

**Performance of Adhesive Joints Programme
Project PAJ1 - Failure Criteria and their Application to
Visco-Elastic/Visco-Plastic Materials**

Project PAJ1: Final Report

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ABSTRACT

Project PAJ1 *Failure Criteria and their Application to Visco-Elastic/Visco-Plastic Materials* was one of three technical projects in the Materials Measurement programme *Performance of Adhesive Joints (1996-1999)*. This report summarises the achievements of the project made in the four technical tasks.

1. Viscosity measurements for visco-elastic materials;
2. Tack;
3. Failure criteria under tensile and shear loading;
4. Failure criteria.

The project has generated new or improved test methods for measuring the process and mechanical properties for flexible adhesives. Greater understanding has been developed about the measurement of tack and the modelling of flexible adhesives using Finite Element Analysis.

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1. SCOPE OF THE PROJECT

Adhesive joining offers many potential advantages to the manufacturer including weight reduction, simplified assembly, reduced part numbers and the ability to join dissimilar materials. However, the uptake of adhesive joining technology is hindered by lack of confidence amongst design engineers as to the performance and durability of adhesive joints. Part of this lack of confidence is due to unfamiliarity with adhesives technology but also stems from a lack of validated design tools, design data or test methods. This was recognised by the DTI [1] and led to the establishment of the MTS programme on the Performance of Adhesive Joints, ADH, (1993-1996) and the subsequent Materials Measurement programme, PAJ, (1996-1999).

Project PAJ1 was one of three research projects making up the DTI Engineering Industries Directorate (EID) Materials Measurement programme '*Performance of Adhesive Joints*'. It concentrated on flexible, visco-elastic adhesives used in diverse industries such as transport, packaging and footwear rather than the stiffer adhesives used in structural bonding applications. Structural adhesives were the subject of the other two projects in the programme, PAJ2 '*Dynamic Performance of Adhesive Joints*' and PAJ3 '*Combined Cyclic Loading and Hostile Environments*'.

Project PAJ1 built on some of the work from the previous MTS project ADH5 [2] on the measurement of rheological and tack properties of adhesives. Work was also initiated in new areas covering the mechanical performance, failure criteria and Finite Element Analysis (FEA) of flexible adhesives. In the context of this work a flexible adhesive is an adhesive whose glass transition temperature is less than room temperature. That is an adhesive whose properties will be rubber-like under most conditions. Although it should be noted that at low temperatures the properties will be more akin to structural adhesives.

The project consisted of four technical tasks:

1. Viscosity measurements for visco-elastic materials;
2. Tack;
3. Failure criteria under tensile and shear loading;
4. Failure criteria.

Additionally, there was a task covering project management and dissemination. Dissemination results for PAJ1 will be included in the over-arching dissemination report produced in project PAJ0. Therefore, details of dissemination are not covered in this report which focuses on the technical outputs of the project.

PAJ1 has produced 18 technical reports, a Measurement Good Practice Guide and a number of conference papers/journal articles. This report summarises the findings reported in these documents. The major technical outputs of the project are listed below.

Main Technical Outputs of Project PAJ1

TASK 1: Viscosity Measurements For Visco-Elastic Materials

- Modifications that were made to a commercial rheometer to extend the measurement range have been adopted by the manufacturer.
- Evaluation of the rheometer for determining dynamic properties of flexible adhesives.
- Study of time-dependent property measurements using the rheometer.

TASK 2: Tack

- Modifications to the NPL/SATRA Tack Tester and commercialisation of the instrument - winning a best new product award from American Shoemaker.
- Round-robin carried out to assess a widely used loop tack test method.
- Improved insight gained into how differences in test methods can lead to different test results.
- Finite Element model of the loop tack test produced to further the understanding of how the mechanical properties of the backing contribute to the results (demo CD-ROM distributed).
- Measurement Good Practice Guide on Adhesive Tack.

