Effect of Bond Thickness

4.1.1. Cleavage Specimens

From the results in Table II it appears that only a small increase in joint strength (4%) resulted from reducing the adhesive thickness in grit-blasted steel cleavage specimens. Specimens bonded with adhesive 0.5 mm thick, however, appear to show a lower coefficient of variation compared with those with 0.1 mm thickness. The small increase in strength that is suggested by the results may be due to the effects of triaxial constraint, adhesive defect populations and thermal shrinkage in the adhesive. Our finding of a decrease in strength with increasing adhesive thickness is not in line with those of Matsui [4], who reported a linear increase in cleavage strength with adhesive thicknesses from 0.1 mm to 2 mm.

The polished specimens, however, showed an opposite trend where cleavage strength decreased by about 11% with decreasing adhesive thickness. A possible reason for this decrease may be poor wetting of polished steel surfaces in the case of small adhesive thickness (0.1 mm), as shown in Figure 9. The use of spacers to achieve thickness control may also have contributed to this defect.

4.1.2. Lap-shear Specimens

The test results from the lap-shear specimens are presented in Table III. The reduction in shear strength with increasing thickness is 22%. This appears to suggest that shear strength is more dependent on adhesive thickness than is cleavage strength (Tab. II). Generally, this effect is more prominent with adhesive thicknesses from 0.1 mm to 0.5 mm. In thicknesses more than 0.5 mm, cohesive strength of the bulk adhesive may determine the bond strength [3]. Guha and Epel

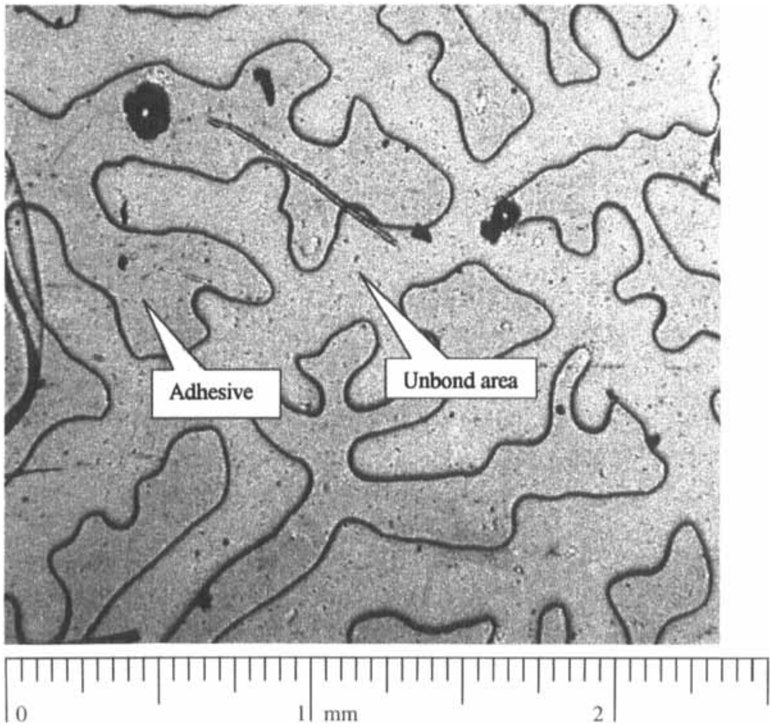


FIGURE 9 Fracture surface of joint (polished steel).

[13] tested a range of adhesives using single-lap-shear joints and found that increasing adhesive thicknesses from 0.25 mm to 1 mm led to a decreased strength of 1 to 25%, depending on the type of adhesive used. In addition, a thickness increase in lap-shear joints increases the bending moment and, hence, cleavage stresses at the edge of the bond line [14].

4.2. Effect of Corrosion

Table IV shows test results for corroded specimens. Polished specimens, in particular, appear to show a considerable drop in strength in comparison with equivalent uncorroded ones (Tab. II). In the case of 0.5 mm adhesive thickness, the strengths of equivalent uncorroded specimens are higher by 600% and 285% for polished and grit-blasted specimens, respectively. These results are only comparative, to show the effect of surface roughness and corrosion. In reality, steel adherends would not be exposed to such an environment prior to bonding. Therefore, the test results can only be considered as a sensitivity measure of the effect of steel corrosion on bond strength.

Examination of joint fracture surfaces clearly indicated that failure initiated from the adherend at the oxide layer. The high scatter in these results is probably due to the nature of exposure, which cannot be controlled in the open environment.

