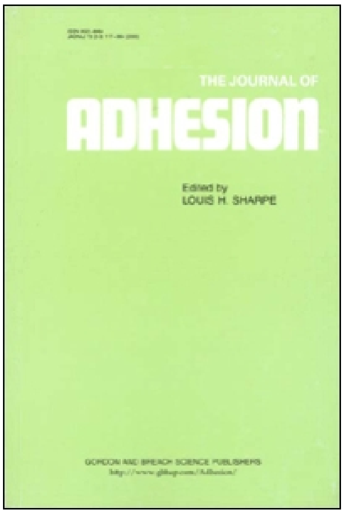

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Strength Predictions in Bonded Joints—Current Thoughts and Research at the University of Bristol, U.K.

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INTRODUCTION

Our basic aim is to devise methods of predicting the strength of adhesively-bonded joints. We recognise that to do this on a full scientific basis, using a combination of material science and advanced numerical analysis for stress and strain analysis, is only possible in a university or advanced industrial laboratory.

As applied scientists, we see this process as germane to our activity. But as engineers, we also see the need to transfer this knowledge and understanding to industry.

But let us see things in perspective. The number of finite elements we use in our mathematical analysis for a single joint is of the same order as is used by an automobile manufacturer to analyse a complete car!

We are therefore in a dilemma. Using the old-fashioned closed-form algebraic analyses based on the classical work of Volkersen[1] and Goland and Reissner[2] involves simplifications so great that reality is lost. But to advocate the blanket use of finite element analysis is equally futile as the learning-curve is long, the cost is high, and, unless great care is used, the results are no more useful than the algebraic methods.

The basic problem is that in all practical joints, a stress concentration exists. At a square or sharp corner (if one exists!) the stress is infinite. Even adhesive plasticity does not help as this only reduces the problem to one of infinite *strain*. We cannot use fracture mechanics as there is no crack present. To postulate the existence of a crack which allows data-fitting is to debase the problem to one of empiricism. And then what length of crack do you assume for some other adhesive or joint geometry. Is the assumed crack length affected by such uncontrollable variables such as bond-line thickness?

In effect, we have to look at the challenge from several directions. First, we recognise the importance of a powerful finite element analysis. Second, we need reliable data (adhesive properties) to put into that analysis. Third, we need to iterate between the predictions of the analysis and experimental results on real joints in order to prove that the failure predictions work. The essence of our work at Bristol is to bring together these three elements in an interdisciplinary approach in order to develop a rational methodology for predicting joint strength.

And how is that to be applied to the design and use of adhesives in industry? First, we need a simplified analysis procedure—but how simple? Second, we need, as before, reliable adhesive properties. Finally, we have to correlate with experiment to prove the validity of the simplified analysis. The secret is the degree of simplification. This can only be satisfactorily determined by studying the results of the scientific investigation. In other words, technology transfer can only be achieved when the fundamental scientific background is fully understood and verified by experimental results. As stated by Sharpe[3], the breaking strength of an adhesive joint is determined by the mechanical properties of the materials used, the geometry, the interfaces, and so on. Fortunately, for the vast majority of well-made structural adhesive joints, failure takes place within the adhesive, which we can characterise, rather than at the interface or in the interphase, the properties of which are difficult to measure.

So how are we tackling this problem with the resources available? I give below details of some of the recent and current work at Bristol which is helping to achieve our objectives.

Finite Element Analysis

We started work on this in 1970, when it was normal to write your own programs for computers which were slow and were often card-fed! Since then, we have progressed enormously with the advantage of cheap, fast, and accurate computers. You should realise that your modern personal computer is similar in performance to the mainframe we had in 1970! Today, it is easy to buy a wide range of software for finite element analysis, although there are still advantages in writing your own dedicated software for specific work such as on adhesive joints.

The paper published by Harris and Adams[4] was on lap joints and was based on earlier work by Peppiatt, Coppendale and Crocombe. The importance of treating the finite element analysis is a problem in non-linear mechanics (owing to joint rotation) as well as non-linear material properties. It illustrated the problem of defining not only adhesive yield in a complex stress system, but also of defining adhesive failure.

Harris' work was developed into a study of the stresses and strains around the corner of the unloaded adherend.[5] It was shown that tiny modifications to the corner geometry had an enormous effect on the stress and strain concentrations. Further, adhesive plasticity also had large influences. This work was continued by Chen and Zhao.

The bonding of composites presents a special problem because of their anistropy. In the direction of the fibres, composites are strong and stiff, but in the direction normal to the fibres, the tensile strength is similar to or less than that of the matrix. We published a paper on this[6] in conjunction with Kinloch. The finite element predictions and adhesive property measurements at Bristol were compared with some experimental results by Kinloch and it was shown that greatly increased lap joint strength was possible by shaping the ends of the joints. Subsequent work at Bristol showed a five times increase in joint strength for a variety of single lap joints. The essence was to remove the initial failure from the composite to the adhesive by reducing the transverse stresses in the composite. (Similar mechanics apply, of course, to the bonded tabs on the ends of composite unidirectional tensile specimens).

Another feature of carbon-based composites is the low coefficient of thermal expansion in the fibre direction. This can lead to substantial thermal stresses both in manufacture and in usage. Recent work at Bristol by Mallick has shown the magnitude of these stresses. Mallick also developed some new software for joints involving composites. Other work was done by Al-Hamdan partly at Bristol and partly at the University of Kuwait.

Zhao has developed the work of Harris and has also given a treatment of the three-dimensional stresses in joints. These exist owing to the differential strains in the adhesive and adherends, and because of Poisson's ratio effects.

More recent work by Grant has been towards the effects of other than tensile loads on joints, and in the analysis of other than lap joints. One feature has been the enormous reduction of lap joint strength (nearly four times) for thick glue lines (3 mm compared with 0.1 mm). Is this well known? It is certainly an important result.

Static and Impact Loads

We have developed apparatus to measure the impact as well as the static adhesive properties (stress vs strain). These properties have been used in the finite element programs to predict joint strength when failure takes place in a few milliseconds rather than a few minutes. The question here is how do bonded joints perform in structures, particularly automotive, during impact. The essence is that the strongest joints are made with non-ductile adherends, but these do not absorb any significant energy by plastic deformation. Judicious choice of adhesive and adherend can optimise impact and static behaviour.

Nondestructive Inspection

Work with Cawley when he was at Bristol and subsequently at Imperial College, London, involved nondestructive testing of composites and adhesives. The results of this collaboration have produced a commercial instrument, the Tapometer, which is, in effect, a smart coin. The principles are described in reference 7.[7]

In addition, the Fokker Bond Tester was analysed and certain comments were made about its operation.[8]

CONCLUSIONS

We are attempting to predict the strength of joints from first principles, and to transfer this understanding to industry. In twenty years, we think we have a good understanding, but this is still not sufficiently exact. *Tempus fugit.*

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