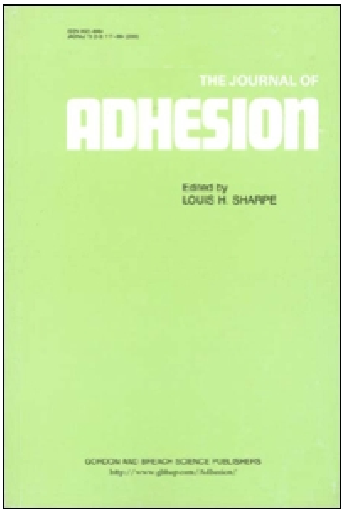

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

The Creep Behaviour of Structural Adhesive Joints II

K. W. Allen[a]; M. E. R. Shanahan[ab]
[a] The City University, London, England [b] Centre de Recherches sur la Physico-Chimie des Surfaces Solides, Mulhouse, France

To cite this Article Allen, K. W. and Shanahan, M. E. R.(1976) 'The Creep Behaviour of Structural Adhesive Joints II', The Journal of Adhesion, 8: 1, 43 — 56
To link to this Article: DOI: 10.1080/00218467608075069
URL: http://dx.doi.org/10.1080/00218467608075069

J. Adhesion, 1976, Vol. 8, pp. 43–56

Printed in Scotland

The Creep Behaviour of Structural Adhesive Joints II

K. W. ALLEN and M. E. R. SHANAHAN†

The City University, London EC1V 4BP, England

(*Received January 23, 1976*)

The creep behaviour of two structural adhesives (a phenolic resin/polyvinyl formal composite and a modified epoxy novolac) has been studied in their glassy state when used to bond high tensile steel lap joints. Curves of adhesive shear creep strain *vs.* ln t consisted of delay periods (times after application of load but before creep is discernible) followed by essentially logarithmic creep. Creep curves were thus classified by recording delay time, t_d, extrapolated creep rate at zero strain, $\dot{\gamma}(t_0)$, and the gradient of the logarithmic creep line, k. By comparing these values for different joint geometries, it has been established that the high stress concentrations found in lap joints under elastic conditions become much reduced as creep progresses. A model is proposed to account for the transition from delay time to creep behaviour.

INTRODUCTION

A study of the creep behaviour of structural adhesive lap joints has been made in which two aspects in particular have been investigated. The variation of behaviour with load and temperature in order to correlate creep with molecular mechanisms, has already been described.[1] This present paper describes work to investigate changes in creep behaviour with overlap length and with glueline thickness in order to obtain correlation between creep behaviour and the stresses within the glueline which cause it. There is also a reciprocal effect in that creep modifies the complex stress distributions found in lap joints under load, so that while the stress causes the creep so also the creep alters the stress.

† Present address: Centre de Recherches sur la Physico-Chimie des Surfaces Solides, 24 Avenue du President Kennedy, 68200 Mulhouse, France.

EXPERIMENTAL

Single lap joints constructed from high tensile steel (BSS514) of 0.2 cm thickness and 1 cm width at the overlap were subjected to constant applied load in spring loaded test rigs and creep was measured with inductance transducers. Details of this technique are given in the earlier paper.[1]

Two adhesives are described here—Redux 775 (a phenolic resin/polyvinyl formal composite) and Redux BSL906 (a modified epoxy novolac) both manufactured by Ciba Geigy (U.K.) Ltd. Overlaps of 1, 1.5 and 2 cm were used to study both adhesives. Surface treatment prior to bonding was in all cases restricted to wet polishing with 600 emery paper followed by distilled water and acetone rinses. Cure was carried out in a spring loaded jig at 150°C for 100 minutes total oven time for Redux 775 and at 120°C for 90 minutes for BSL 906. After cure joints were left for at least 24 hours before testing to allow equilibrium to be attained. For the present work, all Redux 775 creep tests were conducted at 50.5°C and all BSL 906 tests at 75°C. Each lap joint was allowed between 1 and 2 hours at the test temperature to achieve thermal equilibrium before the application of load.

Glueline thicknesses averaged 0.01 cm for Redux 775 and 0.0087 cm for BSL 906 except for one series in which the effect of thin gluelines was studied where the average glueline thickness was 0.0043 cm. All joints except the thin glueline series were constructed using wire spacers parallel to the axis of load in order to obtain gluelines of consistent dimensions. Glueline thickness was measured by removing side fillets of adhesive and using an optical micrometer. Badly aligned joints and those with glueline thicknesses differing greatly from the mean were rejected.

