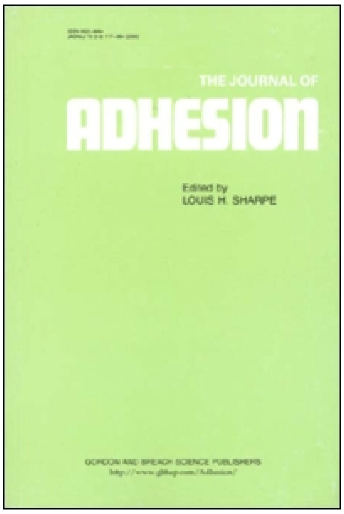

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The Time-Dependent Mechanical Behaviour of an Interlaminar Layer in a Structural Bonded Model

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The main problems involved in the adhesive bonding of structural systems stem from the low stiffness and strength of the interlaminar adhesive layer (IAL), its non-linear time-dependent mechanical behaviour, and its sensitivity to temperature and humidity. The present article, which is a continuation of previous papers on this subject, focuses on the time-dependency of the state of stress and strain within an adhesive layer under mechanical loading up to the non-linear range.

The prediction of the interlaminar stresses and strains was obtained by an iterative numerical procedure, using the finite element method. The solution is based on a non-linear, time-dependent effective loading function derived from an empirical stress-strain relationship of the adhesive material and from a postulated function describing the relationship between the stress and the strain tensors of each element, on the one hand, and their respective effective values. The findings indicate the expected trend of stress decrease and strain increase with time.

INTRODUCTION

The interlaminar adhesive layer (IAL) serving as a bonding phase between structural elements may be treated as an equivalent material layer in the multimaterial laminate. The particularity of the IAL, however, stems from its low stiffness and strength, its non-linear visco-plastic stress–strain–time behaviour, and its sensitivity to hygrothermal effects.

The solution of IAL stress and strain distributions, which is crucial for the failure prediction of the bonded system, is highly involved due to these characteristics. Singularities stemming from geometrical edge effects, material heterogeneity, and the three-dimensional state of stress, eliminate the close-form analytical solution and lead to numerical solutions, *e.g.*, the finite element methods (FEM).[1,2] Such methods can deal with complex geometrical and material parameters but leave the problem of material non-linearity and time-dependency still to be tackled. Most of the numerical solutions are confined to the elastic linear range,[3] where they could, in certain cases, be extended to deal with a simplified elasto-plastic model[4] or with bilinear behaviour.[5] Recently the problem was analysed in the non-linear range by being referred to a bonded doubler model.[6,7] That solution was based on an empirical effective stress–strain relationship according to the Von-Mises assumption. Results permit the evaluation of IAL behaviour up to the plastic range and even beyond it.

The object of the present work was the extension of that solution to the treatment of the time-dependency of the stress and strain distribution within the IAL at different viscoplastic stages. In a later phase of the ongoing research project, hygrothermal effects in time will be considered. The findings will, it is hoped, provide the means for predicting the mechanical behaviour of a bonded joint at different loading levels in actual service conditions.

THE BONDED MODEL

A symmetrical doubler was selected as the model to represent the complex material system typical of a bonded structure. The model consists of a central uniaxially loaded adherend layer and two external adherends bonded to the central layer by two interlaminar adhesive layers (IAL) (Figure 1).

The adherend materials were either aluminum 2024–T3, which was introduced in the present analysis, or unidirectional carbon-fiber-reinforced plastic (CFRP). The IALs were made of eopxy resin consisting of 70% Epon 815 monomer and 30% Versamid V-140 hardener. For the numerical solution, the adhesive layer was successively divided into 2 and 4 sub-layers so as to represent the effect of thickness on stress distribution, as shown in Figure 2, similar to that in Figure 2C of Ref. 3.

THE ANALYTICAL APPROACH

The IAL stress–strain–time relationship is non-linear and cannot be adequately represented by the linear viscoelastic theory even at a moderate stress level. To tackle this problem, an empirical numerical approach was developed involving an iterative FEM related to the effected stress–strain relationship, which in turn was taken to be representative of the IAL behaviour at different levels of loading and in different time intervals.[7] Such

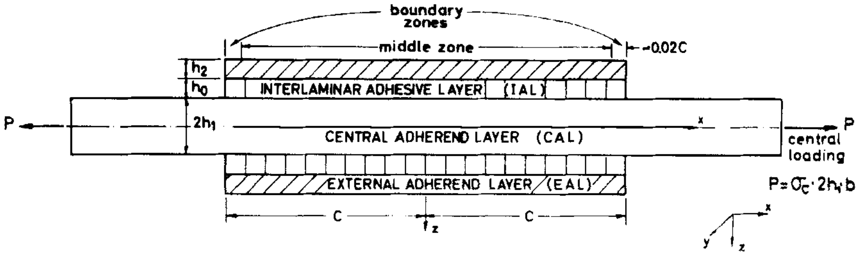

FIGURE 1 Symmetrical doubler model.

