

## Flexible Adhesives

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The NPL research project *Flexible Adhesives* aims to supply guidance to design engineers on selecting material models and obtaining engineering data for designing flexible adhesive bonds. Design stress analyses of adhesively bonded structures may be performed using Finite Element methods provided that suitable material models and mechanical properties data are available. Flexible adhesives, above their glass transition temperatures, are characterised by low stiffness and large strains to failure. These materials appear to be best modelled by the first-order variants of hyperelastic models developed for rubbers.

A typical hyperelastic model, such as the polynomial model (Equation 1), represents the adhesive as a sum of deviatoric (or shear) and volumetric (or hydrostatic) terms. The first-order variant of the polynomial model (where  $N=1$ ) is the classical Mooney-Rivlin model.

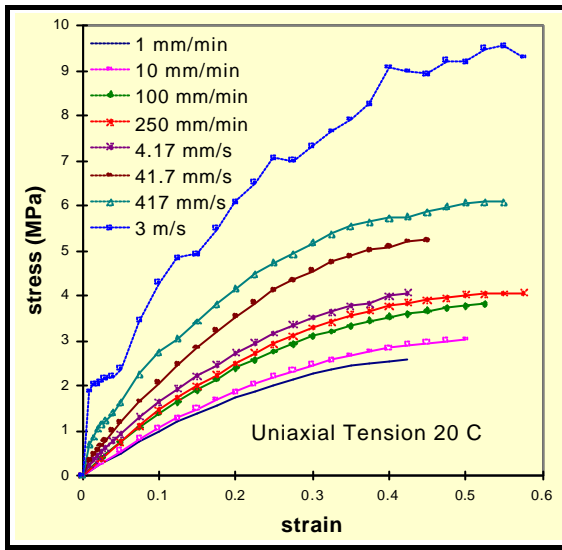
$$U = \sum_{i+j=1}^N C_{ij} (I_1 - 3)^i (I_2 - 3)^j + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i} \quad (1)$$

For rubbers, the deviatoric coefficients ( $C_{ij}$  terms) can be obtained by fitting test data obtained under different states of tensile stress - uniaxial, plane strain and equi-biaxial. The volumetric terms  $D_i$  are obtained from hydrostatic compression tests, although many rubbers are assumed to be incompressible and these terms are often ignored. These test methods may not all be suitable for flexible adhesives. In particular, the plane strain and equi-biaxial test specimens are relatively large which may make it difficult to prepare suitable test specimens. Methods for measuring and analysing these data have been developed but comparisons made between model predictions using coefficients derived from different combinations of tensile test data suggest that there is little improvement in accuracy gained through adding plane strain and equi-biaxial data to the uniaxial test data. Thus, the deviatoric coefficients are most efficiently obtained using only the uniaxial tension test.

Characterisation of many flexible adhesives shows that they are compressible and FE model predictions are improved through the inclusion of volumetric properties. Since the critical stress state leading to failure in an adhesive joint is almost always tensile, volumetric properties obtained in compression may not be relevant. Volumetric strains ( $\epsilon_v$ ) can be determined in the uniaxial tension test from the measurements of axial ( $\epsilon_1$ ) and lateral strains ( $\epsilon_2$  and  $\epsilon_3$ ). Poisson's ratio ( $\nu$ ) is normally assumed equal in the width and through thickness directions ( $\epsilon_2 = \epsilon_3$ ).

$$\mathbf{e}_v = (1 + \mathbf{e}_1)(1 - \mathbf{e}_2)(1 - \mathbf{e}_3); \quad \mathbf{e}_v \geq 1 \text{ for } \mathbf{n} < 0.5 \quad (2)$$