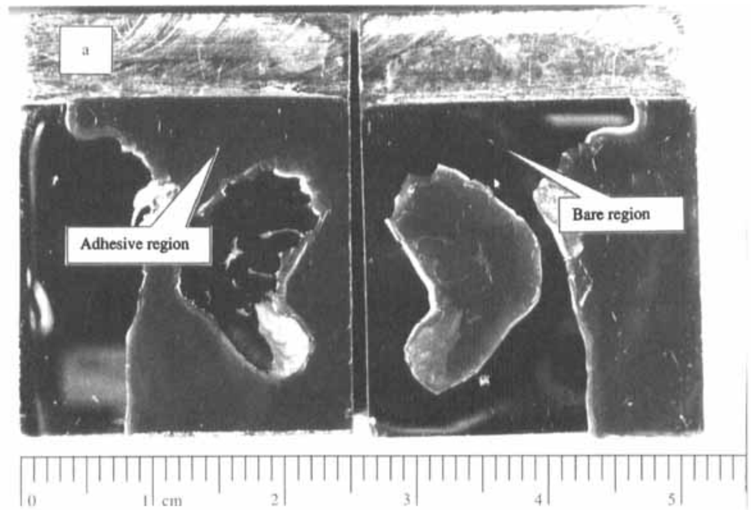
4.3. Effect of Surface Roughness

The relationship between the level of roughness and adhesion is not very simple, as indicated in the previous sections. The optimum surface profile varies from one adhesive to another, and depends upon the type of stresses applied [7]. Advantages attributed to the introduction of surface roughnesses include formation of a large number of scarf joints very close to the interface, increased surface area, provision for keying and the diversion of the failure path away from the interface into the bulk of the adhesive. Actual microscopic distribution of stresses at a rough interface is very complex.

4.3.1. Steel Adherend

It can be seen from Table II that grit blasting (0.5 mm adhesive thickness) gives an 8% higher cleavage strength compared with polished specimens. The fracture surfaces of joints with polished adherends showed bare steel regions and regions with adhesive (Fig. 10a), which is in line with the findings of Jennings [15] in the case of butt joints. Better performance of grit-blasted steel cleavage specimens compared with polished specimens is also in line with the findings of Sargent [16].

Bullet *et al.* [17] tested diamond-polished mild steel specimens and found that the specimens with polished surfaces produced higher joint strength than those with roughness. They also observed that the area of "clean" detachment was least on rough surfaces, which was also seen in the current study (Fig. 10b). They suggested that once a failure initiates it tends to propagate more readily on the smoother surface.



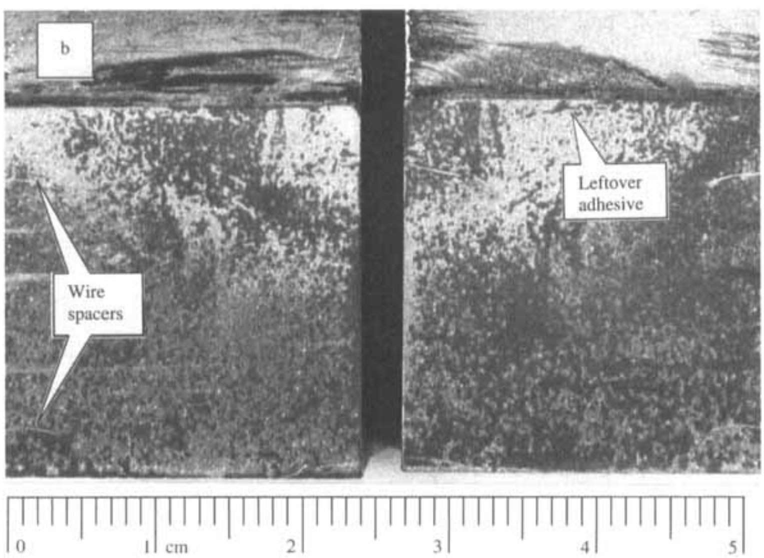


FIGURE 10 Fracture surfaces of steel/steel joints. (a) polished; (b) grit-blasted.

Investigations on aluminium peel test specimens bonded with Redux 775, a modified phenolic adhesive, showed that a distinct correlation between increasing peel strength and increasing surface roughness exists [16]. Jennings [15] tested polished and grit-blasted aluminium and steel butt joints. He concluded that random surface roughness can prevent alignment of flaws or points of stress concentration which is more likely for polished surfaces and those with regular ridges. This finding appears to be in line with our test results, where some polished steel cleavage joints containing air bubbles failed at fairly low load values. Grit-blasted steel specimens containing air bubbles, however, failed at about the same load as other better made ones. This finding also suggests that, in the case of steel, grit-blasting may result in better wetting than polishing.

