

REPORT

The Prediction of Creep Damage in Surface Mount Components using Finite Element Modelling

J Warde and E R Wallach

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ABSTRACT

The objective was to use finite element models to calculate the expected mechanical strains in solder joints between two surface mount components and FR4 circuit boards as a consequence of thermal cycling. Initially, these finite element predictions will be compared by NPL with actual thermal cycling data collected experimentally by them. Ultimately, the predicted strains will be used in existing phenomenological equations to predict lifetimes of joints of different geometries. This approach will help in the development of a predictive modelling capability with the longer term aims of reducing testing time and facilitating the evaluation of new component geometries.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

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SUMMARY OF RESULTS

Finite element (FE) analysis has been used to predict the creep damage occurring during thermal cycling in two surface mount components, namely 0805 and 2512 resistors mounted on an FR4 board.

Initially, a number of simple 2D FE models of both sizes of resistors were considered in order to investigate the effect of the solder joint dimensions on the creep damage. It was found that the profile of the solder at the end of the resistor has a very significant effect on the predicted creep damage. Solder joints which had a large 'effective thickness' of solder at the end of the resistor resulted in smaller amounts of creep damage than joints with a thinner thickness of solder at the resistor end.

The larger 2512 resistors were predicted to generate higher magnitudes of creep damage compared to the smaller 0805 resistors. This is expected since the additional resistor length will result in a larger relative movement between resistor and solder at the ends of the resistor. Therefore, the service lifetimes of the 2512 resistors would be expected to be significantly shorter for given service conditions than those for the 0805 resistors.

3D FE models were generated for both resistors. As with the 2D work, it was predicted that more creep damage would be generated in the 2512 resistors than the smaller 0805 resistors. However, for each resistor, maximum creep damage was located in the outer surface plane of the solder; this plane cannot be modelled in 2D. This indicates that 2D modelling alone may not be sufficient to predict the precise magnitude of creep damage arising from thermal cycling, although relative measurements may be reasonable.

1 BACKGROUND

Rapid design changes are occurring in the electronics industry to meet the need for greater reliability as well as allowing higher component and connection densities to be used. However, even when using accelerated tests, obtaining test data to assess solder joint reliability is both time-consuming to collect and then difficult to extrapolate to predict operational reliability. The aim of a research programme in the University of Cambridge is to investigate computer simulations of thermally cycled soldered joints of various geometries. Finite element analysis is being used to predict the strains that occur within solder joints due to temperature cycling; the data then are combined with models of interactive fatigue-creep in order to predict lifetimes under given operational conditions. Initially in the work with NPL, two surface mount components have been modelled and emphasis given to changing the geometries of the soldered region for these components; this will allow the modelling predictions to be compared with actual experimental thermal cycling data collected by NPL as part of their existing and continuing research programme.

Using this finite element modelling approach, the parameters in any model can be easily changed. Accordingly, predictions can be made of the effects on the overall reliability of soldered joints in service, and also of proposed changes in component design, fabrication methods, operating conditions and/or materials used.

2 GEOMETRIES ORIGINALLY PROPOSED BY NPL

Two ceramic chip resistors (identified as 0805 and 2512) were considered in this work. These were joined to FR4 circuit boards using eutectic 60/40 Pb-Sn solder. A number of joint geometries were considered. The basic FR4 board/resistor combination is shown in Figures 1 and 2 which indicate the potential variables (labelled a-f) that could be investigated in the finite element analysis.

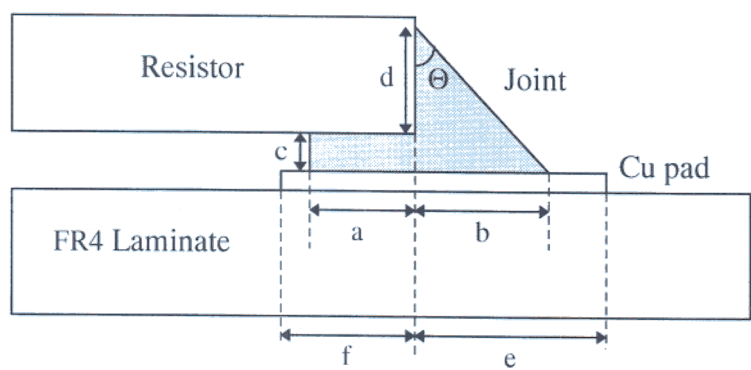


Figure 1 Cross-section through assembly showing dimensions

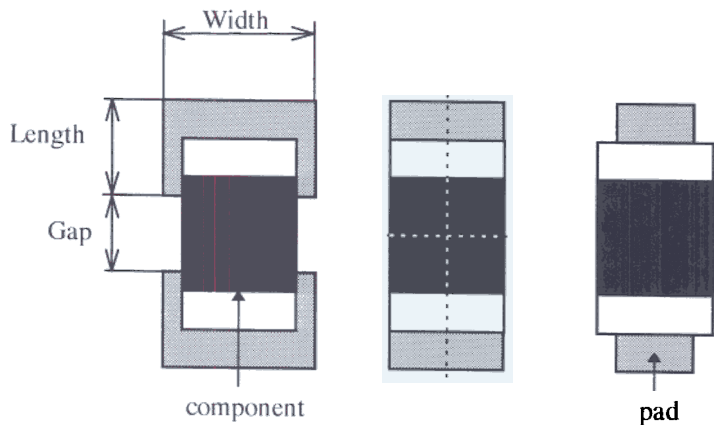


Figure 2 Top view showing dimensions

A number of specific designs (labelled A-G) were originally proposed by NPL and are as given in Tables 1 and 2. It should be noted that the solder dimensions supplied were those estimated before the resistors were joined to the FR4 board. As the real assemblies were manufactured and their profiles measured by NPL, the joint dimensions were modified in order to reflect the real joint shapes.

Design	Length (e+f) [mm]	Width [mm]	Gap [mm]	a [mm]	b [mm]	c [mm]	d [mm]	Θ [°]
A	0.94	1.73	1.02	0.45	0.49	0.15, 0.20, 0.25	0.27, 0.50	20
B	1.02	1.60	1.02	0.45	0.57	0.15, 0.20, 0.25	0.27, 0.50	20
C	1.12	1.45	1.02	0.45	0.67	0.15, 0.20, 0.25	0.27, 0.50	20
D	1.27	1.27	1.02	0.45	0.82	0.15, 0.20, 0.25	0.27, 0.50	20
E	1.45	1.12	1.02	0.45	1.00	0.15, 0.20, 0.25	0.27, 0.50	20
F	1.60	1.02	1.02	0.45	1.15	0.15, 0.20, 0.25	0.27, 0.50	20
G	1.73	0.94	1.02	0.45	1.28	0.15, 0.20, 0.25	0.27, 0.50	20

Table Design dimensions for resistors 0805

Design	Length (e+f) [mm]	Width [mm]	Gap [mm]	a [mm]	b [mm]	c [mm]	d [mm]	Θ [°]
A	1.52	3.68	4.01	0.57	0.96	0.15, 0.20, 0.25	0.27, 0.50	20
B	1.60	3.51	4.01	0.57	1.03	0.15, 0.20, 0.25	0.27, 0.50	20
C	1.68	3.35	4.01	0.57	1.11	0.15, 0.20, 0.25	0.27, 0.50	20
D	1.78	3.15	4.01	0.57	1.21	0.15, 0.20, 0.25	0.27, 0.50	20
E	1.91	2.95	4.01	0.57	1.34	0.15, 0.20, 0.25	0.27, 0.50	20
F	2.03	2.74	4.01	0.57	1.47	0.15, 0.20, 0.25	0.27, 0.50	20
G	2.21	2.54	4.01	0.57	1.64	0.15, 0.20, 0.25	0.27, 0.50	20

Table 2 Design dimensions for resistors 2512

3 MATERIAL PROPERTIES AND CREEP EQUATIONS

Damage occurs during thermal cycling due to the large thermal expansion mismatch between the ceramic resistor ($\alpha = 6 \times 10^{-6} \text{ K}^{-1}$), lead-tin eutectic solder ($\alpha = 25 \times 10^{-6} \text{ K}^{-1}$), and the FR4 circuit board ($\alpha = 14 \times 10^{-6} \text{ K}^{-1}$). The resultant inelastic strains are dominated by creep deformation of the lead-tin solder and which can be described in the finite element (FE) analysis by a sinh law:

$$\frac{d\gamma_c}{dt} = A \left[\sinh(\alpha \sigma) \right]^n \exp \left\{ \frac{Q_A}{RT} \right\}$$

Eqn. 1

where γ_c = creep strain, t = time, Q_A = deformation energy, R = ideal gas constant, T = temperature and A , α and n are constants related to the deformation mechanism. The solder joint was modelled as an homogeneous eutectic solder rather than as a two-phase alloy comprising discrete Sn-rich and Pb-rich grains.

