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MATERIAL MODEL ASSESSMENT ON A STRAIN RATE SENSITIVE ADHESIVE

Engineering

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ABSTRACT

For the adhesive bonded structures, variation in the loads acting on the structure is commonly noted. In some cases because ofadhesive characteristics,strain in the adhesive layer depends upon the time period of load application and magnitude of the load.Strain variations in the adhesivelayer affect adhesive joint behavior. This calls for the study on strain rate dependent characteristics of adhesive. For stress analysis of such adhesive bonded joints a suitable material model of the adhesive is to be selected from the existing ones or a suitable material model is to be developed. In this paper is an attempt is made to identify suitable mathematical representations of the experimental results reported[1] on strain rate sensitive adhesive. An estimation of strain energy variation over a range of strain rates using results of experiment.

KEYWORDS

Adhesive, Creep, Relaxation, Plasticity, Schematization, Yield criteria

INTRODUCTION

Since adhesive is one of prime component of bonding it is necessary to model the adhesive material behavior in order to understand the response of the joint and mechanisms involved in adhesive joint failure.For stress analysis of adhesive bonded joints a suitable material model of the adhesive is to be selected from the existing ones or a suitable material model is to be developed. Development of rate dependent constitutive models for polymeric adhesives is essential for carrying out meaningful stress analyses to sustain fluctuating loads or time dependent loading. There are three important steps involved in developing a material model for a strain rate-dependent adhesive.

1. Producing a complete experimental data for structural adhesive system.
2. Selecting/ formulating an appropriate rate-dependent material model for analysis.
3. Studying how the model can best fit the experimental data.

The time-dependent phenomena has considerable effect on the stress distribution in adhesive. The stress and/or strain at a point in the adhesive may vary significantly with time even though the applied loads are kept constant. X.X.Yu et al.[1] presented a complete range of experimental data for a typical adhesive system including constant strain rate, creep and recovery in tension. The time dependent effects are manifested by creep under constant stress and relaxation of stress under constant strain.The creep and relaxation are common phenomena to many strain rate-dependent materials. Mathematical models for creep and relaxation are available[2] andProny series representation of modulus from strain rate dependent datacan be readily implemented in stress analysis. Mathematically tractable representations for stress-strain-time relations for such adhesives greatly simplify stress analysis.

S.Yadagiri et al.[3] presented finite element analysis of bonded jointsusing viscoelastic adhesive. The viscoelastic constitutive relation under plain strain with constant bulk modulus is described by a hereditary integral.In another work P.C Pandey et al. [4] performed non liner analysis of adhesively bonded lap joints considering viscoplasticity in adhesives. Yielding of the adhesive is represented by a pressure sensitive vonMises yield function.There are a few material models available to study time dependent mechanical behavior of adhesives but, having their own limitations [1]. There is no unique material model available which is applicable to all adhesives for accurate representation of behavior under different loading conditions. Depending on the available experimental data one should select a proper material model for the analysis.

Since strain energy is also an important parameter in modeling the material behavior, in this work an attempt is made to study the strain energy variation at specified strain rates for theavailable experimental results on time dependent behavior of an adhesive[1]. Applicability of mathematical representations relating plastic strain to applied stress under uni axial load is also studied.

TESTING OF ADHESIVES For characterizing a strain rate sensitive adhesive,constant strain rate tensile test, creep and relaxation test data at various temperatures are required to be carried out. A typical two part epoxy adhesive was subjected to extensive testing to prove the hydrostatic sensitive nature of adhesive in both creep and relaxation. The creep and relaxation data are found to have a unique stress strain relationship[1].The creep and relaxation are also affected by temperature variations in polymeric adhesives[6].So, the test results need to be generated considering the temperature range of operation also.

Although not used extensively for the design of adhesive joints few works gave significant insight into non linear viscoelasticity. C.F. Popelar and K M Liechti[8]conducted uniaxial and bulk creep testing for linear viscoelastic characterization of a structural adhesive. Subsequently using a modified Acron configuration non linear response under multi axial loading was evaluated. It was noted that significant amount of nonlinear behavior exists under highly shear dominated loading.

PLASTICITY CHARECTERISTICS OF ADHESIVES

Modern structural adhesives develop large plastic strains to failure. Thus it is necessary to consider what happens to the stress and strain distribution if adhesive can yield. Further, some new adhesives are so strong that may cause adherends to yield. If adherends yield there is increased differential straining of adherends which results in higher adhesive stress leading to adhesive failure.To study the integrity of the adhesive bonded join tunder loading adhesive behavior is to be modeled adequately up to failure.

Generally unmodified epoxy adhesive is almost elastic to failure and rubber toughened epoxy adhesive gives lower strength but, enhanced failure strain. It is necessary to define the yield (of adhesive usually, but sometime of the adherend) and then to adopt a suitable failure criterion. Hart-Smith chose an elastic plastic model such that the total area under the stress-strain curve was equal to that of the true stress-strain curves[5]. Hart-Smith equated the yield stress and failure stress (elastic-perfectly plastic behavior) and stated that failure occurs when adhesive reaches its limiting plastic shear strain.