RESULTS AND ANALYSIS

Creep curves were obtained for 1, 1.5 and 2 cm overlaps with each of the two adhesives at their standard glueline thickness. These results are shown as the percentage of shear strain within the adhesive layer, γ, *vs.* the logarithm of time, t; in Figures 1–3 for Redux 775 and in Figures 4–6 for BSL 906. In addition, similar results were obtained and are shown in Figure 7 for BSL 906 with a thin glueline and 1 cm overlap. The initial elastic strain is not represented, and the applied load is given in kilo Newtons by the figure above each curve.

As is illustrated in Figure 8 these creep curves are conveniently split into a region of delay time, of length t_d, after the application of load but before any creep strain has been detected; and a region of essentially logarithmic creep which can be conveniently quantified by drawing a straight line through the creep curve and extrapolating to intersect the time axis at t_0. The gradient

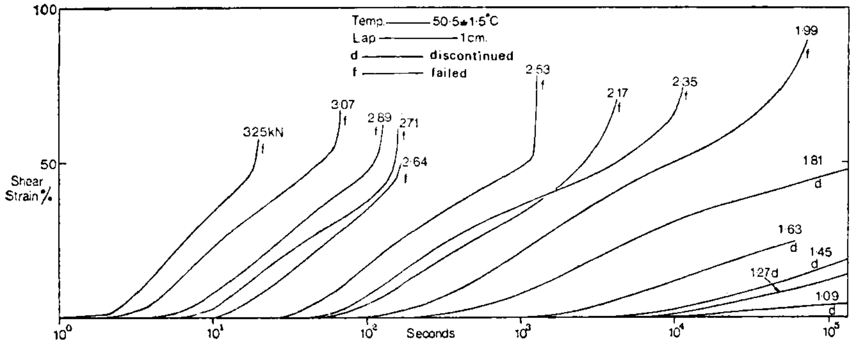

FIGURE 1 Creep; Redux 775.

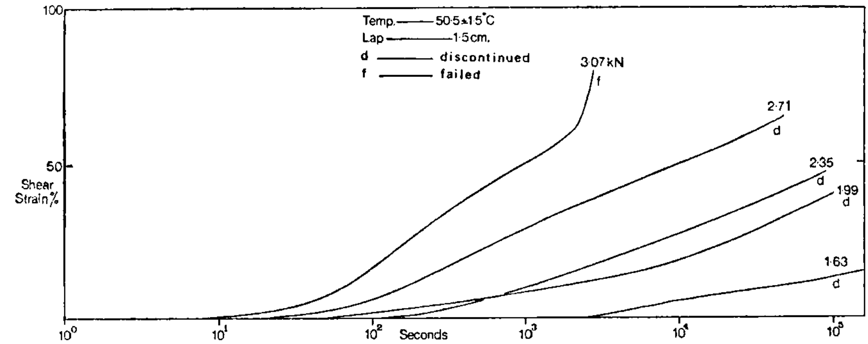

FIGURE 2 Creep; Redux 775.

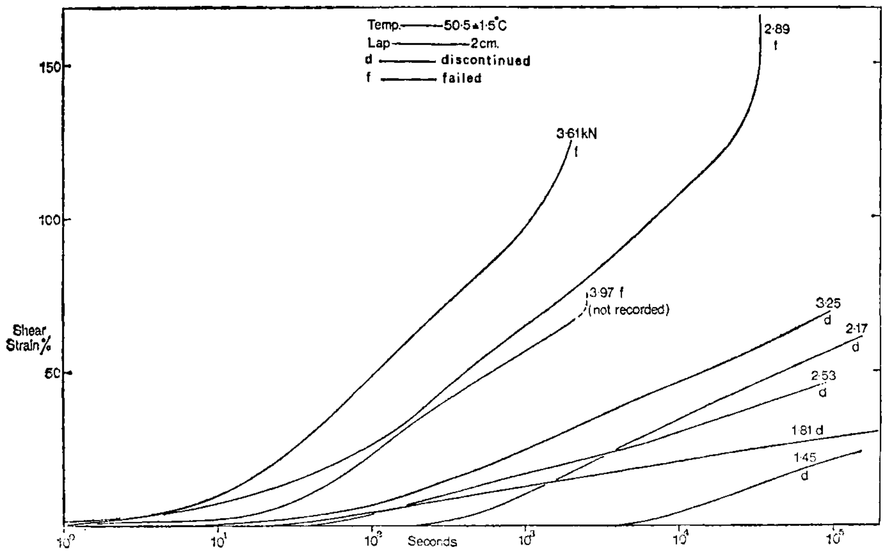

FIGURE 3 Creep; Redux 775.