The values of the constants in Equation 1 are given in Table 1. All other materials were treated as linear elastic.

	units	Pb/Sn eutectic	90Pb/10Sn
A	(s ⁻¹)	96,200	2.2 x 10 ⁸
α	(MPa ⁻¹)	0.087	0.207
n		3.3	7
Q	(J mol ⁻¹)	67,426	110,826

Table 3: Creep data used in the FE models [1].

THE PACKAGE WAS SUBJECTED TO A THERMAL CYCLE SHOWN IN FIGURE 3, CONSISTING OF A 15 MINUTE RAMP UP FROM -20 TO 100°C, A 30 MINUTE DWELL, 15 MINUTE RAMP BACK DOWN TO -20°C AND FINALLY A DWELL OF 30 MINUTES. THE RESULTING THERMAL STRAINS AND STRESSES, INCLUDING ASSOCIATED CREEP DAMAGE, WERE PREDICTED USING ABAQUS, A COMMERCIALY AVAILABLE FINITE ELEMENT PACKAGE.

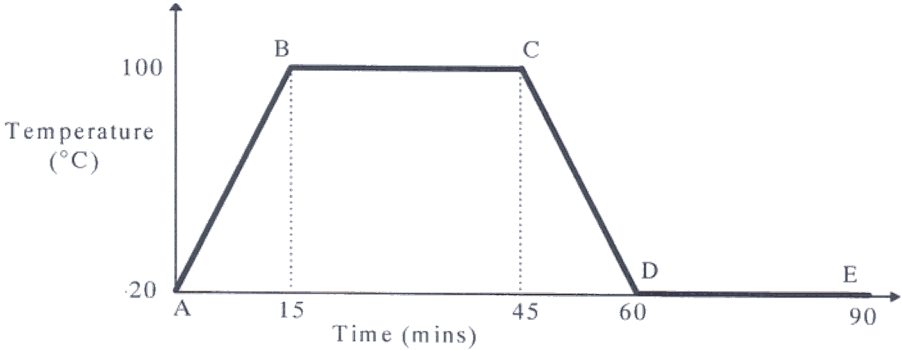


Figure 3 The thermal cycle

Traditionally, the life of a component, expressed as the number of cycles to failure N_f , is predicted using the maximum creep strain range, $\Delta\gamma_{\max}$, experienced in the solder. The creep strain range is defined as the difference between the creep strain at the end of the high temperature dwell (C in figure 3) and that at the end of the low temperature dwell (E) of the same cycle. Common empirical lifing equations relating $\Delta\gamma_{\max}$ to N_f include:

Coffin-Manson [2-4]:

$$N_f = \left(\frac{\Delta\gamma_{\max}}{\epsilon_o} \right)^c \quad \text{Eqn. 2}$$

where ϵ_o and c are empirical constants.

IBM-Katchmar [5-7].

$$N_{f_2} = N_{f_1} \left(\frac{\Delta\gamma_{\max 1}}{\Delta\gamma_{\max 2}} \right)^z \left(\frac{f_2}{f_1} \exp \left\{ \frac{\Delta H}{k} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right\} \right)^w \quad \text{Eqn. 3}$$

where $\Delta\gamma$ = creep strain range, f = number of cycles per day and T = maximum cycle temperature under two sets of conditions, ΔH = activation energy, k = Boltzmann's constant, and z & w are empirical constants.

Norris-Landzberg [8]:

$$N = N_{f_1} \left(\frac{\Delta\gamma_{\max 1}}{\Delta\gamma_{\max 2}} \right) \left(\frac{f_2}{f_1} \right)^{\frac{1}{3}} \left(\frac{\Delta T_1}{\Delta T_2} \right)^{\frac{1}{3}} \quad \text{Eqn. 4}$$

where $\Delta\gamma$ = creep strain range, f = number of cycles per day and ΔT = temperature range of the thermal cycle under two sets of conditions.

Note that no attempt has yet been made in the current programme to estimate lifetimes expected since the constants in the above equations have not been obtained for the specific geometries of the surface mount resistors used. This is to be investigated in future work.

4 FINITE ELEMENT MODELLING AND CREEP DAMAGE

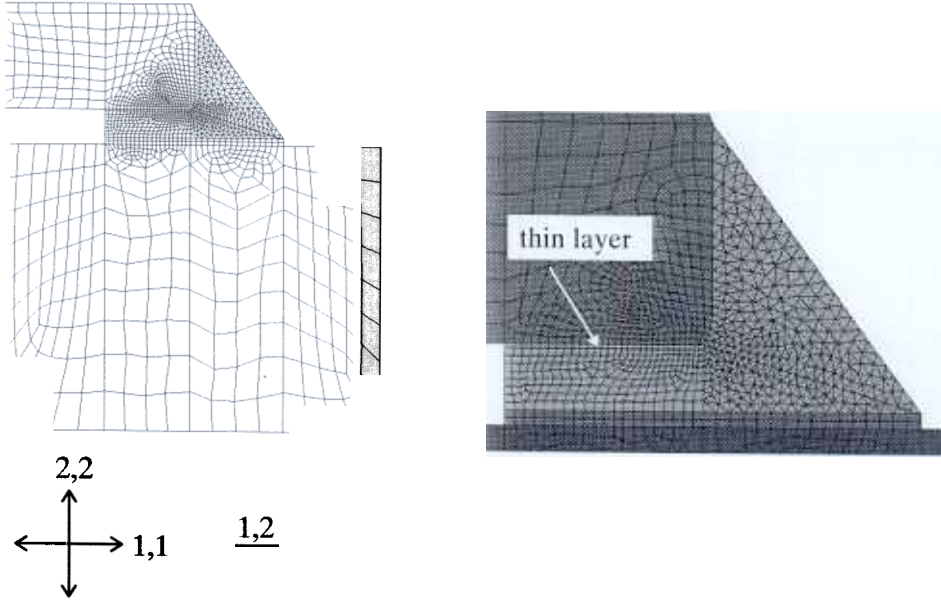


Figure 4 Example of a 2D finite element mesh at low and high magnifications.
(Strain and stress directions are also defined.)

A thin layer of elements was added to the mesh at the underside of the resistor, see Figure 4. The distribution and size of these elements were maintained at constant values in all the models. Hence, any effect of the mesh size at the interface to the resistor is removed, see appendix.

Two measures of creep damage were considered:

- (i) the maximum shear creep strain range, $\Delta \epsilon_{12_{\max}}$, which is defined as the difference between the shear creep strains (ϵ_{12}) at the end of the high and low temperature dwells (points C and E respectively in Figure 3);
- (ii) the creep strain energy density, $CENER$, which is the area of the stress - creep strain loop summed over the number of thermal cycles completed, as defined by:

$$CENER = \int_t \left(\int_V \sigma \dot{\epsilon}_c dV \right) dt \quad \text{Eqn. 5}$$

where σ is the stress and $\dot{\epsilon}_c$ is the creep strain rate. Figure 5 shows a typical stress strain deformation loop; for simplicity only the shear component is plotted. The points A to E correspond to those shown for the thermal cycle in Figure 3.