The yield behavior of many polymers including epoxy resins is dependent on both hydrostatic (dilatational) and shear (deviatoric) components. Thus there is difference between yield stress in tension and yield stress in compression. For epoxy resins the ratios of compressive to yield stresses are of the order of 1.3. A parabolic yield criterion was proposed for using in finite element analysis.

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2+(2(\sigma_c-\sigma_t)(\sigma_1+\sigma_2+\sigma_3))=2\sigma_c\sigma_t$$

Where is σ_1, $\sigma_2$and σ_3 are principal stresses, σ_c and σ_t are the uni-axial compressive and tensile yield stresses respectively (neglecting the

signs). The above yield criterion applies to many amorphous polymers over a wide range of stress states. It was found that later failure in ductile adhesives best correlates with the tensile strain to failure in a bulk specimen, whereas in brittle adhesives (that have less than 3% strain at failure) tensile stress at failure gives best correlation.
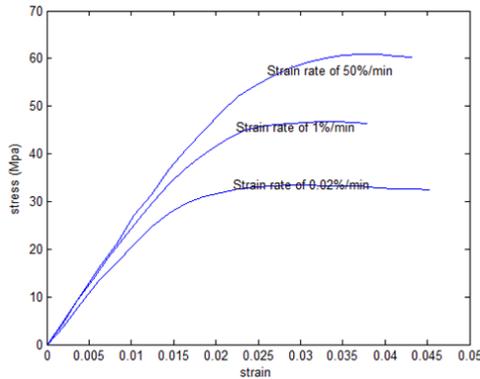

Fig.1. Stress-Strain curves of an adhesive at specified strain rates[1]

The rate of loading has a significant impact on yielding of polymeric adhesives. As the rate of loading increases the slope of the linear portion stress -strain curve increases, indicating the raise of modulus (Fig.1).The effect of strain rate on the plastic strain energy was studied using the available experimental results[1].

The plastic strain energy is estimated, by numerical integration of the stress- plastic strain curves at different strain rates. The variation of plastic strain energy with respect to plastic strain rate is given in Fig.2.
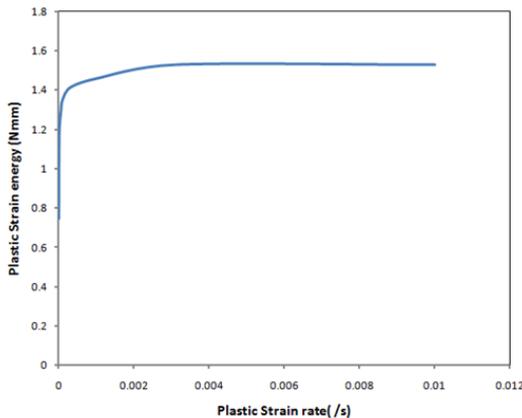

Fig.2. Strain rate -plastic strain energy per unit volume

The curve remains asymptotic with respect to particular value on strain energy axis (1.5N mm). Initially as strain rate increases plastic strain energy also increases and reaches a constant value and any further increase in strain rate does not increase the strain energy considerably. This is the limiting value of plastic strain energy per unit volume contained by the specimen.

SCHEMATIZATION OF EXPERIMENTAL RESULTS

Theory of plasticity deals with stress- strain and load- deflection relationship for plastically deforming material or structure. Establishing such relationships involves experimental and mathematical observations.In order to utilize the experiment data in theoretical analysis, empirical formulae are to be obtained through proper mathematical representation, known as"schematization". In this work an attempt is made to identify a suitable asymptotically perfectly plastic schematization for the available experimental results[1] at three specifiedplastic strain rates.

The following asymptotically perfectly plastic schematizations are used

(1) Prager's tangent hyperbolic law[9]

$$\sigma = \sigma_0 Tanh\left(\frac{E\varepsilon}{\sigma_0}\right)$$

(2) Betten's generalized tangent hyperbolic law[10,11]

$$\frac{\sigma}{\sigma_0} = Tanh\left[\left(\frac{E\varepsilon}{\sigma_0}\right)^m\right]^{\frac{1}{m}}, \qquad m > 1$$

(3) Betten's generalized asymptotic approximation[10,11]

$$\sigma = \frac{E\varepsilon}{\left[1 + \left(\frac{E\varepsilon}{\sigma_0}\right)^m\right]^{\left(\frac{1}{m}\right)}}$$

(4) Generalized expression for schematization[12]

$$\sigma = \frac{E\varepsilon}{\left[1 + \left(\frac{E\varepsilon}{\varepsilon_0}\right)^m\right]^{\left(\frac{1}{m}\right)}}$$

Where σ and ε are applied stress and plastic strain respectively. E, $\sigma 0$ and $\varepsilon 0$denote Modulus, referencestress and reference strain respectively. Exponent 'm' is to be evaluated if required at each strain rate. Input for schematization is given in Table-1., Plots of test data (in legends) and schematized values (curves) are given inFigs.3 to 6. Table-2 gives maximum % variation of schematized values with respect to experimental data.