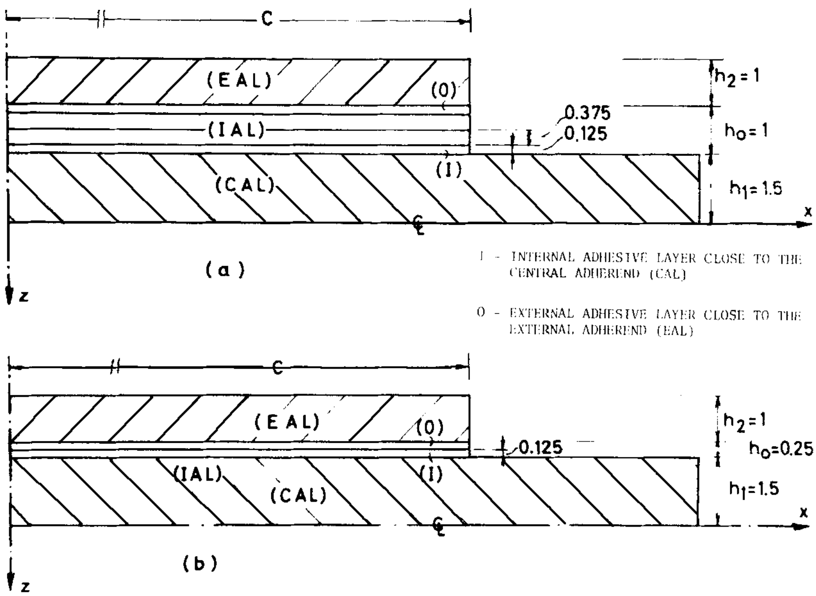

FIGURE 2 Illustration of FEM scheme for different IAL thicknesses.

procedure is similar to that used for treating non-linear stress–strain relationship and is described in detail in Ref. 6. Constant strain elements were used in the present analysis. The solution is based on the assumption that the material behaviour of the IAL can be treated, after a modification of material parameters of the different elements, as a function of stress, strain and time, variables. The representation of the stress and strain states by means of their respective effective value is justified, when a functional relationship exists between the effective stress ($\bar{s}$) and the effective strain ($\bar{e}$), on the one hand, and the respective stress and strain second invariants, on the other. Such a functional relation must hold good throughout the whole range of the stress–strain relationship and for any combined state of stress. For the present study the functional relationship according to Von-Mises, Hencky and others was assumed to apply, as follows:[8]

$$\bar{s} = \frac{\sqrt{2}}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]^{1/2} \tag{1}$$

$$\bar{e} = \frac{\sqrt{2}}{2(1+\bar{\nu})}[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2]^{1/2} \tag{2}$$

$\bar{\nu}$—effective Poisson's ratio, which is dependent on the strain and stress levels.

THE EMPIRICAL NUMERICAL SOLUTION

The validity of the effective stress–strain relationship of the adhesive material investigated was verified experimentally by combined torsion–tension loading tests[9] as shown in Figure 3.

Based on other investigations, it can be assumed that, as long as the failure mode of the bonded system is cohesive and initiates within the IAL[10] (Figure 4), the mechanical *in-situ* behaviour of a bonded adhesive is represented by the corresponding bulk properties of the adhesive. Thus, the uniaxial–tension bulk stress–strain relationship of the epoxy adhesive can provide the effective loading function for the numerical FEM solution. In this way the nonlinear relationship between effective stress ($\bar{e}$) is expressed as a function of strain rate, temperature, and humidity, *viz*: $\bar{s} = F(\bar{e}, \dot{e}, T, RH)$, which follows the real material behaviour as determined empirically (Figure 5).

STRAIN RATE EFFECT

When strain–rate effect is considered, such a relationship may be expressed by the Ramberg–Osgood function[11] as expanded by McLellan[12] to represent non-linear curves obtained empirically from loading tests at different strain-rate levels:

$$\bar{e} = \frac{\bar{s}}{c\dot{e}^d}+a\dot{e}^b\bar{s}^N \tag{3}$$

where N, a, b, c and d are material constants derived experimentally.

