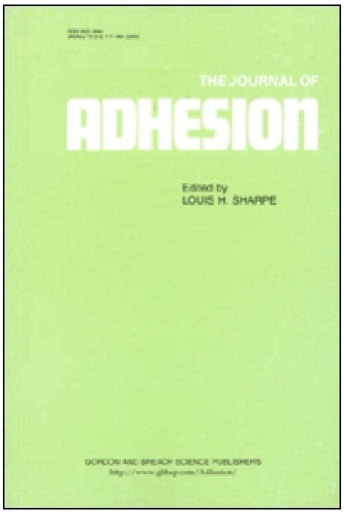
This article was downloaded by:
On: *22 January 2011*
Access details: *Access Details: Free Access*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



The Journal of Adhesion

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Non-destructive Inspection of Adhesively-bonded Joints

R. D. Adams[a]; P. Cawley[b]; C. C. H. Guyott[b]
[a] Department of Mechanical Engineering, University of Bristol, Bristol, U.K. [b] Department of Mechanical Engineering, Imperial College, London, U.K.

To cite this Article Adams, R. D. , Cawley, P. and Guyott, C. C. H.(1987) 'Non-destructive Inspection of Adhesively-bonded Joints', The Journal of Adhesion, 21: 3, 279 — 290

To link to this Article: DOI: 10.1080/00218468708074975

URL: http://dx.doi.org/10.1080/00218468708074975

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

J. Adhesion, 1987, Vol. 21, pp. 279–290
Photocopying permitted by license only

Printed in the United Kingdom

Non-destructive Inspection of Adhesively-bonded Joints†

R. D. ADAMS

Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR, U.K.

P. CAWLEY and C. C. H. GUYOTT

Department of Mechanical Engineering, Imperial College, London SW7 2BX, U.K.

(Received September 2, 1986)

The objective of any system of non-destructively examining an adhesive joint must be to obtain a direct correlation between the strength of the joint and some mechanical, physical or chemical parameter which can readily be measured without causing damage. Faults or defects are defined as anything which adversely affect the short or long term strength of a joint. There are two basic areas for examination, the cohesive strength of the polymeric adhesive, and the adhesive strength of the bond between polymer and substrate.

Adhesive strength is very difficult to measure since it is an interfacial phenomenon involving a very thin layer of material, thin even in comparison with bond-line dimensions. Effectively, it would be necessary to assess intermolecular forces and this is not readily possible with existing techniques. This aspect of quality control is usually reduced to assessing the nature of the adherend surfaces prior to bonding.

The cohesive strength of the adhesive is really the only parameter which can be estimated with any degree of confidence, and it is this which features most on destructive tests of bonded joints.

In this paper, defects including porosity, surface un-bonds, zero-volume unbonds, poor cure and so on are discussed, together with the various methods currently used (and some new methods) for physical non-destructive testing.

KEY WORDS Non-destructive inspection; Defects; Ultrasonics; Coin tapping; Cohesive strength; Adhesive strength.

---

† Presented at the Tenth Annual Meeting of The Adhesion Society, Inc., Williamsburg, Virginia, U.S.A., February 22–27, 1987.

1 INTRODUCTION

The strength of an adhesively-bonded joint depends on the nature of the materials being joined and the loading. The loads may be steady or alternating, of long or short duration, and may be associated with aggressive environments. At the same time, the designer must bear in mind the manufacturing process which will lead to the production of his joint. As to whether the joint is satisfactory is a question that can be answered in part by experience of making similar joints, by building and testing a series of prototypes, and by over-design where ignorance and uncertainty cannot be eliminated. But there is a further possibility, that of non-destructively examining the joint prior to (or even during) its use.

Non-destructive testing (NDT) is well-established in engineering practice in fields as widely ranging as welds in nuclear reactors to printed circuit boards in electronics. The objective of any system of non-destructive testing is to correlate the strength of the component (however defined) with some mechanical, physical or chemical parameter which can readily be measured without causing damage.

2 THE NATURE OF THE DEFECTS

Several types of defect may occur in bonded structures.

Porosity is caused by volatiles and entrained air in the adhesive. It is therefore present in most bond-lines to some extent. *Adhesive cracks* are due to problems with curing (cure and/or thermal shrinkage) or to large applied stresses, either one-off or repeated (fatigue).

Voids in the adhesive are similar to porosity, except that the individual defect volume can be much greater. It is caused by air or gases becoming trapped by the pattern of laying the adhesive, or to insufficient adhesive being applied. Large voids cannot be caused by volatiles, unless something is very wrong with the adhesive system. *Surface unbonds* are an alternative form of void, often caused when adhesive is applied to one adherend only and unevenly.