TASK 3: Failure Criteria Under Tensile And Shear Loading

- identification of Hyperelastic material models and strain energy based failure criteria for flexible adhesives.
- Development of mechanical test methods and apparatus for Hyperelastic materials;
 - planar tension test;
 - equi-biaxial test.
- Mechanical properties data measured for 3 adhesives over a wide range of temperatures.
- Improved understanding of modelling flexible adhesives.
- Comparison between FE predicted and experimentally measured performance of an adhesive joint.
- Demonstration of the suitability of 2-D approximation in FE models for describing 3-D Hyperelastic systems.

TASK 4: Failure Criteria

- Evaluation of test methods for generating time-dependent properties.
- Creep data generated on two flexible adhesives at several temperatures.
- Determination of a possible relationship between failure criteria under creep and failure in quasi- static tests at elevated temperatures.
- Problems with the accuracy of FE predictions of creep performance reported.

2. VISCOSITY MEASUREMENTS FOR VISCO-ELASTIC ADHESIVES

Problems exist in testing flexible materials due to their very high extensibilities and low stiffness. These create difficulties in the use of contact extensometry. The previous programme [3] established that the rotational rheological instruments used primarily to measure the flow properties of adhesives could also be used to some effect for characterising their mechanical properties. A review of rheological measurement methods was undertaken to determine the strengths and weaknesses of the various measurement techniques with regard to adhesives [4].

The previous project (ADH5) had made modifications to a commercial controlled-stress rotational rheometer. Development of this NPL reference rheometer (a TA Instruments Carrimed CSL 500) was continued with the aim of increasing the stiffness and, hence, the effective measurement range of the instrument. A new air bearing shaft that had splines machined into it to provide a 'key-fit' connection to the measurement geometries was installed. This modification reduced the instrument compliance from 1.96 mrad/Nm to 1.64 mrad/Nm, i.e. by approximately 15% of its original value [5]. The new splined fitting also removed the dependence of the rheometer compliance on the fastening torque of the draw rod. This improves measurement repeatability. Many of the modifications proposed for the rotational rheometer have been adopted in commercial instruments.

One of the key features of the rheometer for adhesives research is its capability of measuring the properties from the liquid/paste state through cure to the solid state. Thus, both processing and material performance properties could be measured on a single instrument.

To demonstrate the versatility of this multi-purpose adhesives test station, evaluations of the capabilities of the modified rheometer for measuring the mechanical properties and time-dependent properties of 'flexible', solid visco-elastic adhesives were performed [6-8]. In an oscillatory operating mode, the rotational rheometer ought to perform as a Dynamic Mechanical Thermal Analysis (DMTA) instrument. A series of experiments was carried out to compare the rheometry technique with flexural DMTA measurements [6]. This showed that:

- corrections for the compliance of the rheometer are needed to give reasonable accuracy;
- uncertainties in the compliance correction severely limit the measurement accuracy as the stiffness of the sample approaches that of the instrument;
- for the instrument and measurement geometry studied, measurement accuracy was limited above a material modulus of 100 MPa - for such materials the DMTA method is much more reliable;
- the high sensitivity of the rheometer to small forces allows good accuracy for low modulus materials (such as flexible adhesives) - in this region the rheometer out performs the DMTA; and,
- the frequency and temperature sweep capabilities of the rheometer enable determination of features in the properties of the polymers, such as the glass transition temperature (T_g), much as in DMTA.

Modern rheometers are computer controlled. Often the measurement software contains functions for measuring and analysing time-dependent properties, such as creep or stress relaxation. Although these functions were designed for the study of gels and pastes, it was

thought that they may be applicable to 'solid' flexible adhesives [7, 8]. Evaluation of the controlled stress rheometer in creep-control mode showed that the results produced for the visco-elastic adhesives tended to be unreliable. Relaxation measurements using a controlled strain rheometer showed more promise [8]. However, rotational rheometers are expensive instruments and it would be uneconomic to dedicate such equipment to long-term testing.