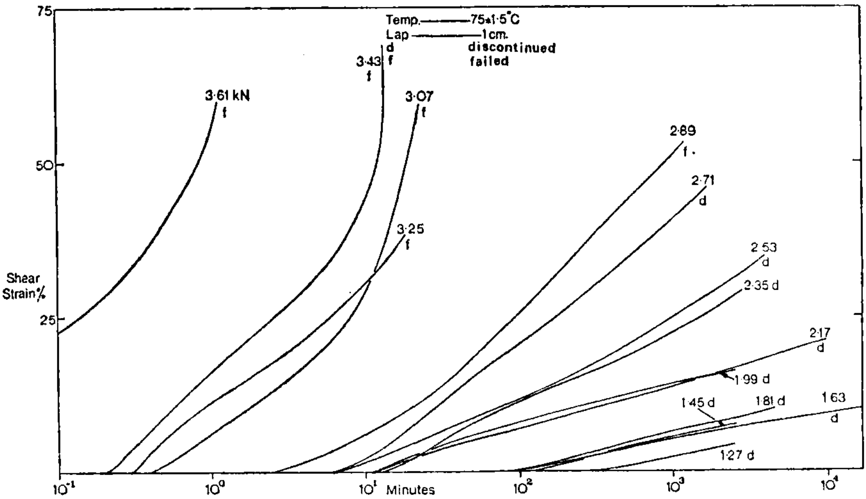

FIGURE 4 Creep; Redux BSL906.

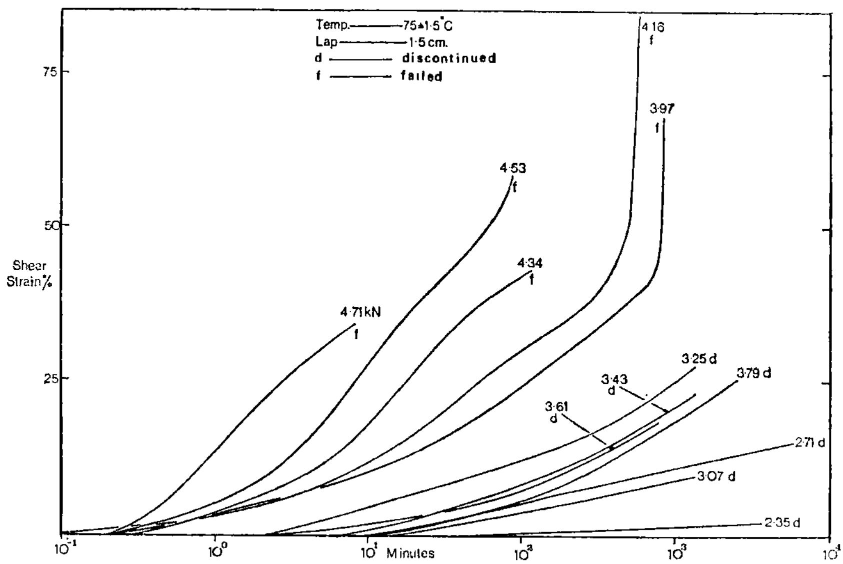

FIGURE 5 Creep; Redux BSL906.

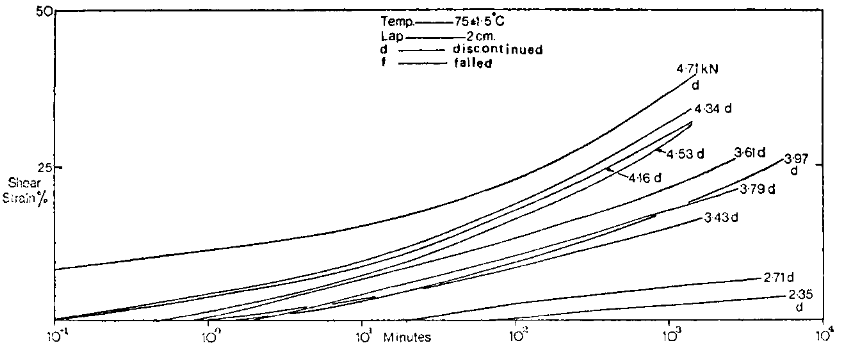

FIGURE 6 Creep; Redux BSL906.

of the creep curve, k, is readily shown to be given by $k = \gamma(\ln(t/t_0)$, and the extrapolated creep rate at t_0, $\dot{\gamma}(t_0)$ is given by $\dot{\gamma}(t_0) = k/t_0$. It has been shown[1] that the relationship between applied load, L, and either ln t_d or ln$\dot{\gamma}(t_0)$ at a given temperature is approximately linear for high stresses; although some deviation is found near an endurance limit, or load below which creep does not occur.