The above relationship provides the basis for deriving the strain–rate effect on stress and strain distribution within the IAL. The solution takes into account the different strain-rate conditions at each IAL element under a

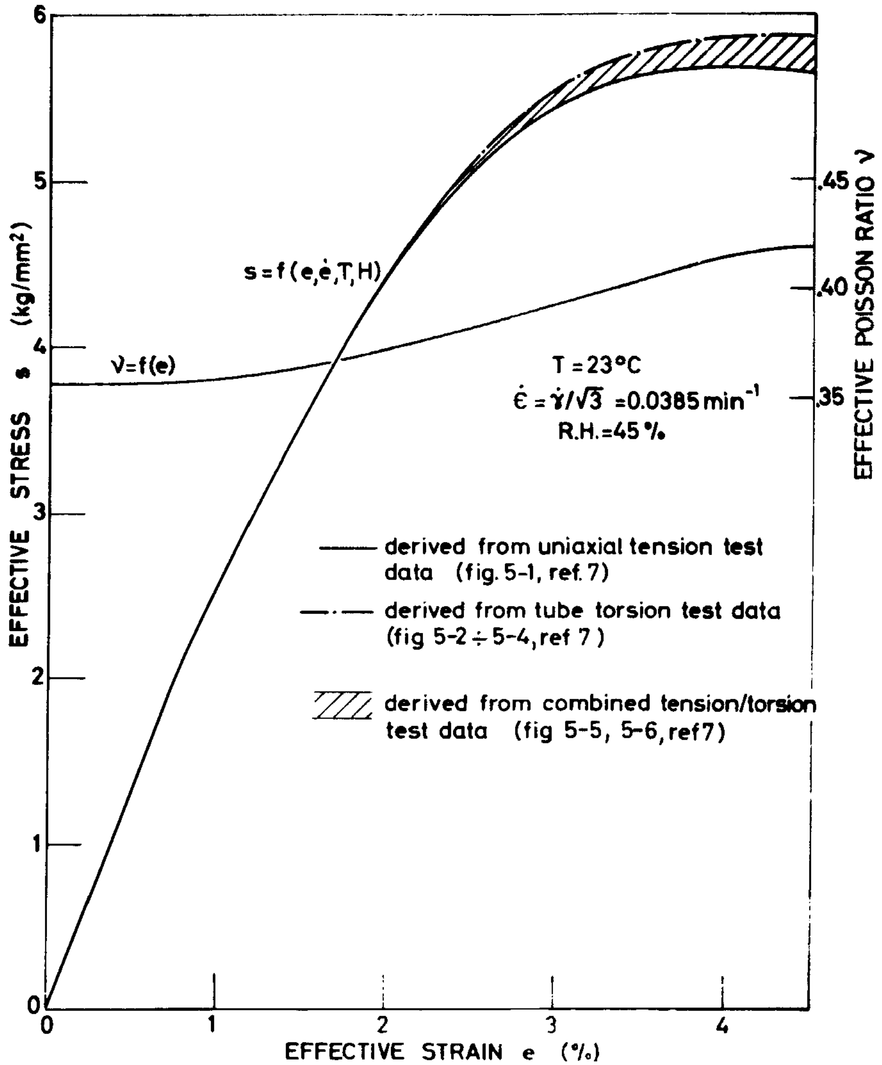

FIGURE 3 Effective stress-strain relationship for epoxy resin used as adhesive layer.

certain external loading rate applied to the bonded model. The modified stress–strain curves under the actual strain-rate at the different elements are shown in Figure 5. IAL stresses τ_{xzo} and σ_{zo} in the critical zone, determined when non-linearity and strain-rate effect are considered, and significantly lower than the corresponding data derived by the simplified linear elastic solution (Figures 6, 7).