3. TACK

Tack is the property of an adhesive that describes its ability to form a bond with another surface after brief contact under light pressure. In other words, tack is a measurement of the stickiness of the adhesive. Although the concept of tack is simple to describe, it is a difficult 'property' to measure or control accurately. This is because tack is not a simple 'material' property of the adhesive. It also depends on the way the adhesive is prepared, the bond formation conditions and the method of testing. Despite this, tack is one of the most important process measurements for adhesives in many applications ranging from footwear manufacture to adhesive tapes. In recognition of the importance of tack to many industrial sectors this task was performed in collaboration with SATRA Footwear Technology Centre and Pira International (Packaging Industry Research Association).

In project ADH5, a test method and instrument for determining the tack of footwear adhesives was developed in a collaboration between NPL and SATRA to replace the subjective peel test that had been used previously [9]. Part of the need for a new test method was the requirement to substitute water-based adhesives for solvent-based adhesives in order to reduce volatile organic compound (VOC) emissions to comply with new environmental legislation. The NPL/SATRA Tack Tester supplies more reliable test data to aid the selection of alternative adhesives. This instrument was further developed within PAJ1. Modifications were made to allow improved control over the contact pressure when bringing the sole and upper together in the test (this is known to be a major variable in the test procedure). The instrument has been commercialised (winning an award from American Shoemaker as a best new product of 1997).

The modified shoe tack tester was used by SATRA to investigate a number of factors influencing tack measurements [10]. The results showed the influence of testing parameters such as the compliance of the substrates or separation rate on the tack results. The study also showed the influence of processing parameters such as adhesive activation temperature, drying time and contact pressure that could help optimise the bonding operation.

Tack is particularly important in the packaging sector where the use of pressure sensitive adhesives, tapes and labels is widespread. A survey of the standard tack measurement methods for adhesive tapes employed by UK companies [11] found that the most popular method was the FINAT 'Quick Stick' method FTM9. This is a loop tack test method. An intercomparison, 'round-robin' exercise was organised by Pira International to investigate the reproducibility of this test method [12]. Thirteen laboratories took part in this exercise. The findings indicated that whilst the repeatability within a laboratory tended to be good, the reproducibility between laboratories was rather scattered. The differences between laboratories were thought to be due to the following factors:

- difficulties in forming loops from the tapes (one of the tapes had a very thin backing and was difficult to handle, this tape gave the worst reproducibility);

- inexperience in performing the test;
- differences in methods of stating results (average 'peak' force vs. peak force); and,
- differences in sampling equipment (higher sampling rates tend to produce higher peak forces).

Work undertaken by NPL [13, 14] investigated some of the parameters that affect the measurement of tack. Three of the principal methods for the measurement of tack of pressure sensitive adhesives (rolling ball, loop tack and probe tack) were compared. This work concluded that for the loop tack and probe tack test methods the measured tack values can be influenced by:

- substrate material (20 % difference between float glass and stainless steel for the tapes used);
- stiffness of the backing tape;
- contact pressure;
- dwell time; and,
- separation speed.

Direct comparison of the ranking of different tapes by the three test techniques showed that the rolling ball test can produce results in variance to the other methods. This is because the 'tack' measured from the distance to halt the rolling ball is also strongly dependent on the thickness of the adhesive layer.

The loop and probe tack tests tend to similarly distinguish tapes with high, medium and low tack adhesives. The exact ranking of similar tapes by the two methods may vary. Variations can be due to differences between the methods (particularly dwell time and contact pressure). Where adhesive tapes with similar tack have different sensitivities to these test parameters the variation between the test methods may be sufficient to alter the ranking of the tapes.

A Finite Element simulation of the loop tack test was created to investigate the dependence of the test results on the properties of the backing tape [15]. A series of analyses was performed where the adhesion strength between the nodes on the substrate and the nodes on the tape was kept constant. The thickness and modulus of the backing were varied. The maximum force to detach from the substrate was predicted to decrease substantially as the stiffness of the tape increased. The initial model was fairly unrefined but served to illustrate how the Finite Element method could be used to explore factors that influence tack. A demonstration CD-ROM has been produced describing the analysis of the loop tack test. The FE simulation has since been further developed to include an 'adhesion' element where the force-extension properties of the adhesive may be specified.