Figures 9 and 10 show as dotted lines ln t_d *vs.* L for the two adhesives from experimental results analysed by the method of least squares in Ref 1. It is reasonable to assume that the maximum adhesive shear stresses determine the overall creep behaviour and these occur at the ends of the overlap. It is also assumed that the behaviour is linear since both t_d and $\dot{\gamma}(t_0)$, correspond

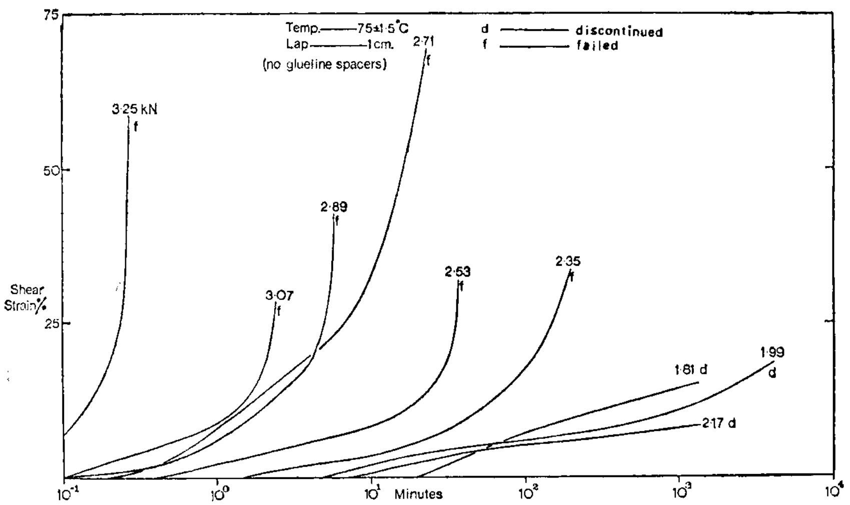

FIGURE 7 Creep; Redux BSL906.

to states of little or no creep strain. Accepting these assumptions, which have been considered in more detail elsewhere,[1,3] a stress factor $m(= \tau_{max}/L)$ exists for a given type of joint under equivalent conditions of strain and temperature. Thus for a given value of t_d (or $\dot{\gamma}(t_0)$), $L_2 = m_1L_1/m_2$ where suffixes refer to joints of different geometry (assuming no change from the elastic stress distribution during delay time because strain has not noticeably changed). A factor, F_x, therefore relates loads applied to joints of different

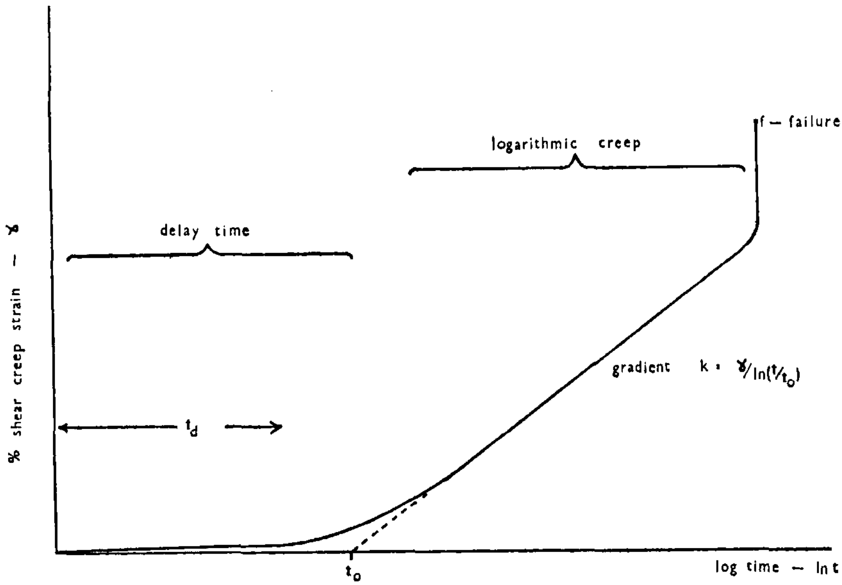

FIGURE 8 Schematic representation of creep *vs*. time.