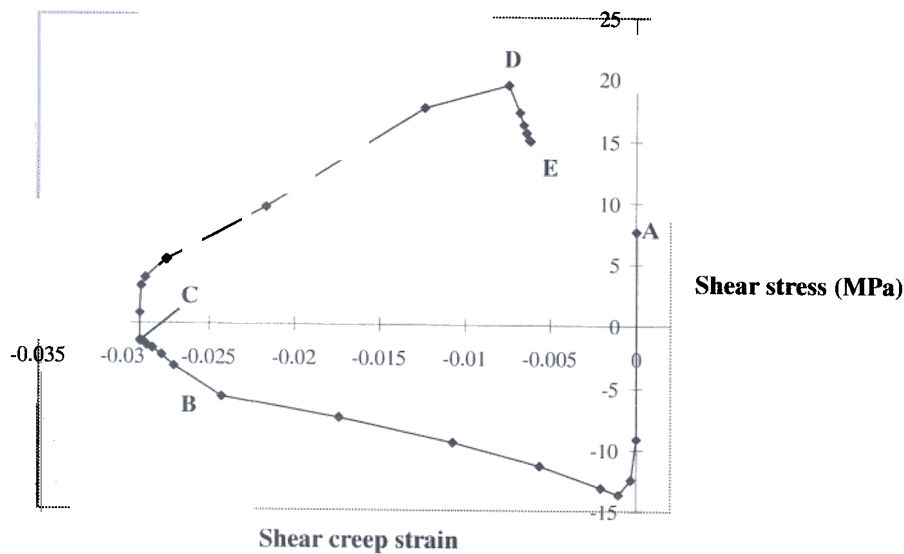


Figure 5: Typical shear stress - shear creep strain deformation loop for one thermal cycle.

5 RESULTS FOR 0805 RESISTORS

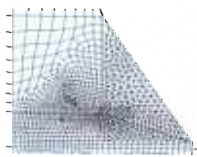
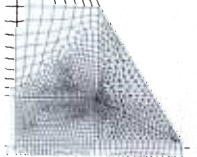
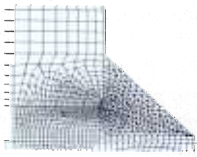
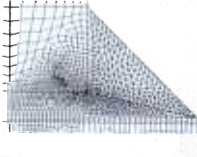
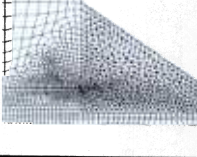
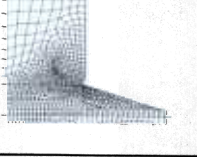
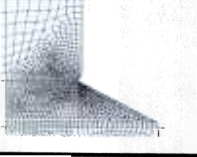
5.1 ROLE OF GEOMETRICAL VARIABLES

Initially, a series of simple 2D joints were considered; these are summarised in Table 4 which includes values for the predicted maximum creep strain range $\Delta\epsilon_{12_{max}}$. Joint dimensions were varied in a systematic manner. Therefore, in theory, the influence of one joint dimension could be investigated in isolation from the others. However, it should be noted that the volume of solder in the joint varied from joint to joint. The effects of changes when keeping the volume of the solder constant are described in section 5.2.

Figure 6 shows the development of $\Delta\epsilon_{12_{max}}$ over the first 50 thermal cycles. It can be seen that $\Delta\epsilon_{12_{max}}$ reaches a constant value after only 5 thermal cycles and this is the value that is used in Table 4.

The creep damage in a typical joint as measured by the creep strain energy density CENER is shown in Figure 7. As was observed for the maximum creep strain range $\Delta\epsilon_{12_{max}}$, the maximum value, $CENER_{max}$, was found in the solder adjacent to the lower right corner of the resistor (furthest from the neutral axis); this point will be referred to as point R in future discussion. Significant creep damage can also be observed at two other points, L and T, on the interface between the resistor and solder, although the extent of damage is smaller than at point R. Damage occurring at point T was found to be related to the magnitude of the contact angle, θ . A shear creep strain range $\Delta\epsilon_{12}$ of

1.25% was predicted at point T in the standard joint ($\theta=36^\circ$) compared with a value for $\Delta\epsilon_{12}$ of only 0.38% in the reduced volume joint ($\theta=18^\circ$). This effect is due to the larger thermal expansion coefficient of the solder compared to the ceramic resistor. On heating, expansion of the solder is constrained along the resistor joint interface resulting in the generation of shear creep damage at T. When the contact angle is reduced, and hence the volume of solder at the end of the resistor is less, the shear force exerted by the bulk solder is reduced and hence the shear creep damage decreases.

	Name (file ID)	Geometry	Dimensions (mm)	Max strain range, $\Delta\gamma_{\max}$ ¹	
				average ²	peak ³
1	standard (A_te_c1_d2)		Design A c=0.15 d=0.5 b=0.49	1.61	2.25
2	increased stand-off (A_te_c3_d2)		Design A c=0.25 d=0.5 b=0.49	1.81	2.39
3	decreased wetting (A_te_c1_d1)		Design A c=0.15 d=0.27 b=0.49	1.73	2.58
4	reduced volume (A_arc_te_c1_d2)		Design A c=0.15 d=0.5 b=0.49	1.70	2.44
5	increased pad 1 (C_te_c1_d2)		Design C c=0.15 d=0.5 b=0.67	1.60	2.27
6	increased pad 2 (E_te_c1_d2)		Design E c=0.15 d=0.5 b=1.0	1.66	2.30
7	zero wetting 1 (norise_te_c1)		Design A c=0.15 d=0 b=0.49	4.28	7.59
8	zero wetting 2 (norise_te_c3)		Design A c=0.25 d=0 b=0.49	4.58	8.21

¹ at the most critical element (in solder beneath the lower right corner of resistor)

² averaged over 9 integration points within the element

³ maximum value at one integration point within element

Table 4: 0805 resistor - effects of solder joint geometrical variables on the maximum shear creep strain range, $\Delta\epsilon_{12\max}$.

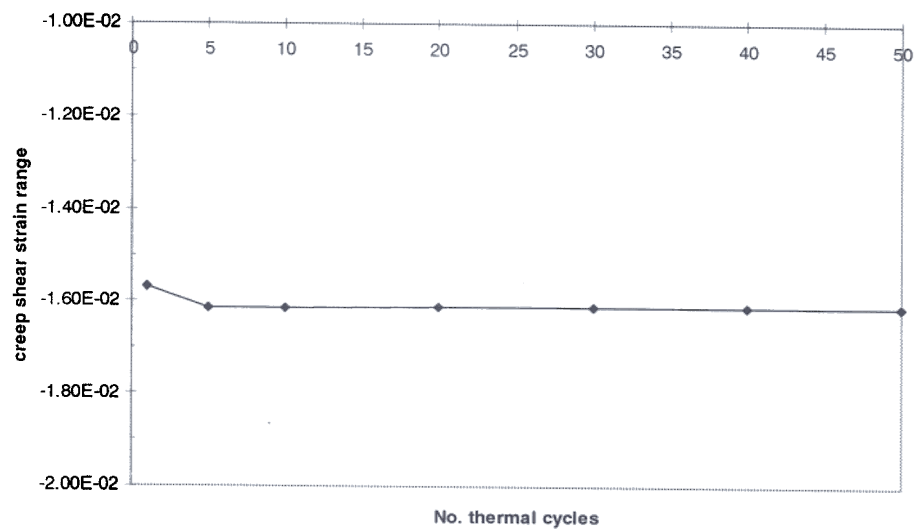


Figure 6: Maximum creep shear strain range, $\Delta\gamma_{\max}$, as a function of the number of thermal cycles experienced for the 0805 resistor. ($\Delta\gamma_{\max}$ is located in the solder beneath the lower right corner of the resistor.)