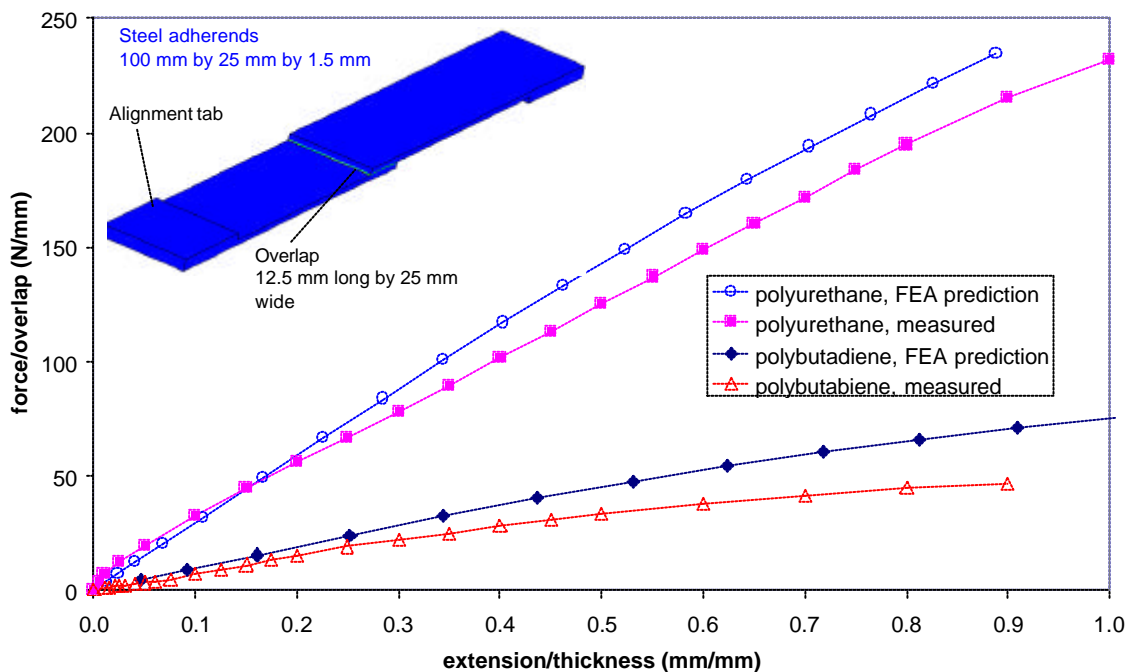
Video extensometry provides a useful tool for the determination of strains in uniaxial tension tests on flexible adhesives.



**Strain rate dependence of tensile properties**

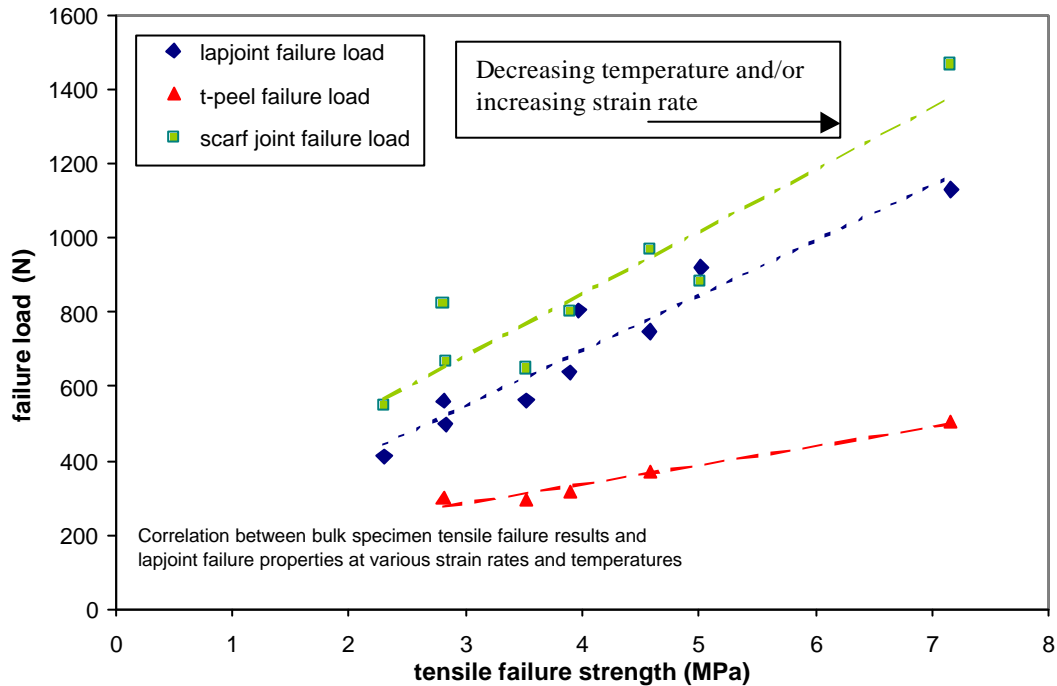
The mechanical properties of the adhesive depend on the strain rate and temperature. For accurate modelling these need to be obtained from tests performed under similar conditions to the situation being modelled. It is relatively easy to perform uniaxial tension tests under a wide range of test conditions. In most cases, since hyperelastic models rely on fitted coefficients, it is difficult to directly determine strain rate and temperature dependence of these coefficients. However, measured stress-strain responses may be interpolated to calculate input data under other test conditions. Visco-elastic relaxation models and the time-temperature superposition principle show some promise as tools for characterising rate and temperature dependence of flexible adhesives.

The effectiveness of the hyperelastic models for predicting the behaviour of adhesively bonded structures is being assessed through comparisons of measured and predicted behaviour in adhesive joint tests, for example the thin single lap shear joint. Some materials seem to be better represented by the hyperelastic models than others. The suitability of the models may depend on the types and levels of additives in the adhesive formulations.