geometry giving equivalent behaviour. It is readily shown from Volkersen's elastic stress analysis of the lap joint with identical adherends and of unit width[2] that:

$$\tau_{max} = \frac{L}{2}\left[\frac{2G}{Egh}\right]^{\frac{1}{2}} \coth\left[\left(\frac{2G}{Egh}\right)^{\frac{1}{2}}\right] \tag{1}$$

where G is the shear modulus of the adhesive, E is the Young's modulus of the adherend, c is half the overlap length, g and h are the thicknesses of the adhesive and adherends respectively. Values of G at the temperatures in question were respectively 1.18 and 0.69 GN m^{-2} for Redux 775 and BSL 906 found from torsional pendulum data[3] and E was 193 GN m^{-2}. Using these data, the theoretical factor relating equivalent loads for different geometries was calculated. The heavily dashed lines in Figures 9 and 10 represent predictions.

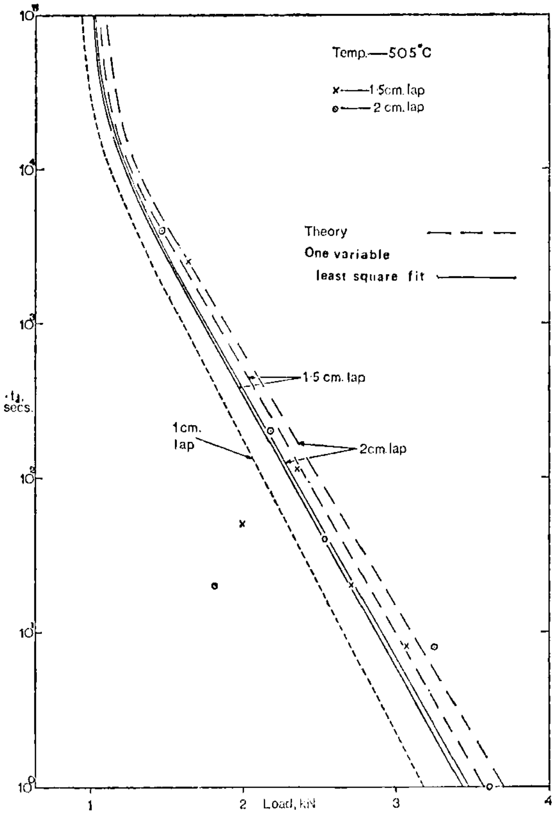

FIGURE 9 Delay times; Redux 775.

An alternative approach is to use the method of least squares with one variable parameter to calculate the lines best representing the experimental points in Figures 9 and 10. This amounts to rotation of a line passing through the intercept on the ln t axis of the original best line for 1 cm overlap results. The method is straightforward and details are given elsewhere.[3] The solid lines in Figures 6 and 7 were calculated by this method.

No predictions of load factors, m, may be made using ln $\dot{\gamma}(t_0)$ since this corresponds to creep and Eq. (1) will no longer apply. However, the one variable method of least squares may be used if it assumed that behaviour is still linear.

The gradient, k, is also related logarithmically to load, L, and can be analysed using the same one-variable least-squares fit. Since ln $t_0 \simeq$ ln t_d, both ln t_d and ln $\dot{\gamma}(t_0)$ are related linearly to L, and $\dot{\gamma}(t_0) = k/t_0$; it follows that ln k must be related linearly to L. By a similar argument, if this least-squares procedure is valid for the analysis of both ln t_d and ln $\dot{\gamma}(t_0)$, it is readily shown that it is also valid for ln k.

Values of F, derived in all these ways together with predictions made from the Volkersen analysis are given in Tables I and II.

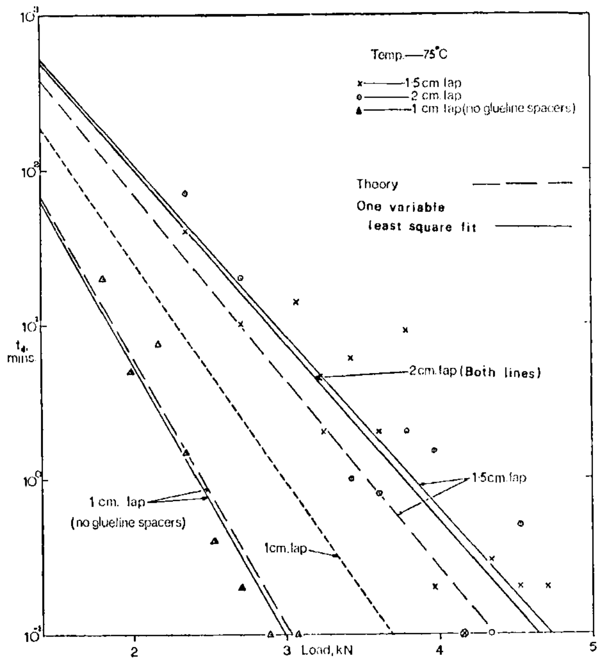

FIGURE 10 Delay times; Redux BSL906.