Table.1. Input for Schematization			
Prager's tangent hyperbolic law			
Plastic Strain rate (/s)	5.60e-06	1.0e-04	1.0e-2
Modulus, E, (MPa)	50995.2	73622.45	130247.6
Ref. stress , s0, (MPa)	39.48	50.96	60.6805
Betten's generalized tangent hyperbolic law			
Plastic Strain rate (/s)	5.60e-06	1.0e-04	1.0e-2
Modulus, E, (MPa)	50995.2	73622.45	130247.6
Ref. stress , s0, (MPa)	39.48	50.96	60.6805
Exponent , m	1.012	0.85	0.55
Betten's generalized asymptotic approximation			
Plastic Strain rate (/s)	5.60e-06	1.0e-04	1.0e-2
Modulus, E, (MPa)	50995.2	73622.45	130247.6
Ref. stress , s0, (MPa)	39.48	50.96	60.6805
Exponent , m	1.15	1.12	1.108
Generalized asymptotic approximation[12]			
Plastic Strain rate (/s)	5.60e-06	1.0e-04	1.0e-2
Modulus, E, (MPa)	50995.2	73622.45	130247.6
Ref. stress , s0, (MPa)	39.48	50.96	60.6805
Exponent , m	3.52	2.04815	1.622216

| Table-2: Maximum % variation of schematized values with respect to experimental results[1]			
Schematization	Plastic Strain rate (/s)		
	5.60e-06	1.0e-04	1.0e-2
Prager's tangent hyperbolic law	-14.53	-13.9	-27.08
Betten's generalized tangent hyperbolic law	-14.4	-13.68	-13.25
Betten's generalized asymptotic approximation	35.5	15.6	7.15
Generalized asymptotic Approximation	-13.1	-4.8	-12.68
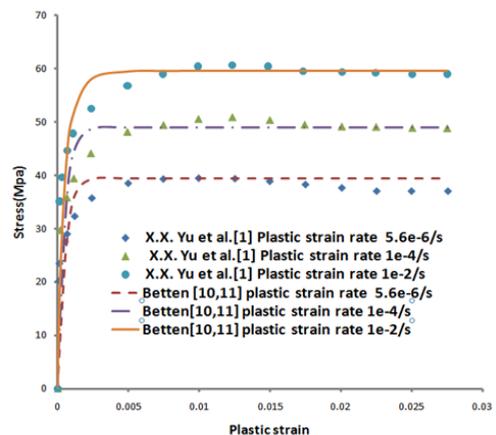
Fig.3 Schematization using Prager' stangent hyperbolic law
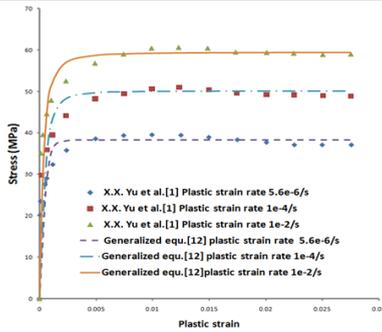
Fig.4.Schematization using Betten's generalized asymptotic approximation
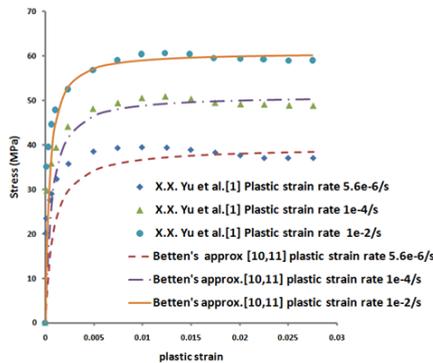

Fig.5 Schematization using Betten's generalized tangent hyperbol

From Table.-2 it is noted that generalized asymptotic approximation schematizes the test data to a reasonable accuracy at the specified strain rates. Negative % variation indicates higher stress predicted by schematization with respect to test results and vice versa. Prager's tangent hyperbolic law fails toschematize test results corresponding to maximum specified strain rate(0.01/s).Betten's generalized asymptotic approximation gives sufficiently accurate schematization of testresults at maximum specified strain rate (0.01/s) within 7.15% variation and fails to schematize test results corresponding to minimum strain rate (5.6e-06/s).

CONCLUSION
Since adhesive forms the binding interface between adherends, the adhesive mechanical characteristics have to be studied. Since some adhesives exhibit strong time-dependent mechanical characteristics and attempt has been made to study the effect of strain rate on adhesive mechanical behavior using the experimental results available[1].When the strain rate is increased the slope linear portion stress-strain curve increasincrease of young's modulus. Area under each stress-strain curve for each specifiedstrain rate has been numerically estimated, which gives the strain energy storied in the specimen until failure. It has been noted that strain energy per unit volume increases when strain rate is increasedup to certain limits. Further increase in strain rate doesn't increase strain energy considerably. This defines an upper limit for the strain energy contained by the specimen until failure.

Applicability of schematizations relating plastic strain to applied stress for the experimental results is studied.It is noted that generalized asymptotic approximation schematizes the experimental results to a reasonable accuracy at the specified strain rates.

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