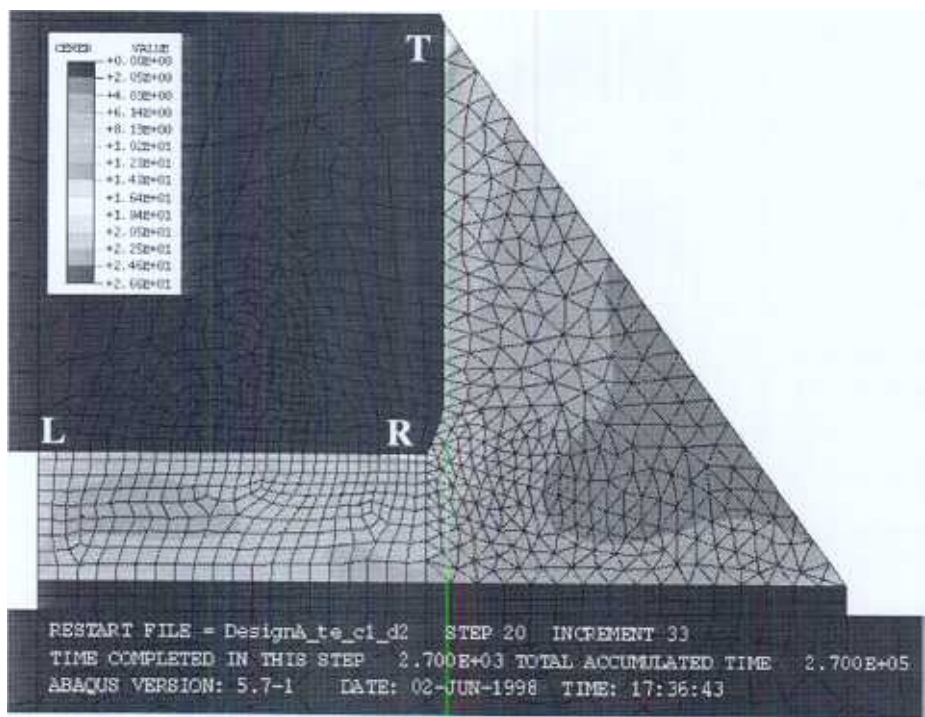
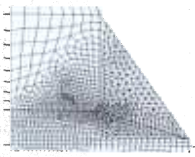
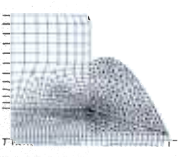
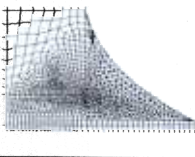


Figure 7: Distribution of creep strain energy density CENER ($\times 10^3 \text{ MPa m}^{-3}$) for the 0805 resistor after 50 thermal cycles.

5.2 CONSTANT VOLUME VARIATIONS

A second set of joint geometries was modelled where the volume of the joint (area of joint in 2D model) was maintained at a constant value. These variations in joint shape are closer to those found in practice. The results are summarised in Table 5.

	Name (file ID)	Geometry	Dimensions (mm)	Max strain range, $\Delta\gamma_{\max}$	
				average ²	peak ³
1	standard (A_te_c1_d2)		Design A c=0.15 d=0.5 b=0.49	1.61	2.25
9	Constant - stand-off (ConstA_te_c3_d2)		Design A c=0.25 d=0.5 b=0.49	2.12	3.11
10	Constant - wetting (ConstA_te_c1_d1)		Design A c=0.15 d=0.27 b=0.49	1.65	2.45
11	Constant -pad size (ConstC_te_c1_d2)		Design C c=0.15 d=0.5 b=0.67	1.65	2.38

¹ at the most critical element (in solder beneath lower right corner of resistor)

² averaged over 9 integration points within the element

³ maximum value at one integration point within element

Table 5: 0805 resistor - effects of solder geometry variables on the maximum shear creep strain range, $\Delta\epsilon_{12_{\max}}$, when the volume of solder in the joint is kept constant.

5.3 DISCUSSION OF MAIN RESULTS

i. Profile shape

Generally it was found that the profile of the solder at the end of the resistor had a very large effect on the maximum creep damage predicted. In particular, the ‘effective joint thickness’, as defined in Figure 9, was found to be significant; the specific role of each solder dimension will be discussed later. Figure 8 shows how the predicted maximum shear creep strain range, $\Delta\epsilon_{12_{max}}$, for each 2D model (0805 resistor) varies as a function of the ‘effective joint thickness’. It can be seen that as the solder thickness decreases, the maximum shear creep strain range increases. This is because the thickness of solder at the end of the resistor determines the constraint imposed on the relative movement of the board and resistor. As the solder thickness decreases, there is much less constraint between the board and resistor and so the solder in the critical region (adjacent to the bottom corner of the resistor) is much freer to deform. Conversely as the solder thickness increases, relative movement of the resistor and board is much more constrained and hence creep damage is reduced.

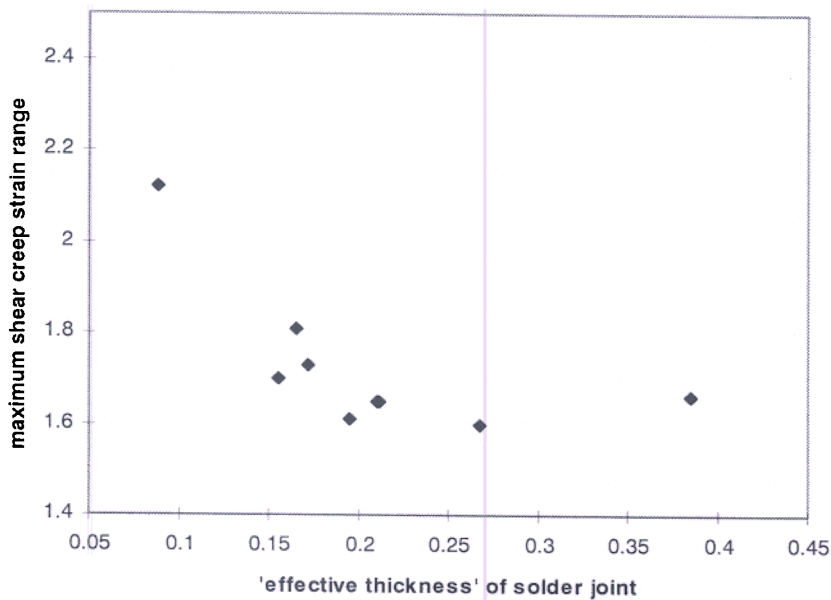


Figure 8: Predicted maximum shear creep strain range, $\Delta\epsilon_{12_{max}}$, as a function of ‘effective solder thickness’.

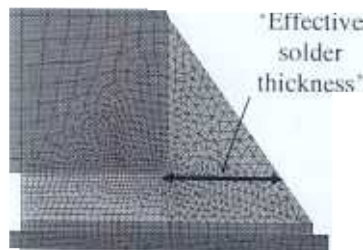


Figure 9: Definition of 'effective solder thickness'

ii. Joint volume

It would be expected that as the volume of solder in the joint is decreased, the maximum creep damage will increase. Comparison of the standard (1) and reduced volume (4) joints in Table 4 shows that the maximum shear creep strain range increases from 2.25 to 2.44% as the solder volume is reduced. As the solder volume is reduced, the 'effective solder thickness' decreases and this results in a less constrained joint and hence greater creep damage. This is consistent with the above result for profile shape.

iii. Stand-off

It is predicted that creep damage increases and hence lifetime is reduced as the stand-off (dimension c in figure 1) is increased. This was found both in the initial 0805 models, standard (1) compared with increased stand-off (2), and in the constant volume variations, standard (1) versus constant - stand-off (9). The effect is more pronounced in the constant volume variations. This is because when the stand-off is increased, the volume of solder under the resistor increases with a corresponding reduction in that at the end of the resistor, i.e. a reduction in the 'effective solder thickness'.

iv. Pad size

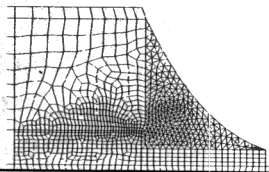
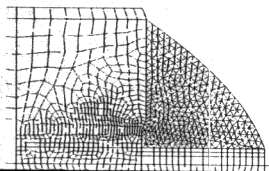
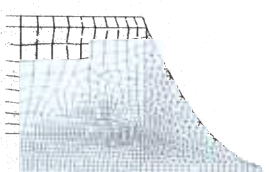
Variations in the pad length (dimension b) were predicted to have a very small effect on the creep damage. When the pad length was doubled from 0.5 to 1.0 mm, the peak strain range increased marginally from 2.25 to 2.30%. The length of the pad which lies underneath the resistor body, e , was not varied in this work as the flow of solder under the resistor will be determined by the termination length, a , which was constant for each resistor size.

v. Wetting height

It was predicted that creep damage would increase as wetting at the end of the resistor is reduced. When the wetting height, d , was reduced from 0.5 to 0.27 mm, standard (1) compared with decreased wetting (3), the shear strain range increased from 2.25 to 2.58%. In the extreme case of zero wetting, a dramatic increase in creep damage was predicted; for example, the peak strain range increased from 2.25 to 7.59% as the wetting height was reduced to zero (7). Again, this is consistent with the reduction in the constraint imposed by the solder at the end of the resistor.