TABLE I

Load factor with respect to 1 cm lap joints for 1.5 and 2 cm overlap using Redux 775

Overlap x	Predicted (Volkersen)	Load factors for overlap x cm from overlap 1 cm: Applied to delay times t_d	Applied to $\dot{\gamma}(t_0)$	Applied to gradient of creep curve k
1.5 cm	1.13	1.08 ± 0.09	1.19 ± 0.08	1.22 ± 0.23
2.0 cm	1.17	1.09 ± 0.11	1.25 ± 0.12	1.32 ± 0.25

TABLE II

Load factors with respect to 1 cm lap joints (0.0087 cm glueline) for 1.15 and 2 cm overlap (0.0087 cm glueline) and also for 1 cm overlap (0.0043 cm glueline) using BSL 906

Overlap x and glueline thickness	Predicted (Volkersen)	Load factors for overlap x cm from overlap 1 cm: Applied to delay times t_d	Applied to $\dot{\gamma}(t_0)$	Applied gradient of creep curve k
1.5 cm, 0.0087 cm	1.18	1.28±0.12	1.53±0.18	1.40±0.22
2.0 cm, 0.0087 cm	1.26	1.26±0.12	1.60±0.19	1.90±0.33
1.0 cm, 0.0043 cm	0.82	0.81±0.07	0.91±0.10	1.05±0.18

DISCUSSION

Despite considerable scatter of experimental results, the effect of which is minimised by the use of statistical methods, the predicted ratios of applied loads causing equivalent delay time behaviour agree reasonably well with those calculated by the method of least squares. This evidence supports the view that it is the maximum shear stresses within the adhesive layer at the ends of the overlap which should be associated with the rate of adherend separation or overall creep of the joint.

It is clear that the general trend is $F(t_d) < F(\dot{\gamma}(t_0)) < F(k)$ for both adhesives. The first inequality implies that stress concentrations at the ends of the overlap are reduced during creep although the stress pattern is still qualitatively similar to that predicted by Volkersen's theory, with the highest stresses at the ends. Were the adhesive to behave plastically during creep, the adhesive shear stress would be the same everywhere and equal to the applied load divided by the overlap area. If this were the case at the onset of creep, values of $F(\dot{\gamma}(t_0))$ would be $1\frac{1}{2}$ and 2 for the $1\frac{1}{2}$ and 2 cm overlap results and 1 for the thin glueline series since the ratio of applied loads would be the same as the ratio of the overlap areas for a given set of conditions. It is thus clear from Tables 1 and 2 that shear stress concentrations are reduced but not eliminated during creep.

The fact that $F(\dot{\gamma}(t_0)) < F(k)$ implies that stress amelioration continues as creep progresses from the following reasoning. The empirical equation for creep rate is readily shown to be:

$$\dot{\gamma}(t) = k/t = \dot{\gamma}(t_0) \exp\left[-\gamma(t)/k\right] \tag{2}$$

and it follows that:

$$\frac{\dot{\gamma}_1}{\dot{\gamma}_x} = \frac{\dot{\gamma}_1(t_0)}{\dot{\gamma}_x(t_0)} \exp\left\{\gamma\left[\frac{1}{k_x} - \frac{1}{k_1}\right]\right\} \tag{3}$$

where suffixes refer to the original 1 cm overlap behaviour and a general geometry specified by x.

For the case of $\dot{\gamma}_1(t_0) = \dot{\gamma}_x(t_0)$, it is clear that $k_1 > k_x$ from Tables I and II (N.B. the values of t_0 for the two joints are not the same) and therefore:

$$\frac{\dot{\gamma}_1}{\dot{\gamma}_x} = \exp\left[\gamma\frac{k_1 - k_x}{k_1 k_x}\right] \tag{4}$$

