STRUCTURAL BONDING USING FLEXIBLE ADHESIVES

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Flexible adhesives, characterised by low modulus and large extensions to failure, are already widely used in applications such as sealing and vibration control. However, owing to their capability for distributing loads and sustaining relatively large extensions, flexible adhesives are increasingly being considered for use in structural applications. Hence, the mechanical performance of the adhesive assumes greater importance and Finite Element Modelling design calculations may be desired to ensure joint performance at the design stage. Accurate materials properties and valid material models are essential to obtain accurate design predictions. There are many hyperelastic models available for characterising rubber materials however their suitability for use with flexible adhesives, often complex multi-phase materials, has yet to be established. Similarly, combinations of test data under different states of stress are recommended for the determination of model coefficients. The objective of the work presented was to establish suitable models and materials properties data for representing flexible adhesives in design predictions.

Hyperelastic models, such as the polynomial model, derive energy potentials (U) from a combination of deviatoric strain invariants I_1 and I_2 with fitted coefficients C_{ij} and the elastic volume ratio J^{el} with fitted coefficients D_i.

$$U = \sum_{i+j=1}^{N} C_{ij}\left(I_1 - 3\right)^i \left(I_2 - 3\right)^j + \sum_{i=1}^{N} \frac{1}{D_i}\left(J^{el} - 1\right)^{2i}$$

The higher the model order (N) the more complex the function and the greater the number of constants. Higher order functions are required to fit the complex shapes of the stress-strain curves of high strain true rubbers but may lead to instability in the FE solver code causing convergence problems in analyses. Since most flexible adhesives do not sustain strains greater than ca. 1.0, the lowest order models (N=1) should be most appropriate. For polynomial models the N=1 case is the classical Mooney-Rivlin model. Other first order models are the Neo Hooke (reduced polynomial with N=1) and Arruda-Boyce. Polynomial, reduced polynomial and Ogden models are available in FEA packages with orders N = 1, 2 or 3. When hyperelastic models of order 2 or higher were used to represent adhesives in FE simulations of bonded joint specimens it was often noticed that the shapes of the predicted curves did not match those of the first order models or measured test data.

The deviatoric coefficients are determined through least square fits to data determined under various states of tension. FE packages such as ABAQUS recommend that a combination of unixial tension, planar tension and equibiaxial tension tests be used to determine the deviatoric constants. For a visco-elastic material these tests must be performed at the same temperatures and strain rates to be fully compatible. An assumption of material incompressibility is often made for rubber materials in which case the volumetric terms can be neglected. However, this requires a Poisson’s ratio equal to 0.5 and measured values for flexible adhesives tend to be much lower than this suggesting that these materials are compressible and that volumetric properties should be included in the model. For volumetric coefficients test data from a volumetric compression test are recommended. However, for adhesive joints, the critical stress state leading to failure will be tensile rather than compressive. Hence, there is an argument for determining volumetric data under states of tension.

The full test data requirements for obtaining input data require a large amount of testing using test methods that are not particularly suited to adhesives. Although both planar and equibiaxial tension measurements (Figure 1) have been developed as part of this work, neither of these tests is straightforward to carry out. The planar tension test requires large test specimens (typically 200 mm by 60 mm) and it is often difficult to prepare good quality adhesive sheets to the dimensions required. In the equibiaxial test, stress distributions in the specimen are non-uniform and it is not possible to accurately determine the stress in the gauge region of the specimen from the measured forces, a problem common to all biaxial tests. In addition, stress concentrations at the grips cause the specimen to tear, limiting the ultimate strains available from these tests. This limits the range of validity of the derived model coefficients. Thus, consideration was given to limiting the input test data to uniaxial tension data only. The test specimen requires smaller quantities of adhesive and is easier to prepare. Uniaxial tension test equipment is readily available. Through the use of dual-axes video extensometers simultaneous measurements of tensile and transverse strains can be made. From these data volumetric strains can be calculated. Therefore, stress-strain data for determining deviatoric coefficients and pressure-volumetric strain data for determining volumetric coefficients can be measured in the same test.