6 RESULTS FOR 2512 RESISTORS

The FE profile geometry generated was based on both the proposed geometry dimensions (Table 2) and cross-section micrographs plus profile measurements provided at a later date by NPL. As a result, the stand-off height (*c*) was reduced from 0.15 mm as specified in the original proposal to 0.08 mm. The pad size was based on Design A.

	Name (file ID)	Geometry	Dimensions (mm)	Max strain range, $\Delta\gamma_{max}$ ¹	
				average ²	peak ³
12	standard (2512_A)		Design A 100 stencil <i>c</i> =0.08	1.72	2.47
13	increased volume (2512_A_200)		Design A 200 stencil <i>c</i> =0.08	1.64	2.30
14	increased stand-off (2512_A_incc)		Design A 100 stencil <i>c</i> =0.15	2.04	2.91

¹ at the most critical element (in solder beneath lower right corner of resistor)

² averaged over 9 integration points within the element

³ maximum value at one integration point within element

Table 6: 2512 resistors - effects of solder joint geometrical variables on the maximum shear creep strain range $\Delta\epsilon_{12_{max}}$.

(i) Distribution of creep damage

The creep damage (CENER) occurring in the standard 2512 joint is shown in Figure 10 after 50 thermal cycles. Two significant areas of creep damage can be seen at points L and R (as identified in Figure 7). Creep damage at point T is relatively small due to the small wetting angle, θ , as discussed earlier in section 5.1.

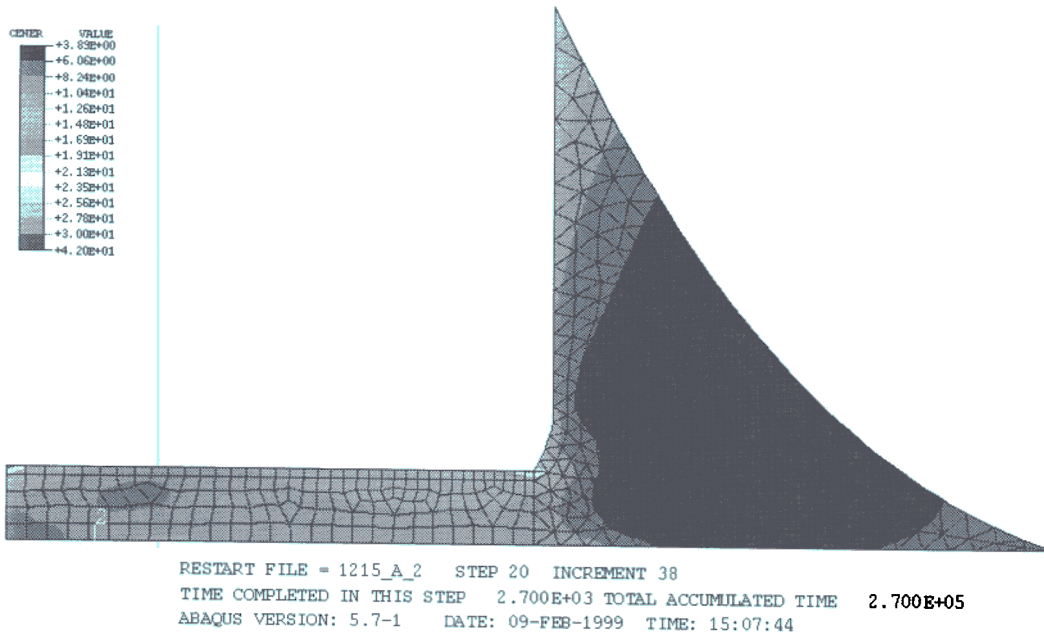


Figure 10: Distribution of creep strain energy density CENER ($\times 10^3 \text{ MPam}^{-3}$) after 50 thermal cycles

(ii) Effect of joint shape

As with the 0805 resistors, it is evident from Table 6 that the 'effective joint thickness' is of great significance. As the volume (stencil thickness) is increased and hence the 'solder thickness' increases, it is predicted that the creep damage will be reduced from 2.47 to 2.30%. Conversely, as the stand-off height is increased and more solder is sucked under the resistor, the 'solder thickness' decreases leading to an increase in creep damage from 2.47 to 2.91%.

7 COMPARISON OF 2512 AND 0805 RESISTORS

The values of CENER and $\Delta\epsilon_{12}$ at L and R for the standard 0805 and 2512 joints are compared in Table 7. As expected, the creep damage at point R increases with the component size and hence distance from the neutral axis. However, the results for the corner L are less clear. Creep damage, as measured by CENER, increases significantly from the smaller 0805 to the larger 2512. However, $\Delta\epsilon_{12}$ at L decreases as the component increases in size. It should also be noted that the value of $\Delta\epsilon_{12}$ is relatively much smaller than the value of CENER. This suggests firstly that in both joints the total creep damage (CENER) at L is not dominated by the shear component; the tensile 1,1 and/or 2,2 components must be of more significance. This is shown in Table 8 where all the creep strain components are given for both positions. Note the large components of 1,1 and 2,2 creep strain range in position L compared to position R. This was also found to be the case for the smaller 0805 resistor. Large tensile components of creep damage at point L may arise due to either reduced constraint in the solder in the 1,1 and 2,2 directions at the free surface, and/or larger tensile (2,2) stresses due to the bending

moment generated by the difference in thermal expansion coefficients of the resistor and board.

	2512 resistor	0805 resistor
right corner R		
$\Delta\epsilon_{12}$ (%)	1.72	1.61
CENER ($\times 10^3$ MPa m ⁻³)	21.1	18.4
left corner L		
$\Delta\epsilon_{12}$ (%)	0.15	0.52
CENER ($\times 10^3$ MPa m ⁻³)	22.4	12.3

Table 7: Creep damage occurring at points L and R in the ‘standard’ 2512 joint (12) and ‘standard’ 0805 joint (1).

The dramatic increase in creep damage at L when the resistor size is increased could be due to a number of factors - larger distance from neutral axis, reduced stand-off c , or increased termination length a . Reduced stand-off can be ruled out as the dominant factor since the ‘increased stand-off’ model (14), which has a larger stand-off (identical to the 0805 models), also gives a relatively large CENER value at L of 19.6×10^3 MPa m⁻³.

	Position L average	Position R average
$\Delta\epsilon_{11}^*$ (%)	0.25	0.06
$\Delta\epsilon_{22}^*$ (%)	0.58	0.37
$\Delta\epsilon_{12}^*$ (%)	0.15	1.72
CENER* ($\times 10^3$ MPa m ⁻³)	22.4	21.1

* averaged over 9 integration point within the element.

Table 8: Components of creep strain range at position L and R in the 2512 resistor. Note the large components of 1,1 and 2,2 strain in position L compared to position R.

In summary, the larger resistor results in a higher shear creep strain range and creep energy density in the solder at position R, i.e. at the end of the resistor. This is as expected since there will be a larger relative strain (i.e. movement arising from the differences in coefficients of thermal expansion) between the resistor and solder at this position. However, interpretation of the predictions for the solder at position L, adjacent to the termination is more complex. There is a large increase in the strain energy density on increasing resistor size but a decrease in the shear creep strain range. This apparent discrepancy in the two ways of assessing creep damage may be accounted for when including the tensile creep components ($\Delta\epsilon_{11}$ and $\Delta\epsilon_{22}$). This aspect is to be investigated further.