Since γ_1, k_1 and k_x are all positive, it follows that $\dot{\gamma}_1/\dot{\gamma}_x$ is always greater than 1 and increased with increasing strain. The joint x has a creep rate which is decreasing with respect to joint 1. Since it is known that creep rate is an increasing function of shear stress at the ends of the overlap (for a given creep stain), it follows that stress concentration amelioration is greater for joint x. This can be explained by the hypothesis that the stress distribution becomes more even as strain increases. Stress concentrations are initially higher for long joints or those with a thin glueline and therefore as stress concentrations are reduced, the creep rate of joint x will fall with respect to the equivalent shorter or thicker joint. From Eq. (4), it is clear that stress concentrations are reduced as creep strain increases but it is not known whether or not the truly plastic state is realised before joint failure. The situation is shown schematically in Figure 11. This type of behaviour might be expected since creep effectively reduces the value of adhesive shear modulus and this in turn is known to reduce stress concentrations. It can be seen that F approaches unity for 1 cm lap joints with a thin glueline because although under elastic conditions, stress concentrations are greater, in the limit of plasticity, only overlap area is relevant. The anomaly of $F_{1 \cdot 5}(\dot{\gamma}(t_0))$ being greater than $F_{1 \cdot 5}(k)$ for BSL 906 can be accounted for by the standard errors and clearly $F_{1 \cdot 5}(\dot{\gamma}(t_0))$ cannot be greater than 1.5 anyway (ignoring errors).

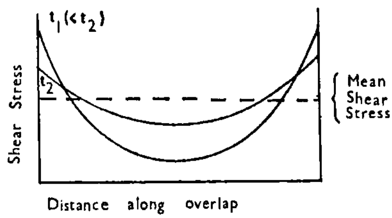

FIGURE 11 Schematic representation of adhesive shear stress amelioration due to creep.

Although analysis has been made using the simplifying assumption that creep curves consist of a delay time, followed by logarithmic creep, actual creep curves display a smooth transition between the two. Separate mechanisms are thought to be responsible for delay time and creep behaviour[1] and the authors' ideas concerning stress pattern modification during the transition are given in the Appendix.

CONCLUSIONS

It has been established that a consequence of creep in adhesive bonded lap joints is a reduction in the well-known stress concentrations found at the ends of the overlap under elastic conditions. This means that creep curves obtained from lap joints will not correspond directly to bulk creep experiments under similar constant stress. It is of interest to note that Hahn[4, 5] believed that delay times were a consequence of changing stress concentrations; and that creep could only start when the initially lightly stressed central part of the overlap took a significant proportion of the applied load after stress relaxation had produced a more even stress distribution within the adhesive layer. This is in contrast to the present work which suggests that the stress distribution remains virtually constant during the delay time and is only modified when creep occurs. However, both theories agree that during creep, stress concentrations are continually being reduced. A pertinent technological consequence of this is that the long overlap joint, normally avoided under elastic conditions because of its inefficiency due to high stress concentrations, is beneficial in circumstances in which creep is likely to arise. If some creep is permissible, the long joint has an inherent secondary safety factor in that stresses causing creep are quite rapidly reduced.

Despite the relatively simple stress analysis used, it has been shown that the stresses directly relevant to adherend separation are the maximum adhesive shear stresses at the ends of the overlap.

APPENDIX

Proposed explanation of transition from delay time to steady creep

With both Redux 775 and BSL 906, real creep curves have a transition period between the regions of delay time and of logarithmic creep, and although the end of the transition is ill-defined experimentally, the following theory is believed to approximate to behaviour during this period.

It is assumed that two types of load bearing element are present within the adhesive.[1] A primary type corresponds to a high shear modulus and (while intact) carries most of the load. The secondary type, of lower shear modulus, only bears a significant part of the load after failure of the primary type. The two kinds are responsible respectively for delay time and creep behaviour.

Suppose the time to failure, t_f, for the primary bonds of a sample under constant stress, s, is $t_f = A/f(s)$ where $f(s)$ is a function of stress and A is a constant. It is assumed that for constant stress, no appreciable increase in strain appears until t_f. For a varying stress, the equivalent equation is:

$$\int_0^{t_f} f(s)\,dt = A \qquad \text{(A1)}$$

The function $g(t)$ is defined as:

$$g(t) = \int_0^t f(s)\, dt \qquad \text{(A2)}$$

For a lap joint under load with the highest stresses at the ends, t_f will occur first at the ends of the overlap and then later for points further in the joint. Taking one end of the overlap to be the zero of the coordinate x along the load axis of the joint, the primary bond failure criterion for two points Δx apart is:

$$g(x,t) = g(x+\Delta x,\, t+\Delta t) = A \qquad \text{(A.3)}$$

This is readily shown to be equivalent to:

$$\frac{\partial g}{\partial t} = -\frac{\partial g}{\partial x}\frac{dx}{dt} \qquad \text{(A4)}$$