Disbonds or *zero-volume unbonds* can occur during manufacture due to the presence of a contaminant, such as grease, on an adherend. The surfaces of a disbond are generally in close proximity, or are touching, but are incapable of transferring load from the adherend to the adhesive. Disbonds also occur as a result of impact or environmental degradation after manufacture.

Less obvious, but potentially very serious, defects, such as a weak adhesive layer and a poor bond between the adhesive and adherend, can also occur. A weak adhesive layer, giving poor cohesive properties, can result from either incomplete mixing, incorrect formulation, or from insufficient cure of the adhesive. *Adhesion failure,* or failure of a weak bond between the adherend and adhesive often results from poor surface preparation or the presence of a contaminant on an adherend.

Detecting defects is not the same as knowing whether they are critical as this depends on their extent, position, and the nature of the applied stresses. Their presence is more likely to be indicative of poor joint manufacture than of an impending failure site, especially for short-term loading. For example, Wang *et al.*[1] used epoxy-bonded aluminium alloy single lap joints with a disbonded area achieved by inserting a polypropylene disc in the central region of the joint. Even though there was a large 'defect' present, the joint strength was essentially unchanged.

The other major form of joint used with structural adhesives is that used in bonding a honeycomb core to skins to form a sandwich construction. The structure is held together by a mesh of fine joints which have to take both shear and direct (tensile or compressive) loading.

Figure 1 illustrates some of the possible forms the skin/honeycomb bond may take. In Figure 1a, we have a well-filled joint in which there is a generous adhesive fillet. In Figure 1b, the moulding pressure, or even gravity, has extruded the adhesive from between the skin and core, but has left a generous fillet which will still carry the loads and is probably as strong if not stronger than the joint in Figure 1a. But in Figure 1c, we see two other possibilities: in one case, the adhesive has formed a thin layer between the skin and core (this is weak and will easily break) but has run down the honeycomb cell wall and has not formed a fillet. In the other case, the adhesive layer on the facing skin has not run to wet the cell wall and again gives a weak bond. Defects of this type shown in Figure 1c may be found by monitoring bond area. There are other forms of

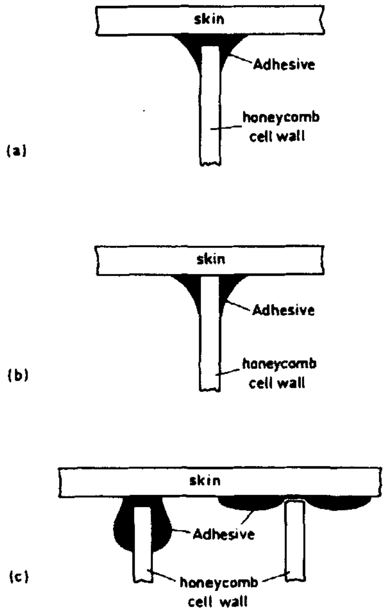


FIGURE 1 Adhesive bonds between the honeycomb cell wall and the facing skin.

defect in honeycomb sandwich construction which are due to lack of attachment between the core and the skin. This may be due to several causes such as locally crushed honeycomb, skin defects, or lack of adhesive. These defects all effectively produce skin-core disbonds. In themselves, none of these defects may prove deleterious to the short-term strength. However, as for the lap joint, they may show poor preparation and may provide sites for fatigue crack propagation.

In addition to monitoring bond area, there are three basic types of defect in adhesive joints which need to be monitored:

i) complete voids, disbonds or porosity;

ii) poor adhesion, *i.e.*, a weak bond between the adhesive and adherend;

iii) poor cohesive strength, *i.e.*, a weak adhesive layer.

3 TESTS PRIOR TO BONDING

Before the adhesive is applied to the joint, the adherend surfaces will have been prepared by washing, abrasion, chemical etching and so on (Adams and Wake[2]). The state of this surface is crucial in making a good bond. The adhesive properties of the surface may be poor if there are present excessive amounts of water vapour, hydrocarbons or other contaminants.

A simple test involves the wettability of the surface, which is a subjective measurement of the contact angle. If the surface is clean, it is readily wetted and a drop of water will spread over a large area. A simple but quantifiable test involves measuring the spread of a liquid drop of constant volume through a transparent gauge placed over the drop.

The Fokker Contamination Tester, described by Bijlmer,[3] uses an oscillating probe to measure the electron emission energy. This varies greatly with the degree of surface contamination, and can even be used to detect residues from alkaline cleaning operations.