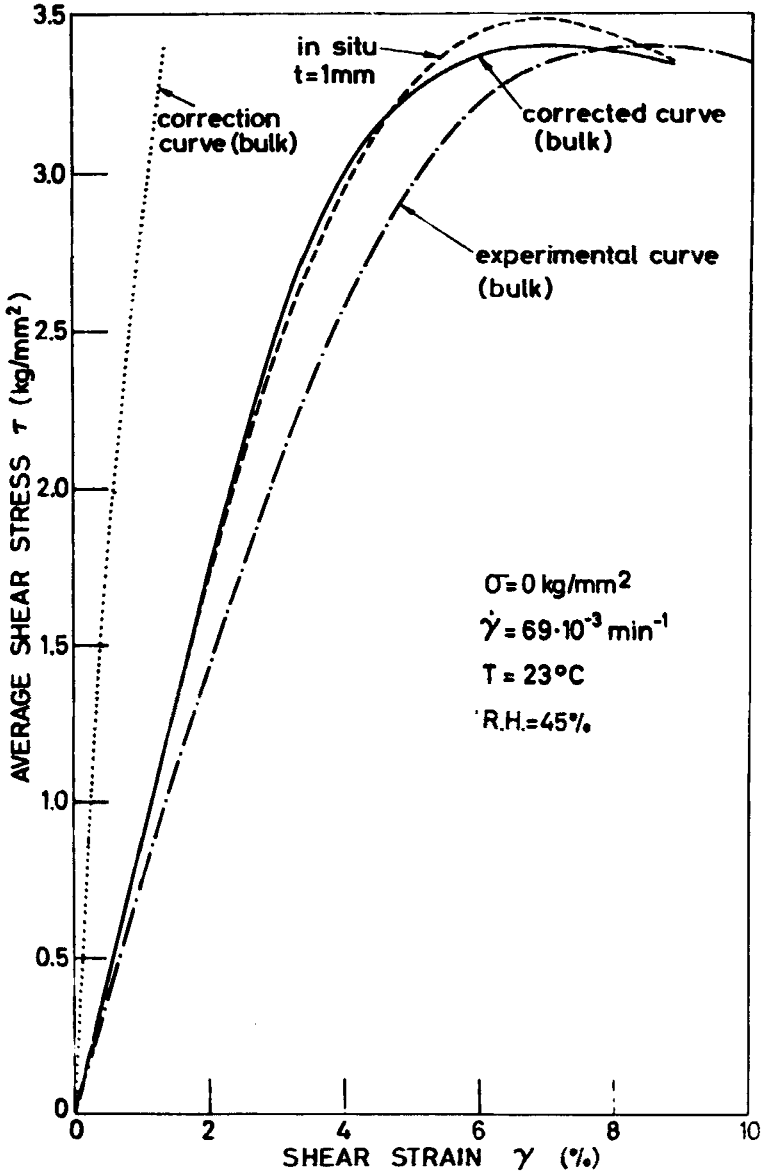

FIGURE 4 Shear stress-strain relationship based on torsional test of tubular specimen compared with ring specimen of the adhesive *in-situ*.

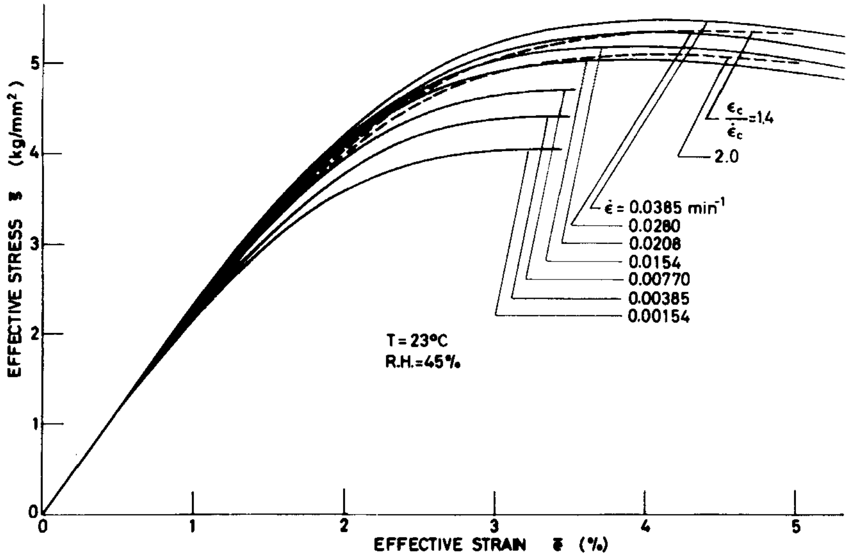

FIGURE 5 Effective stress-strain curves of epoxy resin at different strain rates and relevant work curves in different external loading conditions $\varepsilon_c/\dot{\varepsilon}_c$.