where dx/dt represents the rate of movement towards the centre of the joint of the primary bond fracture or yield front and may be written as $\dot{x}$. By rearranging and differentiating with respect to t, it can be shown that:

$$\frac{\partial^2 g}{\partial x\, \partial t} = \ddot{x}\frac{\partial g}{\partial t} - \dot{x}\frac{\partial^2 g}{\partial t^2} \Big/ \dot{x}^2 \qquad \text{(A5)}$$

where $\ddot{x}$ represents the second differential with respect to t. From Eq. (A.2), using the fact that s and therefore $f(s)$ are explicit functions of x but not t in the present case:

$$\left.\begin{aligned} \frac{\partial g}{\partial t} &= f(s) \\ \frac{\partial^2 g}{\partial x\, \partial t} &= f'(s) \\ \frac{\partial^2 g}{\partial t^2} &= 0 \end{aligned}\right\} \qquad \text{(A6)}$$

where the prime denotes differentiation with respect to x. Substitution into Eq. (A.5) gives:

$$f(s)\, \ddot{x} = f'(s)\, \dot{x}^2 \qquad \text{(A.7)}$$

Solution of this simple differential equation gives:

$$\dot{x} = Bf(s) \qquad \text{(A.8)}$$

where B is a constant. From a study of delay times, it is likely that $f(s) \simeq \exp(as)$, a being a constant. To a first approximation, a joint of overlap length $2c$ has an effective overlap of $2(c\text{-}x)$ when the failure front has reached x since failure fronts approach from each end. The idealised situation corresponding to Figure A.1(a) has a failure front moving at a speed given by combining Eq. (A.8), which is Volkersen's expression for maximum shear stress with the expression for $f(s)$:

$$\dot{x} = B \exp\left\{\frac{aLe}{2} \coth\left[e(c-x)\right]\right\} \tag{A9}$$

where $e = [2G/Egh]^{\frac{1}{2}}$. This corresponds to accelerating yield fronts coming from each end accounting for increasing strain during the transition period since the same applied load is being carried by a rapidly dwindling number of bonds of the primary type. After the two fronts meet, the secondary bonds

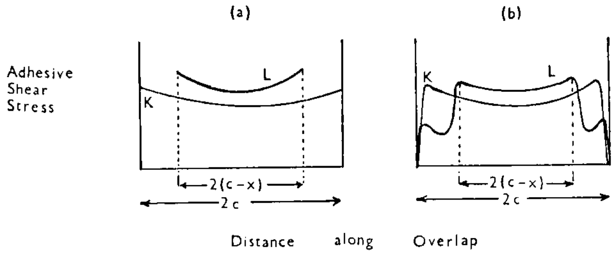

FIGURE A.1. Schematic representation of (a) idealised and (b) real stress distributions occurring during the transition period.

(Stress distribution during *K* delay time, and *L* transition).

then carry the load corresponding to steady creep. A more realistic representation of this ideal is shown in Figure A.1(b) where a certain proportion of the load is carried by secondary bonds during the transition and so no abrupt change in behaviour occurs when the yield fronts meet.

Acknowledgements

The authors wish to thank Professor W. C. Wake of The City University for all his help and encouragement.

The work has been carried out with the support of Procurement Executive, Ministry of Defence.

References

1. M. E. R. Shanahan, *J. Adhesion* **7**, 161 (1975).
2. O. Volkersen, *Luftfahrtforsh* **15**, 41 (1938).
3. M. E. R. Shanahan, Ph.D. thesis, The City University, London, 1974.
4. K. F. Hahn, *Adhesives Age* **4**, 34 (December 1961).
5. K. F. Hahn in Symposium on Adhesion and Adhesives (held in San Francisco, 1959), ASTM Spec. Techn. Publ. No. 271(1961).

Nomenclature

γ	percentage shear creep strain
k	gradient of logarithmic creep curve
t	time
t_0	intercept of creep curve with time axis
$\dot{\gamma}$	creep rate
L	load
t_d	delay time
m	stress factor
τ_{max}	maximum adhesive shear stress
G	adhesive shear modulus
E	adherend Young's modulus
g	glueline thickness
h	adherend thickness
$2c$	overlap length
F	load ratio of lap joints of different geometry showing equivalent creep behaviour

(suffix represents a stated joint geometry).

Appendix

s	stress
t_f	time to failure for primary bonds
$f(s)$	function of stress, s
A, B	constants
$g(t)$	function of time, t
x	distance along overlap of joint

$e = [2G/Egh]^{\frac{1}{2}}$