A brief investigation was performed into the correlation between visco-elastic properties and tack [16]. It was shown using double-sided adhesive tapes that the rotational rheometer, operated in an oscillatory mode, was well suited for measuring the visco-elastic properties of pressure sensitive adhesives. Similar measurements carried out in flexure using a conventional DMTA instrument were dominated by the response of the carrier tape rather than the adhesive. The actual correlation between the visco-elastic properties of the adhesive tapes and their tack properties was relatively poor. The visco-elastic moduli of the tapes increase with test frequency. However, the tack force determined from the probe tack test reaches a peak value then declines as the separation rate is increased. More detailed analysis of the force-time output

from the probe tack tester reveals that whilst the stiffness of the system increases with rate, the deflection to failure decreases. The combination of these effects leads to the peak in the observed tack-separation rate relationship. One conclusion from this study is that it can be misleading to use low-strain visco-elastic properties to characterise relatively large-strain behaviour such as tack of pressure sensitive adhesives.

Tack is a property that is difficult to measure accurately due to the influence of many different factors on the results. Even standard test methods can give variable results. The results of the studies carried out in this task have been reported to various bodies engaged in producing standard methods for tack measurement. However, it must be recognised that many organisations modify standard methods to suit their own applications. Therefore, a guide to good practice for the measurement of tack was produced to help test labs with the selection of standard methods or to aid the development of in-house methods for process optimisation [17].

4. FAILURE CRITERIA UNDER TENSILE AND SHEAR LOADING

Traditionally, flexible adhesives are used in non-structural applications such as sealing or vibration damping. However, as design philosophies change the adhesive is required to contribute more to the load bearing capability of the structure. Finite Element Analysis (FEA) is a widely used tool in the design of adhesively bonded structures. It enables prediction of component performance (e.g. force-deflection) and local stress distributions (to identify areas of stress concentration where failure may initiate). Designing reliably with flexible adhesives requires accurate test data for input into the appropriate material model. Criteria are then needed to assess whether the joint is likely to fail under the service load.

A survey of material models commonly found in FEA software packages [18] concluded that the Elastic-Plastic type material models commonly used for structural adhesives were unlikely to accurately represent flexible adhesives (where the moduli are orders of magnitude smaller but the extensions to failure much greater). These adhesives are non-linear visco-elastic materials. However, these types of models are not available in FEA software and it was proposed that Hyperelastic material models developed for rubbers may be a reasonable approximation for characterising flexible adhesives.

The theories for rubbers solve phenomenological equations of deviatoric (shear) and volumetric components of the stress tensor for the strain energy potential. Hence, strain energy density is often used to predict failure in rubbers and may represent a suitable failure criterion for flexible adhesives [19]. The energy (H_B) dissipated in a rubber stretched to near failure and then returned to its original length can be related to the strain energy at failure (U_B).

$$U_B = KH_B^{2/3}$$

The hysteresis energy can be determined from the area enclosed by the hysteresis stress-strain curve on loading and unloading. The relationship between the hysteresis energy dissipated and the strain energy at break adds little to the understanding of how the adhesive will perform in the monotonic loading situation that was investigated. However, it may be more appropriate for cyclic fatigue loading conditions.

Test data are required under several states of stress to fully characterise the Hyperelastic properties of the adhesives. These tests are only briefly described in the FEA manuals [20]. The

required test data are listed below. The equivalent stress states in compression are given in the brackets.

- uniaxial tension (equi-biaxial compression);
- planar tension (planar compression);
- equi-biaxial tension (uniaxial compression); and,
- volumetric data.

With the exception of the uniaxial tension test, these test methods are not well developed. A normal assumption for rubbers is that they are virtually incompressible and, therefore, as the volumetric terms in the model are insignificant then such test data are not required. The Hyperelastic properties can then be characterised through the uniaxial tension, planar tension and equi-biaxial tension. Development work was carried out to obtain reliable methods for the latter two tests [21-23].