Unfortunately, none of these methods is totally satisfactory and the best means of ensuring that a 'good' surface exists prior to bonding is carefully to control the processes leading to its preparation.

4 TESTS AFTER BONDING

4.1 Ultrasonics

Time-domain ultrasonics is one of the most widely used methods of non-destructive examination. It can be used readily to detect voids and disbonds and has the potential for locating very small defects such as porosity. As the pulse of ultrasound propagates through the joint, part of its energy is reflected at each boundary. The amount of energy reflected at a boundary is dependent on the acoustic impedance of the materials on either side of it. Acoustic impedance, Z, can be defined as

$$Z = c\rho \tag{1}$$

where

c = velocity of sound in the material

ρ = material density.

If there is a large difference in the acoustic impedance of the materials, a large proportion of the energy is reflected. Since a defect containing air or any other low density substance will have a very low acoustic impedance relative to the adhesive or adherend, the ultrasonic pulse will be almost totally reflected.

The magnitude of the reflected echoes is displayed with respect to time and is used to indicate the presence of defects. A display of this type is commonly called an A-scan. Figure 2a shows an A-scan from a good single-lap adhesive joint and Figure 2b shows an A-scan from a similar joint but with a disbond at the top adhesive/adherend interface. The reflections from the lower adhesive/adherend interface are no longer present in the defective joint. Also the reflections from the top adhesive/disbond interface decay more slowly than those from the top adhesive/adherend interface of the sound joint, since more energy is reflected at the disbond.

As there is a large difference in acoustic impedance between air and solid materials, it is difficult to propagate ultrasonic energy from the transducer to the structure to be tested. The transducer is therefore coupled at the structure *via* a medium which has a similar acoustic impedance to the structure. Commonly, the structure and transducer are immersed in a water bath. The ultrasound then propagates across the water filled gap (typically 25–100 mm depending on the transducer) into the test piece. An alternative is to use a water jet transducer in which the ultrasound propagates along a moving column of water (jet).

Serious problems can arise, however, if the couplant or some other liquid such as water or fuel is allowed to penetrate the defect. The presence of the liquid reduces the reflection coefficient and the defect becomes much more difficult to detect.

In addition to an A-scan presentation of the ultrasonic echoes, which only gives information at a single point, a map of defects can be produced by scanning the surface of the structure. The amplitude of a particular echo, such as from the bottom adherend-adhesive interface, is measured as the probe traverses the structure. Since the

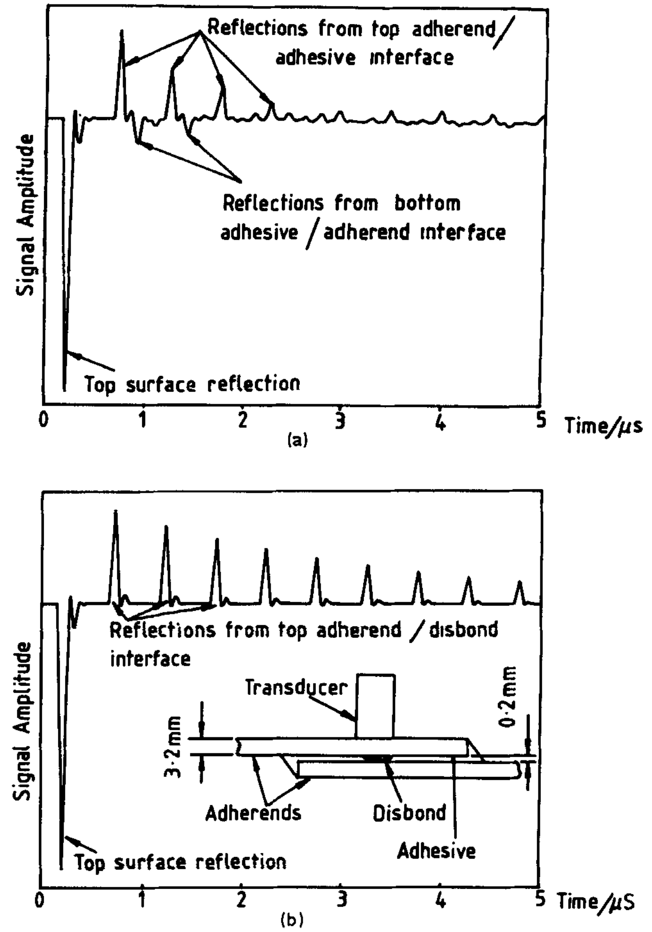


FIGURE 2 A-scan from single lap joints. (a) Well bonded, (b) with defects.

echo amplitude will change in the presence of a defect, a record of defect location is obtained by plotting amplitude against position, see Figure 3. This is usually called the C-scan method. The resolution of small defects, such as porosity, is improved by decreasing the distance between the scan lines, but this also increases the inspection time.