8 3D FINITE ELEMENT MODELLING

8. 0805 RESISTORS

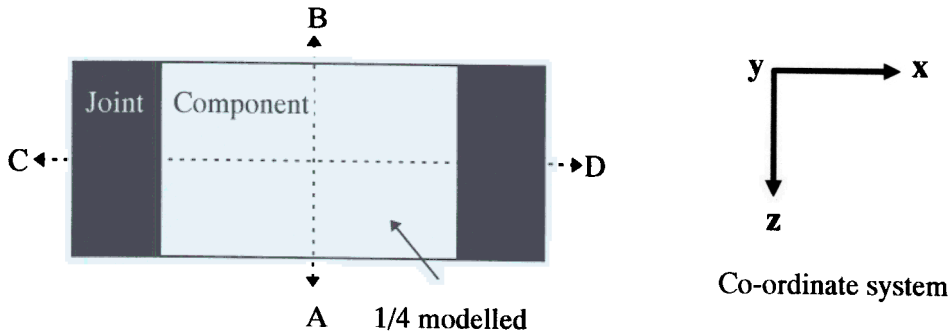


Figure 11 Symmetry of the 3D component and joint

Due to its symmetry, only a quarter of the component needs to be modelled, as shown in Figure 11. As with the 2D models, a thin layer of solder elements was added to the underside of the resistor in order to remove any misleading effects of mesh size. A coarser mesh had to be chosen, relative to the 2D models, in order to reduce the number of elements to a value which the ABAQUS software and workstation could deal with. The model was run for 5 thermal cycles, since the earlier results suggested that constant values for $\Delta\epsilon_{12}$ were then reached. It should be noted that the 2D models correspond to the middle section of the 3D model, shown by the line CD in Figure 11.

Figure 12 shows the distribution of creep damage† (CENER) after 5 thermal cycles. It can be seen that creep damage is concentrated in the front section, furthest away from the CD neutral axis (middle section), of the joint component interface. The maximum value of the creep energy density, CENERmax, was found to be $2.29 \times 10^3 \text{ MPa m}^{-3}$. This is much larger than typical CENER values of $1.1 \times 10^3 \text{ MPa m}^{-3}$ predicted in the middle section. This can be explained in terms of both changed stress state on going from the middle section (plane strain) to the front section (plane stress) and also due to the change in relative movement in the z direction due to thermal expansion mismatch i.e. in the middle section there is zero relative movement in z compared to the front (and back) sections where movement is greatest. Contributions from differences in stress state and expansion in z could be distinguished by comparing two 2D models run under plane stress (very thin section) and plane strain (very thick section) conditions, this will be considered in future work.

† Only creep energy density values, CENER, were used as measures of creep damage in the 3D modelling work since analysis and interpretation of all the individual shear and tensile components in 3D would have been very difficult.

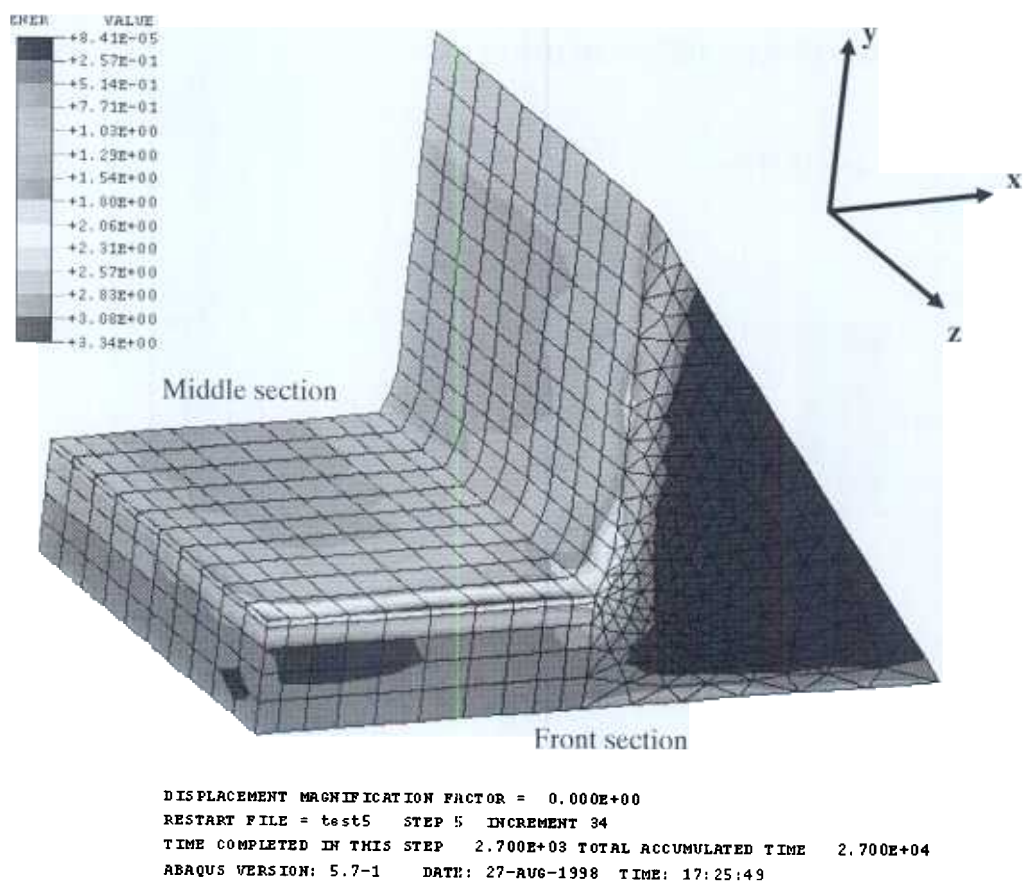


Figure 12 Distribution of creep energy density CENER ($\times 10^3$ MPa m⁻³) after 5 thermal cycles.

8.2 COMPARISON OF 2D AND 3D MODELS

Only the middle section (CD in Figure 11) of the assembly can be compared in both 2D and 3D. In order to make a fair comparison of the 3D and 2D results, the 2D model was re-meshed with an identical mesh size to the 3D model in the middle section. Figures 13 & 14 show the creep damage (CENER) after 5 thermal cycles for positions L, R and T in the middle section of the 3D and 2D models. It can be seen that there is reasonable agreement between the two models; both show concentrations of creep damage at the positions L, R and T. The values of creep damage are given in Table 9.

Position	3D	2D
L	1.10	1.13
R	1.06	1.37
T	1.22	1.35

Table 9 Creep energy densities CENER ($\times 10^3$ MPa m⁻³), at positions L, R and T in the middle section for the 3D and 2D models after 5 thermal cycles.

However, although there is agreement between the 2D and 3D models, the 2D models can only give information regarding the central section of the package. Figure 12 clearly shows that maximum creep damage is concentrated in the front section of the joint. Hence the usefulness of the 2D models maybe somewhat limited since they cannot predict such values. However, if the relative magnitudes of strain remain approximately equivalent in the 2D and 3D models, the advantages of the 2D models is the ease of setting up and faster computation. This will be investigated in future work.

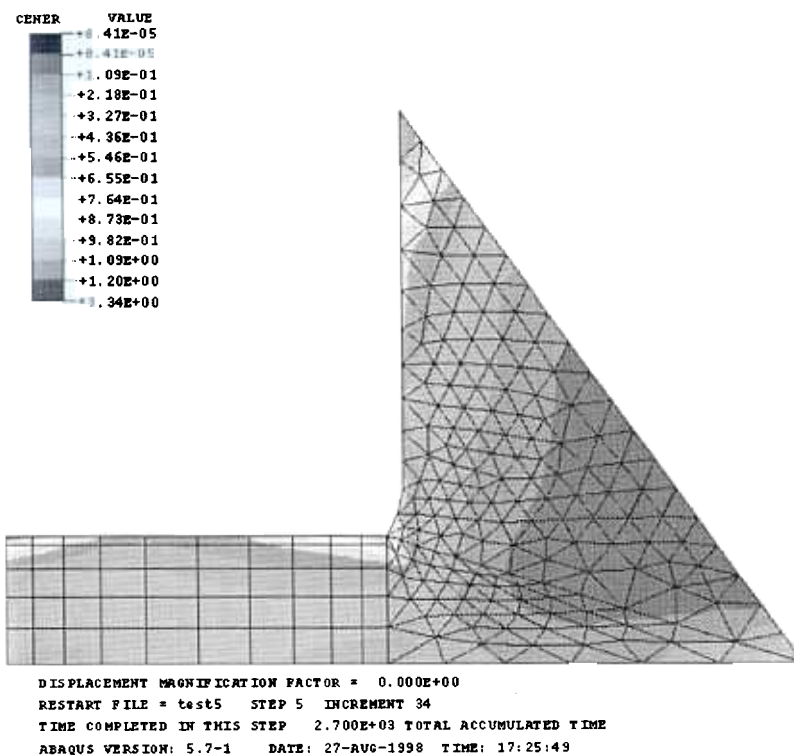


Figure 13: Distribution of creep damage, CENER ($\times 10^3$ MPa m⁻³), in the 3D model in middle section. The minimum and maximum contours have been adjusted from Figure 12 to allow comparison with the 2D model.