The planar tension test applies plane strain conditions to the test specimen (in contrast to the uniaxial test where plane stress conditions exist). This is achieved through the use of specimens with high aspect ratios (ratio of specimen width to grip separation) gripped so that the specimen is constrained from contracting in the direction perpendicular to the axis of extension. Planar tension data were obtained using specimens 200 mm wide and 1-2 mm thick that were clamped with a grip separation of 40 mm. Stress-strain curves obtained using alternative grip separations (20 mm to 50 mm) all overlap and measured transverse contractions are negligible, confirming plane strain conditions [22].

Equi-biaxial tension requires extension of the specimen simultaneously in two orthogonal directions. Mechanical test equipment for performing such tests is rare owing to the expense of such equipment. As part of PAJ1, a test fixture was developed that was capable of biaxially deforming test specimens in a standard uniaxial test machine. The biaxial test fixture pivots in such a way that the test specimen in the centre is extended equally in two directions at $\pm 45^\circ$ to the axis of the test machine. FEA and 2-dimensional strain measurements have confirmed that the stress and strain distributions in the centre of the specimen are equi-biaxial [22]. Due to symmetry, strain can be determined directly from the strain measured from the extension of two gauge marks in the vertical direction. However, the measured force must be corrected to account for the leverage of the test fixture and to resolve the components in the biaxial directions to obtain the biaxial force.

Table 1: Adhesives

Adhesive	Supplier	Type	Cure
DP609	3M	2-part polyurethane	room temperature, > 8 hours
M70	Evode	1-part polybutadiene (elastomeric)	200 °C, 45 minutes
3289Y5000	PPG	1-part epoxy-butadiene	190 °C, 20 minutes

Test data were measured using the three methods outlined above over a range of temperatures between -20 °C and 80 °C to obtain input data on three flexible adhesives described in Table 1.

Three representative Hyperelastic material models were selected for study. These are shown in Table 2. The materials were assumed to be incompressible for the Mooney-Rivlin and Ogden

models. Therefore, D_i values, describing volumetric behaviour in the equations in Table 2, were assumed to be zero. Compressibility was allowed in the Hyperfoam model through the Poisson's ratio (ν). The model coefficients were fitted using a least squares fitting routine in the ABAQUS FEA package. Single element simulations were run to check the agreement between the fitted models and raw test data. These showed varying degrees of correlation between the model predictions and test data.

Table 2: Hyperelastic material models

Model	Order	Function (of strain potential U)
Mooney-Rivlin	$N = 1$	$U = \sum_{i+j=1}^N C_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i}$
Ogden	$N = 3$	$U = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} (\bar{I}_1^{\alpha_i} + \bar{I}_2^{\alpha_i} + \bar{I}_3^{\alpha_i} - 3) + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i}$
Hyperfoam	$N = 1$	$U = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} \left[\hat{I}_1^{\alpha_i} + \hat{I}_2^{\alpha_i} + \hat{I}_3^{\alpha_i} - 3 + \frac{1}{b_i} \left((J^{el})^{-\alpha_i b_i} - 1 \right) \right]$ $b_i = \frac{n_i}{(1 - 2n_i)}$
<p>C_{ij}, D_i, μ_i and α_i are material coefficients fitted from the test data. λ_1, λ_2 and λ_3 are deviatoric principle stretches in the 1, 2, 3 directions respectively; I_1 and I_2 are the first and second deviatoric strain invariants, J^{el} is the elastic volume ratio and ν_1 is the Poisson's ratio.</p>		

A Finite Element model of a single lap joint specimen was produced. As part of the model generation for the adhesive lap joint, alterations were made to TWI's GLUEMAKER pre-processor package for meshing adhesives joints to include Hyperelastic models and an increased number of elements through the thickness of the bondline [24]. FE simulations were run to predict the force-extension behaviour of the joint modelling the adhesive using different material models (and different temperature test data). The stress, strain and strain energy distributions within the adhesive layer were examined to obtain more detail of the local state of the adhesive.

Lap joint specimens, bonded with each of the three adhesives, were tested over the same temperature ranges as the bulk specimens. Force extension curves were measured to failure. Joints bonded with the Evode M70 adhesive all failed cohesively through the centre of the adhesive. Those made with 3M DP609 and PPG Y5000 tended to fail adhesively at the interface. It was shown that the joint strength of the 2-part DP609 adhesive could be improved through post-curing the specimens (suggesting that full cure had not been achieved in the period between manufacture and testing, normally greater than a week). Joint strength could also be increased through more extensive surface preparation [21].