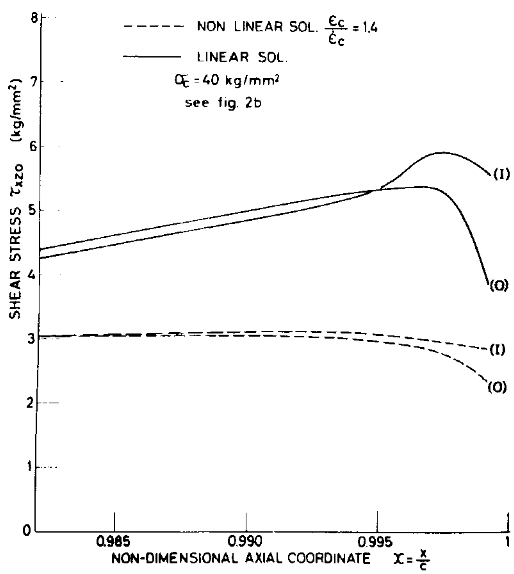

FIGURE 6 Shear stress (τ_{xzo}) distribution within the IAL boundary zone—non-linear solution with strain rate effect (*i.e.*, linear solution).

Varying the adhesive thickness produces two different effects: Along most of the IAL boundary zone, stresses are lower with thicker IAL as was expected, whereas in the critical zone close to the IAL edge, this trend is reversed, higher normal stresses, σ_{zo}, prevailing in the thicker IAL case (Figures 8, 9).

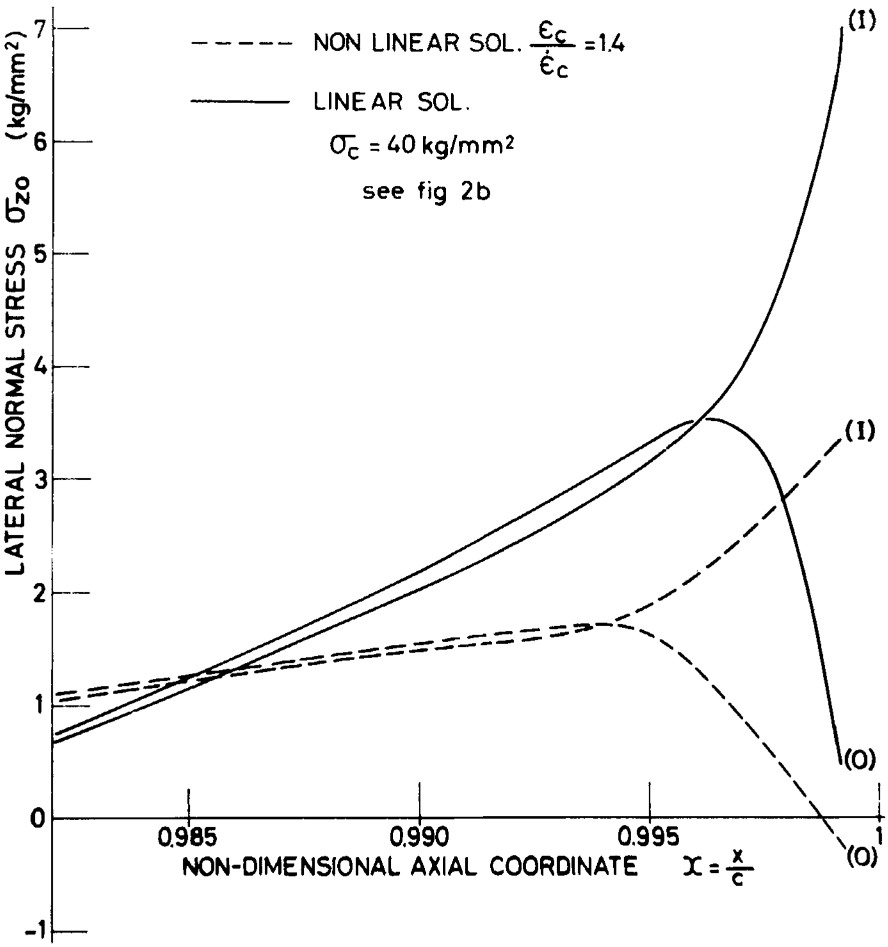

FIGURE 7 Lateral normal stress (σ_{zo}) distribution within the IAL boundary zone—nonlinear solution with strain-rate effect (*i.e.*, linear solution).