4.3.2. Composite Adherend

Grit-blasting of composites appears to produce strength values 18% lower than those obtained with steel specimens (Tabs. II and V). It should, however, be noted that, in the case of grit-blasted composites, failure initiated in the composite adherend (Fig. 11a) confirming the findings in Ref. [18]. This may be due to fibre and resin damage caused

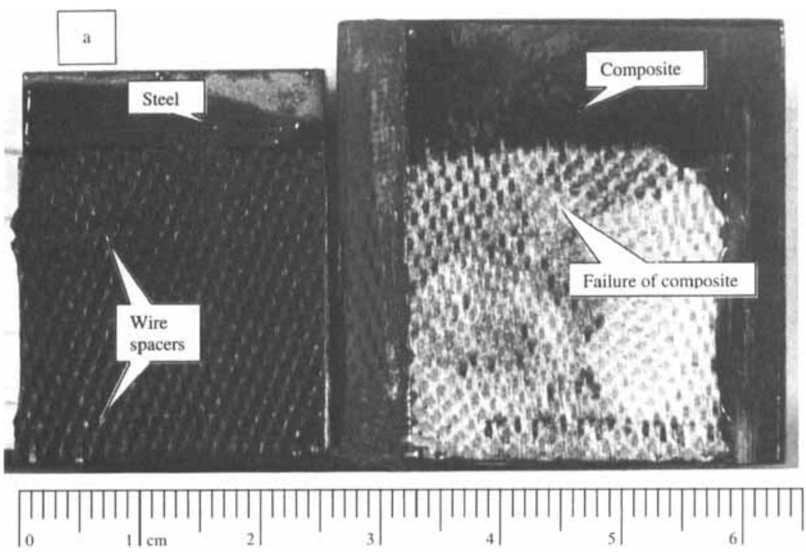


FIGURE 11 Fracture surfaces of steel/GRE laminate joints. (a) polished; (b) grit-blasted.

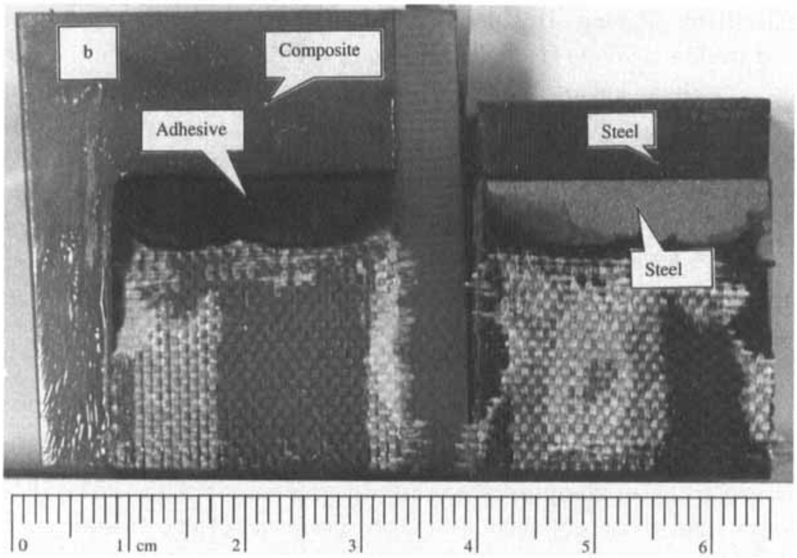


FIGURE 11 (Continued).

by the grit blasting. Polishing outperformed all other surface conditions on the composite and in all specimens failure appeared to initiate at the metal-adhesive interface (Fig. 11b). Possible reasons for increased strength are the total removal of any mould release agent and limited damage to fibres and resin during the polishing operation in comparison with grit blasting.

4.4. Effect of Peel Ply and Fibre Direction

Laminates with peel ply (recommended by the manufacturer) appeared to perform inferiorly to those of grit-blasted and polished laminates. The reduction in strength is approximately 31% compared with grit-blasted laminate. The failure in this case was apparently in adhesion, which could be mainly due to surface contamination of the laminate. Should a better peel ply system be used, the joint strength would probably be higher. This is in contrast to the findings of Cowling *et al.* [19] in a study carried out on polyester matrix laminate. Our own testing on GRP laminates with peel ply on one side and grit-blasting on other side (Tab. VI) also showed that in all specimens cleavage failure occurred on the grit-blasted side. This suggests that the type of resin is an essential element in determining joint strength.

Lower cleavage strength was obtained (Tab. V) in the case of 90° unidirectional surface ply compared with the 0° unidirectional one. The difference in the cleavage strength between the 90°UD and 0°UD case is approximately 11%. The significance of this strength result, however, is reduced by a large coefficient of variation (COV) in the former case. This may be attributed to a lower stiffness epoxy matrix compared with the reinforcing glass fibres. Kairouz *et al.* [20] found that for CFRP specimens tested as a single-lap joint, the stacking sequence does not strongly influence the strength but it influences the failure mechanism, which is dominated by bending stresses. Of course, overall bending does not exist in the cleavage specimen case but local bending at the micro level is a possible behaviour, which requires further work.