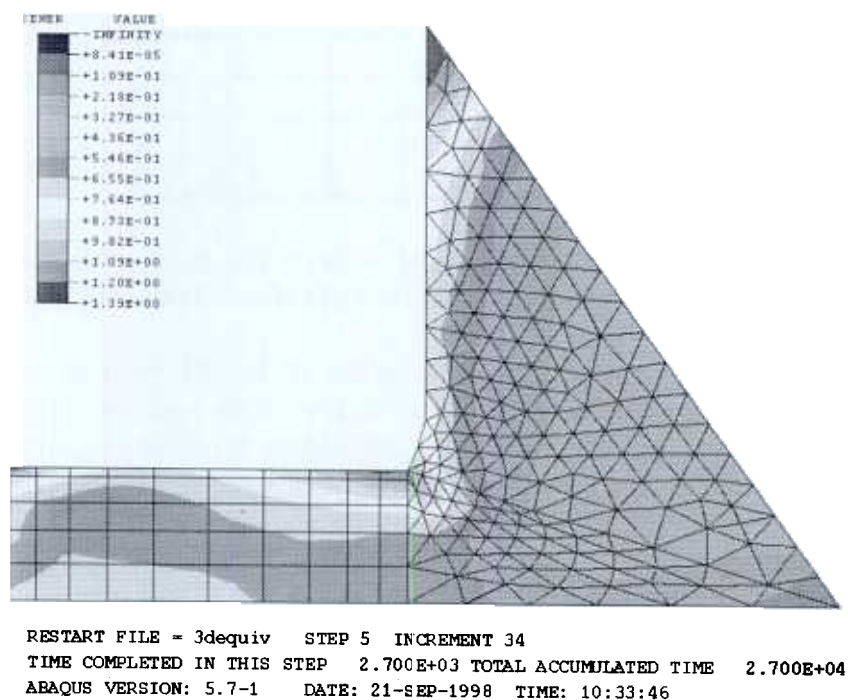


Figure 14: Distribution of creep damage, CENER ($\times 10^3 \text{ MPa m}^{-3}$), in the 2D model.

8.3 2512 RESISTORS

A 3D model of the larger resistor and joint was completed. In the initial trial, the pad width was chosen to be identical to the component width; this is equivalent to design D. Figure 15 shows that the maximum creep damage occurs in the same position as was found in the 0805 resistors, namely along the outside edge of the resistor/joint interface (front section). The maximum creep damage $CENER_{max}$, was found to be significantly greater than in the smaller 0805 resistor, i.e. $3.45 \times 10^3 \text{ MPa m}^{-3}$ compared with $2.29 \times 10^3 \text{ MPa m}^{-3}$. Therefore it would be predicted that the lifetime of the larger 2512 resistor would be significantly shorter than the smaller 0805 resistor.

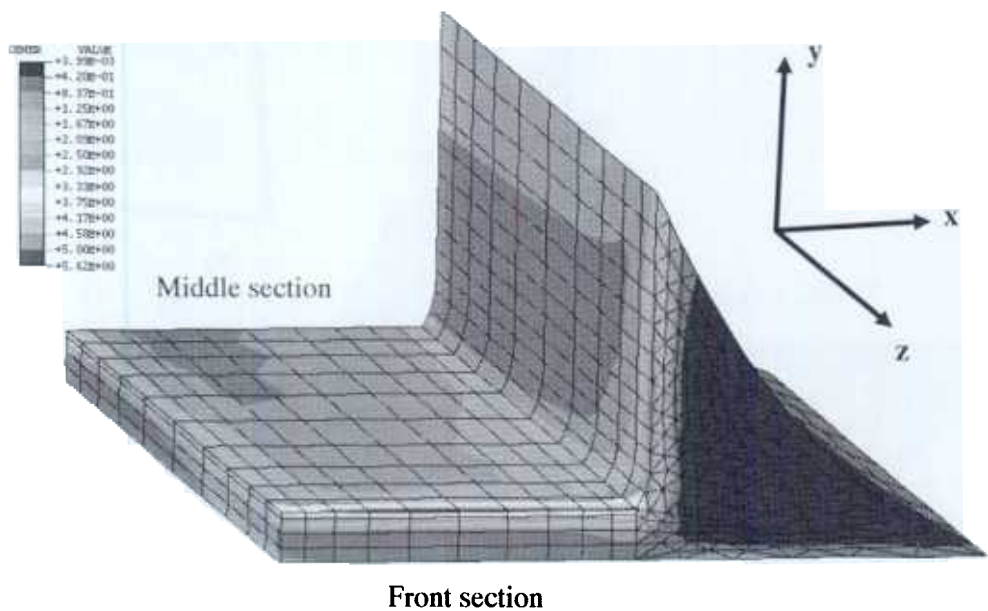


Figure 15: 2512 resistor, design D. Distribution of CENER ($\times 10^3 \text{ MPa m}^{-3}$) after 5 thermal cycles.

A second 3D model was completed where the width of the pad was smaller than the resistor width. This corresponds to design G. The profile shape was taken from profile measurements supplied by NPL. The FE modelling resulted in a creep distribution qualitatively similar to design D. However $\text{CENER}_{\text{max}}$ was larger than for design D, i.e. 3.93×10^3 compared with $3.45 \times 10^3 \text{ MPa m}^{-3}$; thus the lifetime of a design G joint would be predicted to be smaller than a design D joint. This may be because as the pad width, and hence solder, in the z direction is decreased, the movements of the board and resistor are less constrained leading to great damage in the solder. To confirm this, additional 3D models with a range of pad widths will be modelled in future work.

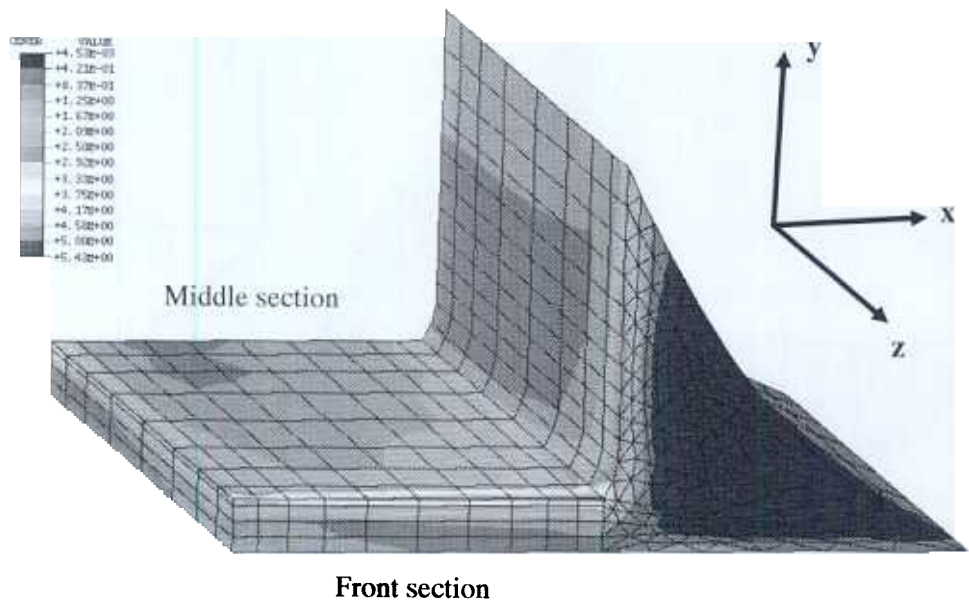


Figure 16: 2512 resistor, design G. Distribution of CENER ($\times 10^3 \text{ MPa m}^{-3}$) after 5 thermal cycles.