The geometry of the lap joint corresponded to the FE model of the lap joint. The results from these tests were compared with the FE predictions. Generally, the agreement between the FE predictions and the experimental predictions were poor.

Some of the findings of this study are listed below [21, 22]:

- Generally, the Hyperelastic models give better agreement with the experimental data than the standard Elastic and Elastic-Plastic models [21].
- The properties of the adhesive in the joint may be different to the bulk adhesive owing to different thermal histories during cure (or at different ages in the case of room temperature curing adhesives). A subsequent study showed that the bulk and joint specimens did experience different thermal histories during high temperature cure [22]. DMTA measurements indicated the difference in cure states through differences in the T_g values.
- The poor correlation between the measured and predicted results meant that the strain energy failure criterion could not be evaluated properly.
- Trends in the temperature-dependence of the joint specimen properties are qualitatively similar to those of the bulk specimen properties [21].
- Two of the materials (M70 and PPG Y5000) reached much larger strains in the joint specimens than in the bulk specimens (which tended to contain voids). This meant that in the FE analyses the material properties need to be extrapolated beyond the test data leading to uncertainties [21].
- FEA performed using a 3-D model of the lap joint gave the same predictions of the force-extension response as the 2-D model. Therefore, the computationally simpler 2-D model is a valid approximation [22].
- Some simulations of minor misalignments of the test machine grips showed that the measured force-extension response is unlikely to be influenced significantly by these. However, the stress distribution showed elevated peak peel stress values which would promote premature failure of the joint; [22].
- The assumption of material incompressibility used to simplify input data needs for the Hyperelastic models may be the source of some of the error in the FEA predictions. Some initial investigations showed that the inclusion of an estimated value for the volumetric term in the Mooney-Rivlin model led to a closer correlation with experimental results [22].

Developing and implementing suitable material models and failure criteria for use in the design of adhesive joints has been a very challenging task. The work carried out in PAJ1 has identified a potential class of material model (including a candidate for a failure criterion) and developed methods for obtaining materials properties data. Much additional work is needed to develop this approach further.

5. FAILURE CRITERIA

In service, a structural adhesive may be required to support load over extended periods of time. Thus, its creep behaviour will be an important design criterion. Flexible adhesives may be more prone to creep than structural adhesives owing to their low stiffness. It was hoped that a study of failure of flexible adhesives would enhance the identification of a suitable failure criterion.

A review of measurement methods identified techniques for carrying out creep and stress relaxation measurements [25]. It is important for long-term properties measurement with polymeric systems to maintain a constant test temperature. A number of lever arm creep machines previously used to study engineering plastics were adapted for carrying out creep measurements on bulk specimens of flexible adhesives [7]. The loading arrangement was

changed to a hanging weight arrangement and long travel displacement transducers were used to measure the movement of the load carriage. This arrangement proved most unsatisfactory - specimens tended to twist or swing when the loads were applied causing large uncertainties in the displacement measurements. Therefore, the creep machines were reconverted to lever arm loading. Creep displacements were still measured from the movement of the grips (using the displacement transducers). This arrangement removed many of the problems with specimen movement when the loads were applied. However, the lever ratio of the machine multiplied the applied force on the test specimens with the result that the minimum stress increments were significant fractions of the static tensile strength of the specimens. A further area of uncertainty was the determination of creep strain from the creep displacement measurements. Some measurements made simultaneously using a video extensometer gave a rough correction factor for converting displacement into strain but there were uncertainties in this factor [25].

Creep tests were performed on bulk samples of two flexible adhesives (3M DP609 and Evode M70 as detailed in Table 1) at temperatures between 20 °C and 80 °C. The time available to perform the series of creep tests was limited. Therefore, samples that had not failed after approximately one week were removed and replaced with a fresh test. Hence, failure data for low stress tests with long durations were limited.