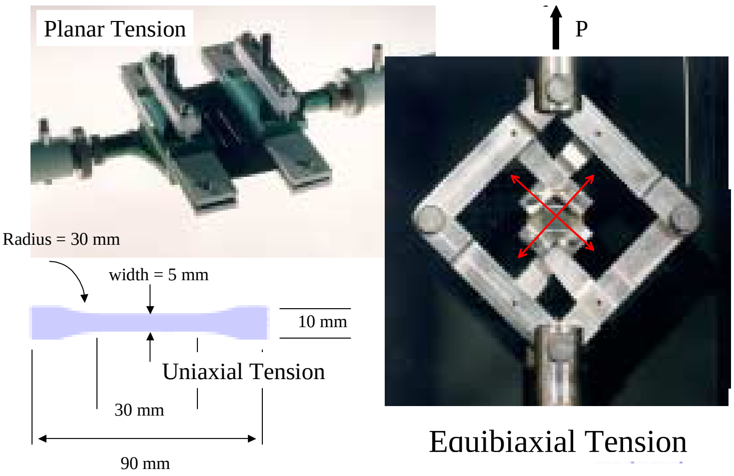

Figure 1: Test methods for hyperelastic properties

Level	Model	Avg Value	Data Type	Avg Value	Temperature	Avg Value	Strain Rate	Avg Value
1	Mooney-Rivlin	0.83	U	0.80	0 C	0.84	3.00E-04	0.65
2	Ogden, N=1	0.79	UBP	0.82	20 C	0.61	3.00E-03	0.78
3	Ogden, N=3	1.04	U+V	0.74	40 C	0.92	3.00E-02	0.94
4	Neo Hooke	0.64	UBP+V	0.78				
5	Arruda-Boyce	0.65						

Table I: Analysis results for full experimental matrix (180 standard FEA experiments) using plane strain elements.

The influence of a range of factors (material model, input data type, temperature and strain rate) on the accuracy of FEA predictions of the force-extension curves for a thin lap shear joint specimen was investigated. A normalised accuracy value was calculated from the sum of the differences between measured and predicted forces (at set strain values). The closer this value to zero the more accurate the prediction. The results of the statistical study are shown in Table I. One of the conclusions of this study is that there is little difference between the accuracy of predictions made using uniaxial tension test data (data type U) and the full set of uniaxial, planar and equi-biaxial (UBP) test data. There is a consistent improvement when volumetric test data (V) are added.

The full analysis of the results outlined in Table I required 180 FE ‘experiments’. An experimental subset consisting of 25 FE ‘experiments’ was identified using statistical design of experiments (DOE) methods. Analysis of this reduced experimental set produced similar conclusions to the full experimental set. There seemed to be significant differences in the capability of FE models to accurately predict the behaviour of joints bonded using different types of flexible adhesive. Figure 2 compares the measured and predicted behaviour of thin lap shear joints bonded using a 2-part polyurethane adhesive (calculated accuracy value = 0.108) and a 1-part polybutadiene adhesive (calculated accuracy value = 0.441).