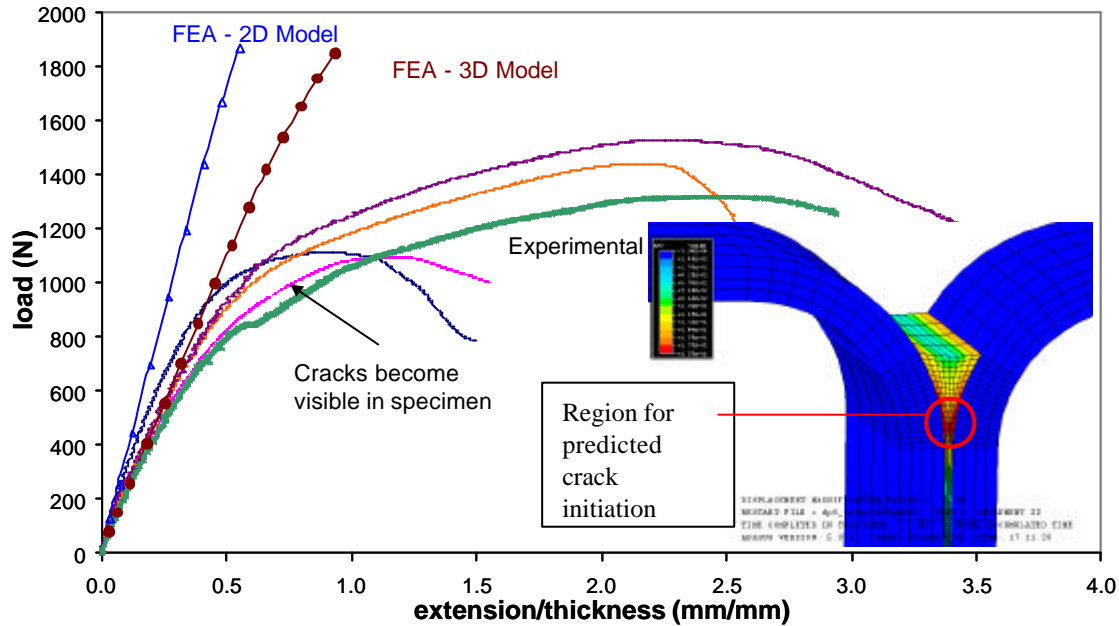
**Comparison of FEA predictions and measured lap joint properties**

Like the stress-strain responses, the failure loads of flexible adhesive joints appear to depend on strain rate and temperature. There seems to be a correlation between failure strength in tension and joint failure load when several types of joint specimen bonded with an elastomeric adhesive are tested at different strain rates and temperatures. However, predicted stress and strain components in the adhesive bond-layer near failure, whilst showing a similar linear relationship with tensile strength, do not appear to correlate between joint types. This suggests that there is unlikely to be a single property that will describe the mechanical or failure properties of the flexible adhesive. Instead an envelope of properties should be considered. Suitable failure criteria for flexible adhesives are being investigated using bulk test specimens and various bonded joint geometries.



**Correlation between bulk tension and adhesive joint failure loads**

One factor complicating the analysis of the adhesive joint tests is that cracks or fractures may occur in the specimen prior to reaching the maximum load on the specimen. Thus the response of the specimen, a combination of large strain material properties and crack growth, cannot be accurately modelled by the continuum mechanics approach employed in the models. For any design purpose, the initiation of cracks in service is undesirable and could be taken as a failure criterion for the design. The T-peel test showed large deviations from the FE model predictions at large strains. This was assumed to be due to the formation of cracks prior to ultimate failure. FE analyses predicted, from the location of the stress concentration, that the cracks would form in the region where the arms of the specimen start to curve apart (however, for a structural adhesive, such as epoxies, this stress concentration would occur at the end of the bond line). Photographs taken of a T-peel specimen during a test showed that cracks did form in the area predicted by the FE modelling. They became visible around 750 N, which is approximately the point where the measurements and predictions started to diverge. Around this load the maximum principal stress in the adhesive was only slightly less than the tensile strength (24 MPa).



### Comparison between FE predictions and measured data in the T-peel test

#### Summary

First-order hyperelastic material models show promise for characterising the large-strain properties of flexible adhesives in quantitative design predictions. The required material properties data, for determining model coefficients, can be obtained most efficiently from the uniaxial tension test. The failure loads of joints bonded with flexible adhesives appears to depend on the tensile strength of the adhesive under similar test conditions (strain rate and temperature). However, the appearance of cracks before ultimate load is reached complicates the analysis. It is recommended that the point of crack initiation is considered as the failure criterion and design stress limits chosen to avoid crack initiation in service.

Further information on this project is available from:

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The *Flexible Adhesives* project is one of several Performance of Adhesive Joints research projects supported by the DTI Materials Metrology programme at the NPL Materials Centre. It aims to finish in 2001, producing Good Practice Guides and reports on measurement and design methods for flexible adhesive joints. Further information on these projects can be obtained from the Materials Enquiry Point at NPL.

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