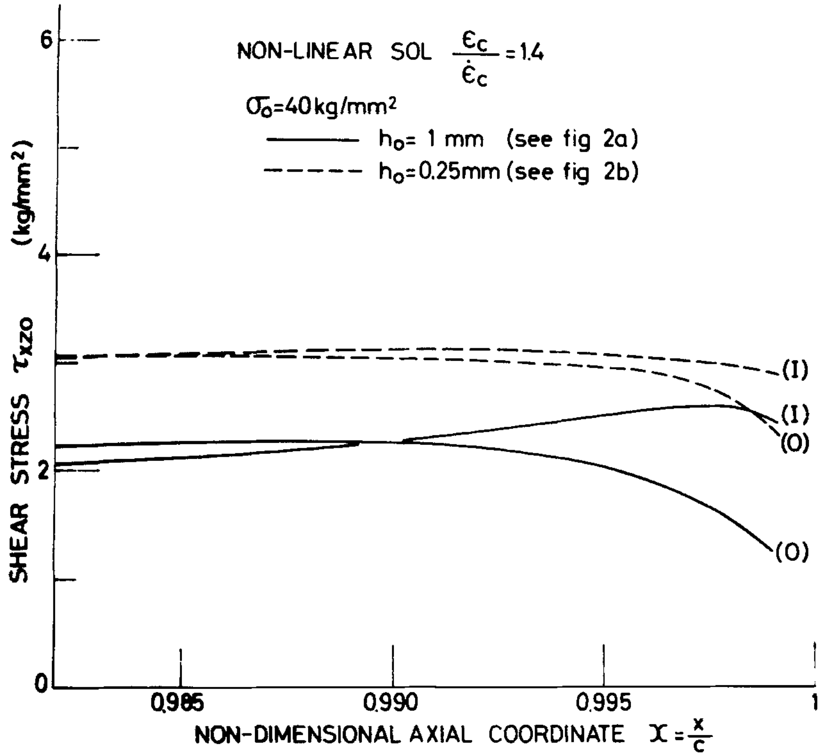

FIGURE 8 The effect of IAL thickness on the shear stress (τ_{xzo}) distribution (nonlinear solution with strain-rate effect).

STRESS RELAXATION

Stress relaxation data of the adhesive bulk material under uniaxial tension are shown in Figure 10 in terms of stress (σ) as a function of time (t) for different constant strain levels ($\dot{\varepsilon}_0$). It can be seen that for a relatively short period after the initial loading stage ($t = 0$), the instantaneous inertia effects—which depend on the strain and strain-rate levels are negligible.

An attempt to assess the states of stress and strain within the IAL for a time interval Δt was made following the endochronic approach.[13,14] The solution is based on the empirical effective stress–strain relationships for different time intervals Δt_i (Figure 11) derived from the experimental stress–relaxation curves of Figure 10. The FEM solution provides an approximate estimate of the states of stresses and strains at each element after a given time interval, Δt.

The effect of time on the stress relaxation, as demonstrated by the shear, τ_{xz0}, and normal σ_{z0} stress distributions within the IAL, is shown in Figures 12 and 13. Here the trend of IAL stress reduction with time is evident.

CONCLUSIONS

The following conclusions can be drawn based on the empirical–numerical FEM solution for the stress and the strain distributions within the IAL of a bonded doubler model:

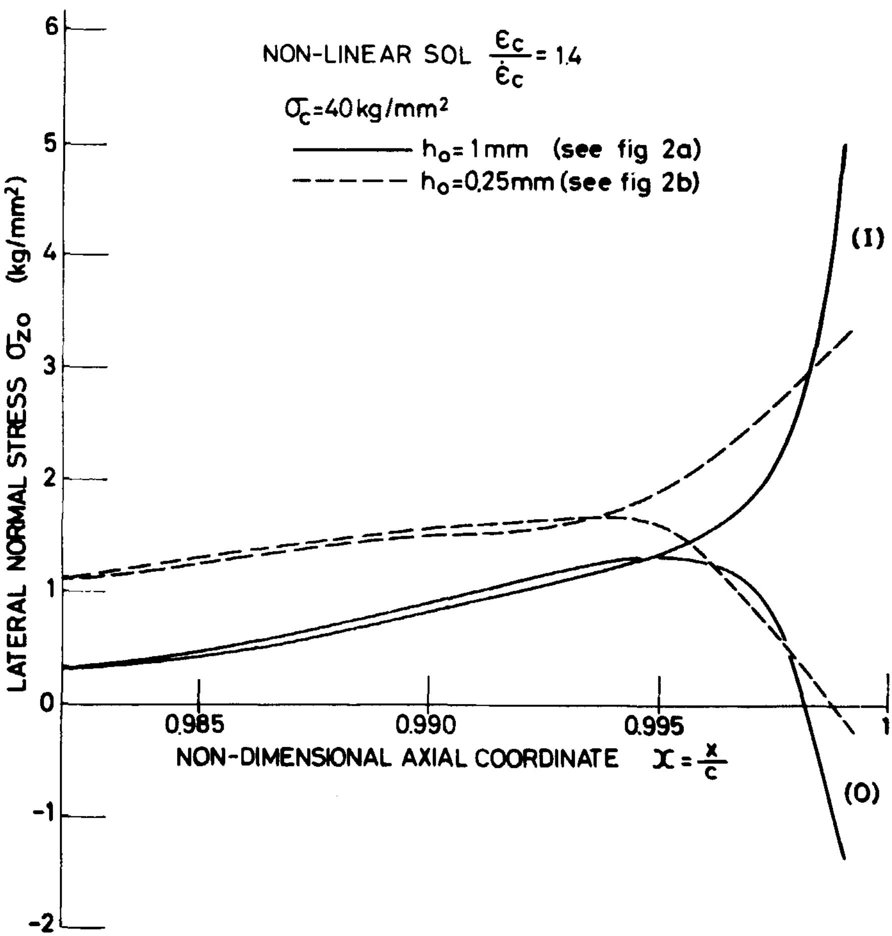

FIGURE 9 The effect of IAL thickness on the lateral normal stress (σ_{z0}) distribution (nonlinear solution with strain-rate effect).

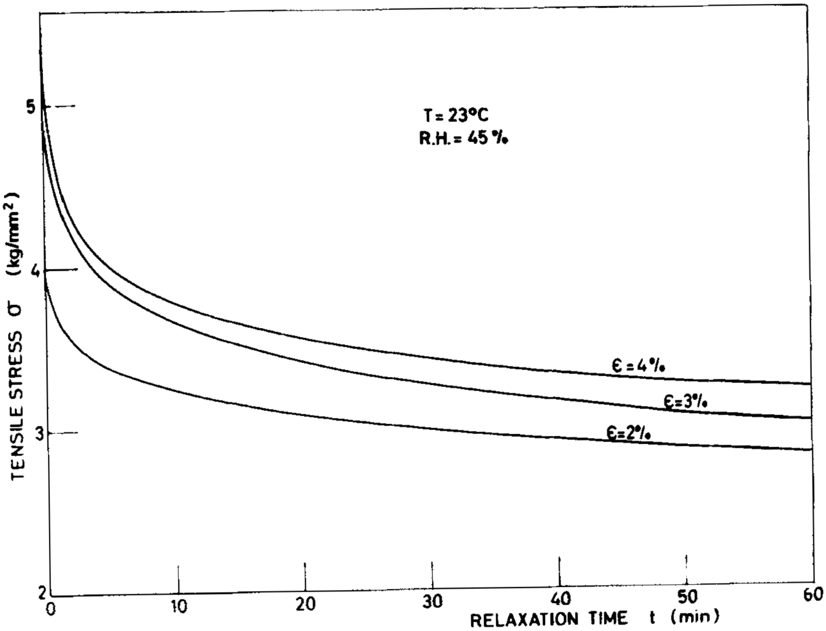

FIGURE 10 Stress relaxation curves as functions of time at different strain (ε_o) levels.

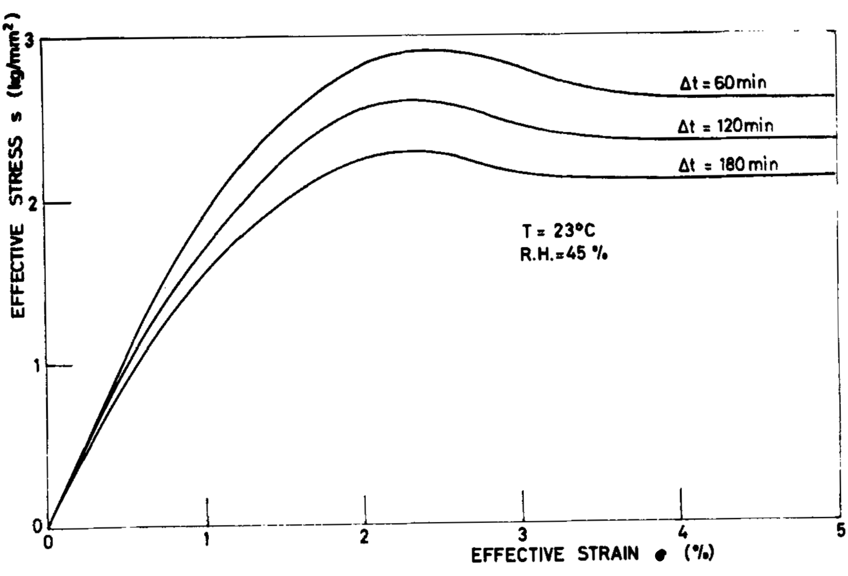

FIGURE 11 Effective stress-strain relationship for different time intervals (Δt).