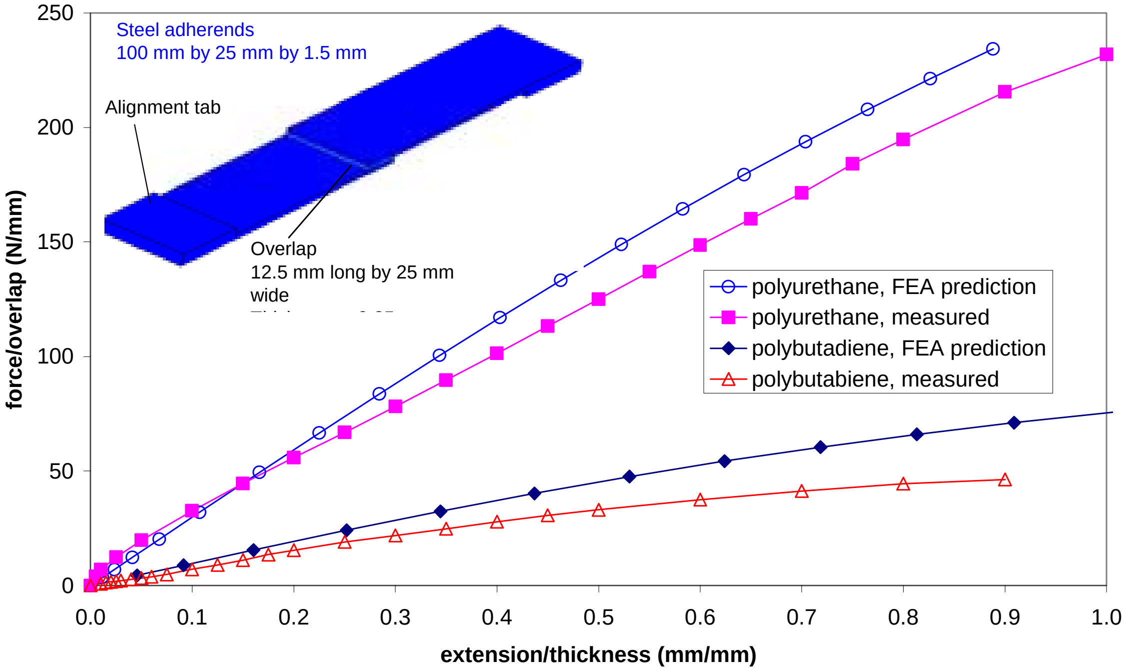

Figure 2: Comparison of FEA predictions and measured lap joint properties

Similar comparisons made using other joint geometries (including scarf and T-peel) also show that the accuracy of predictions is significantly better for the polyurethane adhesive than for the polybutadiene adhesive. The reasons for the relatively poor accuracy of the predictions of the polybutadiene adhesive are not yet clear but may be due to differences in the properties of bulk material and thin adhesive layers (although the thicknesses of bulk sheets and joint bondlines were similar); differences in cure state (however, cure schedules were selected so that both bulk and joint materials experienced the same measured temperature profiles and glass transition temperatures of cured materials were the same) or that the material is not adequately represented by the hyperelastic models.

Mechanical test measurements on bulk samples of flexible adhesives show that both the stress-strain behaviour and ultimate failure strength depend on both strain rate and sample temperature. The failure strength decreases with decreasing strain rate and increasing temperature. These trends are also evident in the properties of bonded joints (Figure 3). Similar correlations are seen between tensile strength and maximum values of stress components predicted in the adhesive layer at the joint failure load. These stress values are not consistent between the different joint geometries but this may be partly due to the presence of stress singularities at sharp corners where the predicted values depend on the mesh density.

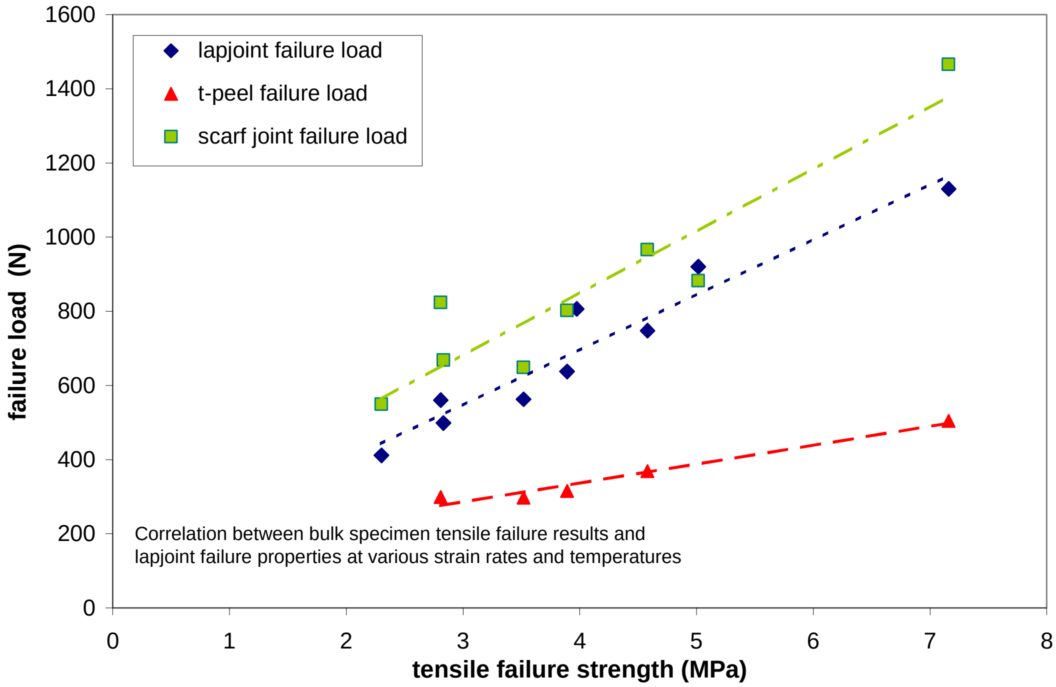

Figure 3: Correlation between bulk tension and adhesive joint failure loads

Hyperelastic models have been shown to be suitable for representing some flexible adhesives in Finite Element Modelling design predictions. However, some validation using bonded test coupons is necessary to ensure the suitability of the materials model and input materials data. The work described here suggests that the necessary data for calculating the hyperelastic coefficients can be obtained from uniaxial tension tests particularly if the specimen contraction is also measured to determine the volumetric strain. Comparisons of different models have shown that simpler hyperelastic models such as the Mooney-Rivlin are probably most relevant for flexible adhesives.

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References

1. LE Crocker, BC Duncan, JM Urquhart, RG Hughes and A Olusanya, The application of rubber models to analyse flexible adhesive joints, Proceedings of Adhesion ’99, Institute of Materials, 1999