Two transducers can be used in this mode, in which separate

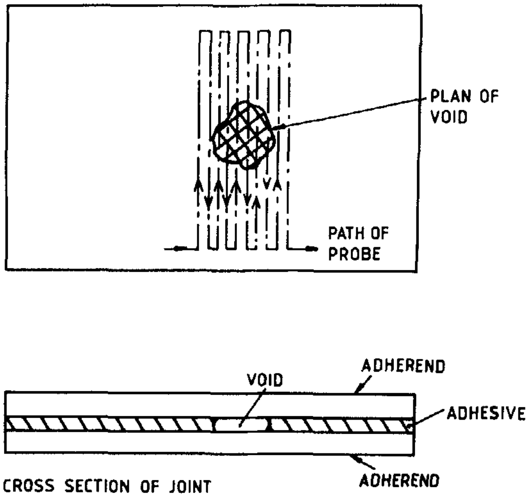


FIGURE 3 C-scan of joint with a void.

transmitting and receiving transducers are positioned either side of the structure and the magnitude of the transmitted signal is used to detect defects. The signal at the receiving transducer either reduces or disappears when a defect is present. Through-transmission is often used for inspecting the bond between the top and bottom skins and the core of a honeycomb structure.

Ultrasonic impedance and resonance tests[4] can also be used to detect small voids and disbonds. However, they will not generally detect such small defects as porosity, unlike time domain ultrasonic techniques.

4.2 Sonic vibrations

A number of sonic vibration techniques, which effectively measure the local stiffness of the structure, are used for the non-destructive testing of adhesive joints. A defect such as a disbond reduces the local stiffness of a structure, measured perpendicular to the surface. The defect can be modelled as a spring, below which is the rest of the structure whose properties are unaltered. The spring stiffness is given by the stiffness of the layer(s) above the defect.

Instruments of this type typically operate at frequencies between 1 and 30 kHz, which is substantially lower than those for the ultrasonic techniques (usually 0.1–25 MHz). They will generally only detect disbonds or voids, the minimum detectable size depending on the depth and hence the thickness of the adherends. Although the minimum detectable size is larger than for the ultrasonic techniques, the tests are often more convenient since they do not require a couplant between the transducer and test structure.

4.2.1 *Mechanical impedance*

Mechanical impedance measurements can be used to give an indication of the stiffness perpendicular to the surface of a structure. Commercially available instruments generally take measurements at a single pre-set frequency, typically between 1 and 10 kHz. As the probe is moved from a good to a disbonded or more compliant area, the impedance decreases. Unfortunately, as the base structure becomes more flexible, the impedance of a defective zone can be higher or lower than that of a good zone, depending on the frequency, and the test becomes unreliable.[5]

Instead of using a couplant, a dry point contact is used between the transducer and structure. This contact has a finite stiffness[6] which must be kept as high as possible, otherwise the sensitivity of the technique will be reduced.

4.2.2 *Coin tap test*

The coin tap test is one of the oldest methods of non-destructive inspection. Until recently, however, the technique has remained largely subjective and there has been considerable uncertainty about the physical principles behind it.

When a structure is struck with a hammer or coin, the characteristics of the impact are dependent on the local impedance of the structure and the hammer used. The local change in structural stiffness produced by a defect changes the nature of the impact. The time history of the force applied by the hammer during the impact may be measured by incorporating a force transducer in the hammer. Typical force-time histories from taps on sound and disbonded areas of an adhesively bonded structure are shown in Figure 4. The impact on the sound structure is more intense and of a shorter duration than that on the damaged area, the impact

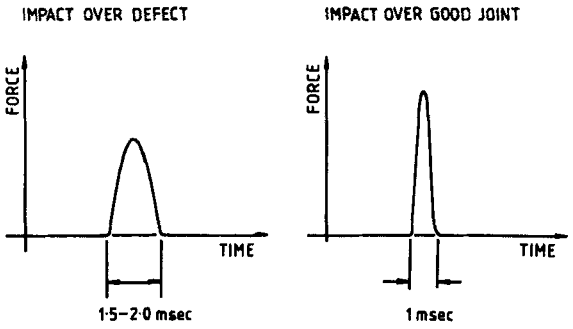


FIGURE 4 Force/time histories.

duration on the sound structure being approximately 1 ms compared with 1.7 ms on the defective zone.