The results showed the expected trends. Time to failure decreased as higher proportions of the static failure stresses were applied. Larger strains at failure were associated with large applied stresses. Analysis of the strains to failure of bulk specimen creep tests carried out at different applied stress showed that there seemed to be no universal strain or strain energy based failure criterion. However, plots of stress-strain at failure in the creep tests agreed very closely with the plot of stress-strain at failure data determined from static tests. It was observed that failure conditions in the creep tests agreed with static failure conditions at higher temperatures. Thus, it seems that time under load equates to an increase in the 'effective' temperature of the specimen. One practical application of this observation is that results from static tests at elevated temperatures may indicate safe operating loads at lower temperatures [26].

Some creep tests were performed on lap joint specimens. It was found that the displacement measurements made at the specimen grip were unreliable. More accurate measurements could be obtained from displacement transducers attached to the lower adherend and the upper grip. However, even the accuracy of these measurements was not as good as desired. The specimens failed in the same mode as the quasi-static tests (i.e. cohesively for M70 and adhesively for DP609). Specimens tended to fail within the maximum week duration of tests at proportions of their static strength corresponding to the results found for the bulk specimens [26].

Creep of visco-elastic materials is modelled in ABAQUS using a sum of exponential relaxations characterised by a relaxation magnitude constant and time constant (the *VISCOELASTIC option). These constants are determined by fitting Prony series to time-dependent input data supplied to the FEA package [20]. Time-dependent data can be supplied as either stress relaxation data or creep data but they must be in a 'normalised' form (with all data divided by the initial, 'elastic' value). This requirement for normalised data is a source of considerable uncertainty in the creep prediction. The 'elastic' creep strain is often difficult to distinguish in the measured data.

FE predictions of the creep of the lap joint specimens were made using the Hyperelastic models and coefficients used in the previous task to define the elastic properties. Creep curves obtained

from the bulk test specimens were used to define the time-dependent properties. The degree of agreement with the measured creep of the joint specimens was extremely variable [26]. Where it is reasonably straightforward to determine the 'elastic' from the creep curve (as for the M70), the predictions look similar to the experimental data. Most of the differences between the predicted and the experimental results probably arise from the inaccuracy of the predicted 'elastic' extension. However, where the creep behaviour is more 'challenging' for example close to the glass transition temperature then the following problems may occur:

- stress-dependence of creep function;
- poorly defined 'elastic' extension; and,
- strong dependence of properties on loading history.

Thus, the accuracy of the predicted creep response can be extremely poor. This was the case for the analysis of DP609 joints at 20 °C (close to the T_g of the adhesive). Since the creep function is normalised with respect to the initial 'elastic' strain, uncertainties in this value are compounded giving major uncertainties in the long-term predictions. In such ill conditioned systems, the analyses may predict creep strains in error by an order of magnitude. Caution should be employed when using the visco-elastic creep functions in FEA packages. It is recommended that a simple joint configuration is modelled and short term creep measurements are made to establish the suitability of the system for analysis. More suitable material models (incorporating stress dependence and using measured rather than normalised compliances) may be needed for accurate FE analysis of creep of flexible adhesive joints.

6. CONCLUDING REMARKS

Considerable progress has been made in the development of test methods for visco-elastic and tack properties. Improved commercial instruments incorporating the findings of this project are available. However, important classes of adhesives, including hot melt adhesives, that are widely used by industry were excluded from the scope of the project. It is recommended that this type of work is extended to measurements for the process properties of these materials.

A start has been made on the challenging task of developing methods for designing with flexible adhesives and the determination of suitable failure criteria. It is clear that the simple Elastic and Elastic-Plastic models available in FEA software are unlikely to accurately represent flexible adhesives. The Hyperelastic approach shows more promise. Progress has been made on developing test methods to provide the required input data for the analyses. However, agreement between predicted and measured joint responses is still relatively poor. There are many issues regarding the presentation of test data, use of materials models and interpretation of the FEA that need to be addressed. Some of these issues shall be studied in the extension to the PAJ programme. Durability of flexible adhesives which was not addressed in either PAJ1 or PAJ3 represents a major design requirement that should be the subject of further study.

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