4.5. Aspects of the Correlation of Results

Figure 12 shows the maximum principal stresses from the FE analyses on the entire bond line and at 2 mm away from the loaded-edge

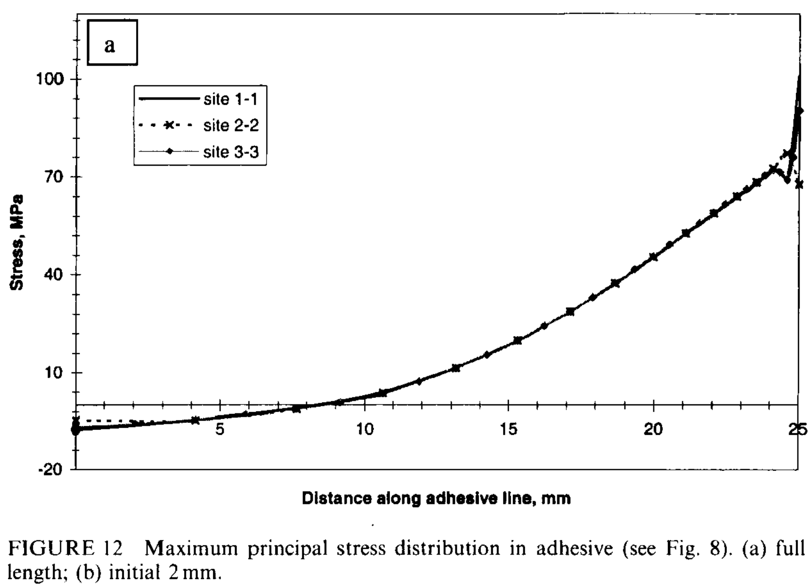


FIGURE 12 Maximum principal stress distribution in adhesive (see Fig. 8). (a) full length; (b) initial 2 mm.

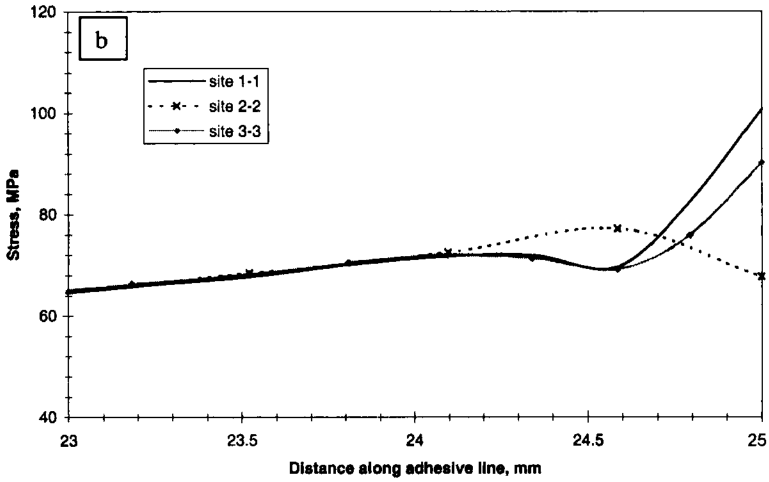


FIGURE 12 (Continued).

region of the macro model. It shows that, apart from within the first few hundred microns of the model, the variation of stresses through the thickness is insignificant. However, at the edges, the steel interface (Site 1 – 1) displays higher stresses than those at the composite interface (Site 3 – 3). This is mainly due to the relatively lower difference in the modulus of elasticity between adhesive and composite. The result suggests that it is more likely for failure to initiate at Site 1 – 1 leaving bare polished steel as shown from the experiments. However, should the details of the roughened steel and composite surfaces be considered, the result might be different. This can only be verified by micro-modelling to take account of surface topography, which is the future work of this study.

5. CONCLUSIONS

From the results obtained so far it may be concluded that:

- The modified cleavage specimen provides a good methodology for testing composite/metal joints.
- Cleavage strength is not strongly dependent upon adhesive thickness within a practical range.

- While a thicker bond line may contain a large void population, it appears to provide better wetting, especially on polished steel.
- Grit-blasting of steel shows better and more consistent results compared with polishing. In addition, highly-corroded, grit-blasted surfaces seem to give better adhesion than polished ones.
- For an ideal steel/GRE composite joint, adhesive failure initiates at the edge of interface with the steel and propagates through the laminate/adhesive interface.
- A polished epoxy composite laminate produces a joint strength consistently higher than that of polished mild steel.
- Adhesive stresses at the interface with the composite are lower than that with steel.
- Laminates based on epoxy resin are significantly more suitable for bonding than polyester-based laminates.

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