9 SUMMARY OF RESULTS (AS PAGE 1)

Finite element (FE) analysis has been used to predict the creep damage occurring during thermal cycling in two surface mount components, namely 0805 and 2512 resistors mounted on an FR4 board.

Initially, a number of simple 2D FE models of both sizes of resistors were considered in order to investigate the effect of the solder joint dimensions on the creep damage. It was found that the profile of the solder at the end of the resistor has a very significant effect on the predicted creep damage. Solder joints which had a large 'effective thickness' of solder at the end of the resistor resulted in smaller amounts of creep damage than joints with a thinner thickness of solder at the resistor end.

The larger 2512 resistors were predicted to generate higher magnitudes of creep damage compared to the smaller 0805 resistors. This is expected since the additional resistor length will result in a larger relative movement between resistor and solder at the ends of the resistor. Therefore, the service lifetimes of the 2512 resistors would be expected to be significantly shorter for given service conditions than those for the 0805 resistors.

3D FE models were generated for both resistors. As with the 2D work, it was predicted that more creep damage would be generated in the 2512 resistors than the smaller 0805 resistors. However, for each resistor, maximum creep damage was located in the outer surface plane of the solder; this plane cannot be modelled in 2D. This indicates that 2D modelling alone may not be sufficient to predict the precise magnitude of creep damage arising from thermal cycling, although relative measurements may be reasonable.

10 FURTHER WORK

- (i) Investigate the origin of the large tensile creep strain range components (1,1 and 2,2) at position L in the larger 2512 resistor.
- (ii) Compare 2D finite element models run under plane stress and plane strain conditions in order to clarify reasons for differences in creep damage between the middle and front sections in the 3D models
- (iii) Generate additional 3D models to systematically investigate the role of the joint geometrical variables (a-f). The trends found in the 3D models will then be compared to those found in the 2D work in order to determine the validity of the 2D models.
- (iv) Investigate in more detail the effect of pad width and length (Figure 2 design A-G); this cannot be investigated using 2D models alone.
- (v) Correlate the modelling results from (iv) with the experimental lifing results from NPL.
- (vi) Predict lifetimes using the lifing equations (see Section 3) with appropriate constants.

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APPENDIX I

Effect of FE mesh size

Four 2D meshes, based on the standard geometry (0805 resistor), were created with each mesh having a different element size and density in the region where the maximum strain range was observed. Each mesh was run for a number of thermal cycles until a constant strain range value was predicted. Figure 17 gives the predicted maximum creep strain range as a function of the finite element area $\dagger$.

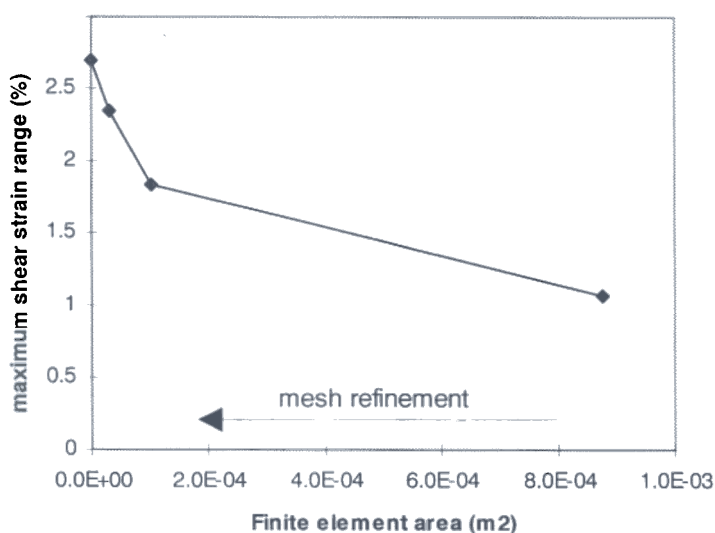
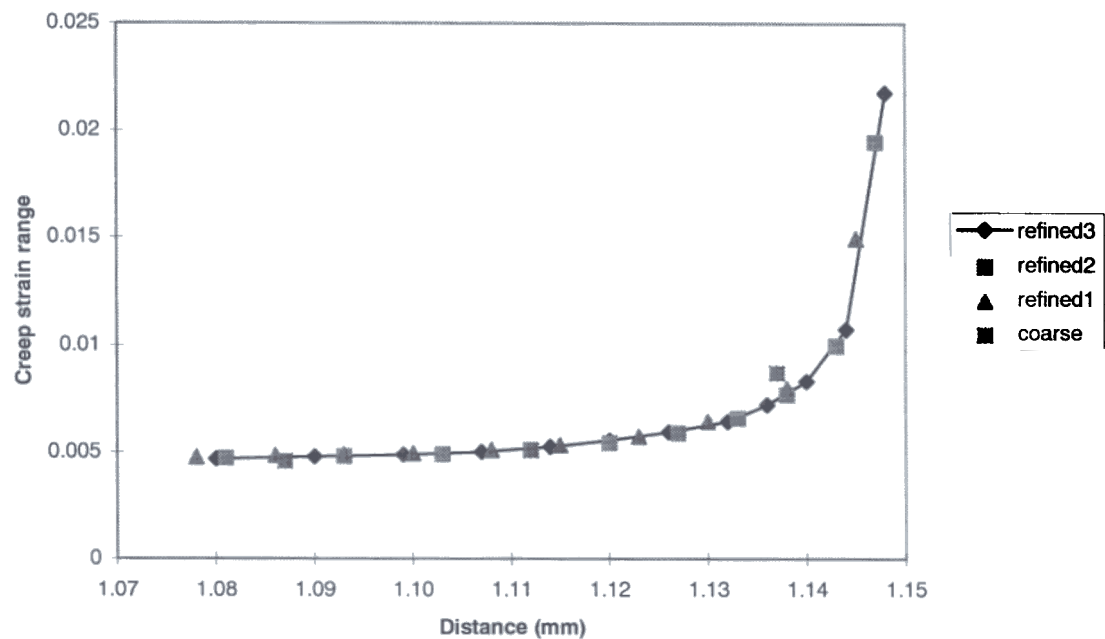


Figure 17: $\Delta\gamma_{\max}$ as a function of finite element area.

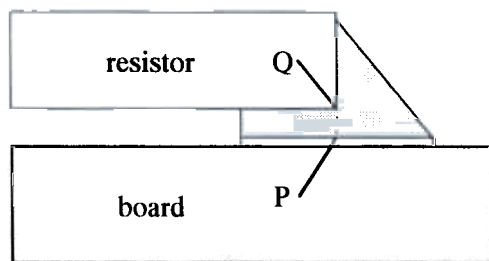
It can be seen that the predicted creep strain range increases rapidly as the mesh is refined. The reason for this behaviour is better illustrated by considering Figure 18a where the creep strain range is plotted along the line PQ as defined in Figure 18b. Each point plotted corresponds to the creep strain range averaged over a finite element, so in the most refined mesh there are many more elements along PQ, hence data points, than for the coarse mesh. It can be seen that on moving from P to Q, the creep strain range increases in an exponential manner. Therefore as the mesh is refined and the element area gets smaller, the calculated creep strain range in the element next to Q will naturally increase since averaging is taken over a much smaller area.

It can also be seen that the data points from the three most refined meshes lie approximately on the same curve as drawn, i.e. these FE models have converged to produce the same results away from Q. However, due to the singularity at Q, the measured creep strain range at this element will be dependent on the mesh size.

$\dagger$ The strain range was calculated by averaging over all integration points in a single element.



(a)



(b)

Figure 18: Creep strain range along the line PQ as a function of mesh size. Note that the points from the three refined meshes lie on a single curve.

To eliminate the effect of the singularity at Q, a thin layer of elements was added to the mesh at the underside of the resistor. The distribution and size of these elements was kept constant in all the models. Hence, any effect of the mesh size at the interface between the solder and the resistor was eliminated.