1) IAL stresses which are determined from the strain-rate dependent non-linear stress–strain behaviour of the adhesive material are significantly lower than the stresses predicted on the basis of linear behaviour.

2). The increase of the strain-rate was found to effect a redistribution of the IAL stress distribution by reducing the more highly strained elements as compared with those of a lower strain level.

3) The general tendency of loaded bonded systems after initial loading is towards a reduction of stresses at the critical elements, and an increase in the corresponding strains with time.

4) These trends point to a possibility of the strain level limit being exceeded and the viscoplastic zone propagating with time within the critical zones of the polymeric IAL.

The present findings demonstrate the facilities available for predicting the behaviour of bonded structural systems in prolonged periods of service conditions. These facilities are based on a combined numerical-empirical approach based on the effective stress–strain relationship.

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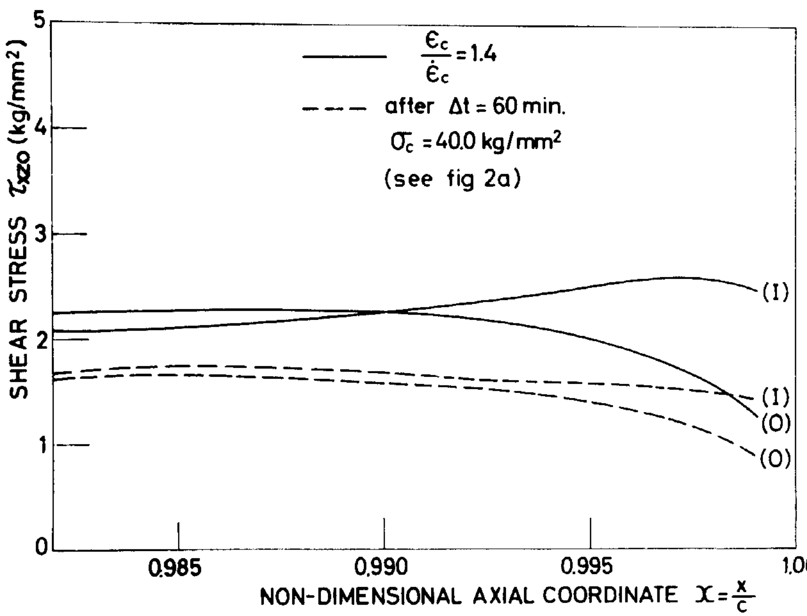

FIGURE 12 Shear stress (τ_{xzo}) distribution within the IAL boundary zone at a time interval of Δt = 60 minutes. (*i.e.*, nonlinear solution with strain rate effect).

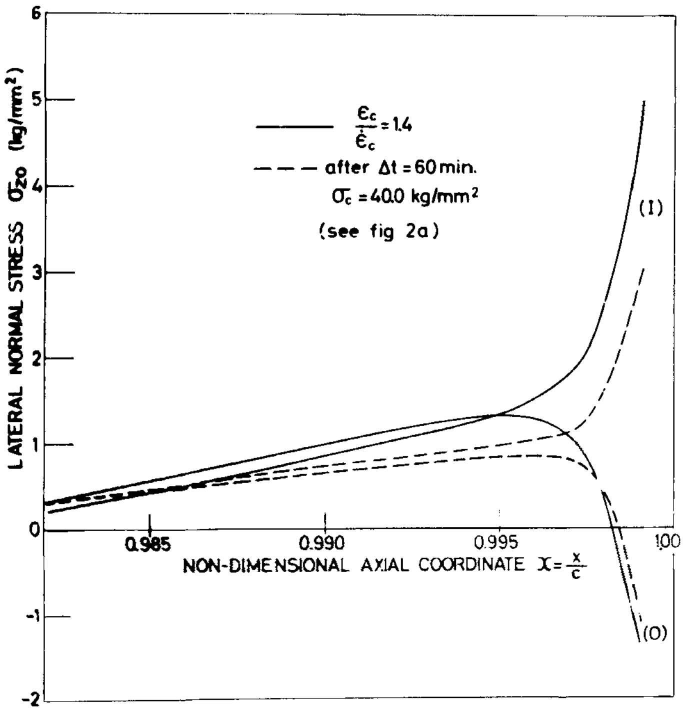

FIGURE 13 Lateral normal stress (σ_{z_0}) distribution within the IAL boundary zone at a time interval of $\Delta t = 60$ minues (*i.e.*, nonlinear solution with strain rate effect).

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