Either the peak force or the duration of the impact can be used to locate defects. Since the method only uses measurements of impact force, no transducers need be attached to the structure, thus avoiding the coupling and alignment problems which arise with, for example, ultrasonic techniques. The sensitivity of the method is increased by further processing of the force time histories and is detailed by Adams *et al.*[7]

5 TECHNIQUES TO LOCATE POOR COHESIVE PROPERTIES

The Fokker Bond Tester Mk II[8] is the only commercially available instrument which attempts to measure the cohesive properties of the adhesive in a joint. It measures frequency and amplitude changes in the first two modes of through thickness vibration of a system comprising of the transducer and the joint. The measured parameters are dependent on both adherend and bond line thickness and the material properties, *i.e.*, adhesive and adherend moduli and damping. The range of frequencies over which the instrument operates depends on the transducer, but it is typically between 0.3–1.0 MHz.

The instrument will reliably detect small voids and disbonds at different depths in a multilayer joint. However, it is more difficult to predict cohesive properties and strengths[9] since the frequency shifts, resulting from a change in cohesive properties or bond line thickness, are small and of a similar magnitude to each other. Consequently, to obtain a true measure of the cohesive properties with this instrument the bond line thickness must be kept constant (or be measured separately).

The technique of ultrasonic spectroscopy[10] is currently being evaluated for measuring the cohesive properties of an adhesive joint. It gives the frequency response over a wide frequency range, typically 1–20 MHz, but difficulties have been experienced in correlating features of the spectrum with adhesive properties and thickness.

6 TECHNIQUES TO LOCATE POOR ADHESION STRENGTH

There is no commercial instrument available that can give an indication of the adhesion strength of a joint after it has been manufactured.

Although acoustic emission has been shown[11] to be able to detect adhesion failure prior to fracture, the joint has to be loaded to approximately 50% of its failure load. While such a technique is partially destructive, there are currently few alternatives if adhesion strength is to be monitored.

7 CONCLUSIONS

A variety of methods is available for the detection of complete disbonds in adhesive joints. However, techniques which attempt to predict cohesive strength, such as ultrasonic spectroscopy and the Fokker Bond Tester Type II, are not yet generally regarded as reliable. Research is continuing in this area and shows considerable promise. The non-destructive measurement of adhesion strength is currently not possible.

In practice, adhesion failure and poor cohesive properties are generally prevented by careful surface preparation and process control. This leaves the bond inspector to monitor the presence of voids and disbonds in the glue line. Of the many techniques used for void and disbond detection, some are more suitable for use in particular circumstances than others.

Since the cost and time spent finding voids and disbonds will generally decrease as defect size increases, it is important to decide on the minimum size of defect to be detected. Other factors, such as the type of testing environment, will also influence the choice of method used for void and disbond location. However, the number of suitable techniques decreases as the defect size decreases.

Small defects, such as porosity, will only be located reliably by time domain ultrasonics combined with a scanning mechanism to give a C-scan presentation. For larger defects, a scanning mechanism will be unnecessary unless a C-scan record is required.

Sonic vibration techniques are particularly suited to the inspection of honeycomb structures and do not require the use of a couplant which is essential with the ultrasonic techniques.

References

1. T. T. Wang, F. W. Ryan and H. Schonhorn, *J. Appl. Polymer Sci.* **16,** 1901 (1971).
2. R. D. Adams and W. C. Wake, *Structural Adhesive Joints in Engineering.* (Elsevier Applied Science, London, 1984).
3. P. F. A. Bijlmmer, in *Adhesion* 2, K. W. Allen, Ed. (Applied Science Publ., London, 1978).
4. M. X. Li, W. Z. Ding and J. M. Chen, *N. D. T. Int.* **15,** 137 (1982).
5. P. Cawley, *N. D. T. Int.* **17,** 59 (1984).
6. Yu. V. Lange and I. I. Teumin, *Soviet J. N.D.T.* **7,** 157 (1971).
7. R. D. Adams, A. M. Allen and P. Cawley, *Proc. 11 WCNDT,* Las Vegas, U.S.A. (1985).
8. R. J. Schliekelmann, *Non-Destructive Testing,* p. 100 (April 1975).
9. G. J. Curtis, in *Ultrasonic Testing-non conventional testing techniques* (Wiley, Chichester, 1982).
10. E. P. Lloyd and A. F. Brown, in *Adhesion 2,* K. W. Allen, Ed. (Applied Science Publishers Ltd., London 1978), p. 133.
11. G. J. Curtis, *Non-destructive Testing,* p. 249, (Oct. 1975).