

**Project PAJex1
Report No 3**

**Analysis of Joint Tests
on an Epoxy Adhesive**

G Dean and L Crocker

July 2001

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ISSN 1473 2734

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SUMMARY

The results of studies of deformation and failure of lap-joint and scarf-joint specimens are reported. The location in the lap joint at which failure initiates has been traced to a region of the bond interface near the end of each adherend. Finite element analyses of the specimen with the adhesive progressively detached from the adherend in this region show that these cracks significantly reduce the load bearing capability of the joint. This explains the departure of measured and predicted force/extension curves for the specimen described in previous reports where no account of premature cracking had been included in the predictions.

A strain-based failure criterion, proposed in earlier work, is seen to be broadly consistent with the onset of failure in the lap-joint specimen. However, calculated strains in a scarf-joint specimen at failure are substantially above those at which failure is predicted by this criterion. The calculated strain levels and distribution are however shown to be sensitive to the model used to describe deformation in the adhesive.

An alternative failure criterion is explored based on a critical level and state of stress at the interface with the adherends. A proper evaluation of any failure criterion is not possible without accurate predictions of stresses and strains in the region of failure initiation. The accuracy of analyses using available materials models in finite element systems is uncertain and these studies should therefore be continued when the new cavitation model has been successfully implemented in ABAQUS.

1 BACKGROUND TO JOINT TESTS ON ADHESIVES

Projects PAJ2 and PAJex1 have been concerned with the use of finite element analysis for predicting the performance of adhesive joints. As part of this work, tests and FE analyses have been carried out on joint test specimens of different geometry. The first geometry studied was a butt joint. Measurements of force/extension curves on butt-joints loaded in tension were compared with predictions using different elastic-plastic materials models in ABAQUS. The exponent Drucker-Prager model was seen to give significantly better predictions for this test than the linear Drucker-Prager or von Mises models. Since the stress state generated in the adhesive in this test is similar to that produced locally in the region of failure initiation in other joint geometries, then failure predictions based on critical levels of stress or strain are likely to be more accurate using the exponent Drucker-Prager model. The tests on butt joints were also analysed in conjunction with results from tensile tests on bulk specimens of the adhesive to explore possible failure criteria for the adhesive. A criterion based on a critical level and state of strain was proposed (1).

Studies of the deformation and failure of lap and scarf joints have been made to establish the validity of this failure criterion for predicting failure in different joint geometries. The studies on lap joints were also aimed at assessing the capability of FE analysis for predicting the deformation behaviour of bonded joints over a range of loading speeds including impact. Early work (2) on the lap joints using a very tough, experimental adhesive formulated by Ciba Ltd revealed significant differences between measured and predicted force/deflection curves which were observed over a range of testing speeds. This discrepancy was considered to be due to differences between the structure, and hence properties, of bulk and joint specimens of the adhesive. This was feasible owing to the unusual structure of the toughening phase in this material. Studies on lap joints were repeated using another rubber-toughened epoxy supplied by Ford Ltd, and similar differences between measured and predicted behaviour were observed (3). In more recent work reported here, photographic evidence has been obtained of the onset and progression of localised failure of the adhesive during the test. This leads to a reduction in the load that the joint can sustain and an explanation for the observed departure of measurements from predictions. Attempts to simulate the failure process are

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described in section 3 of this report. To achieve this simulation without the visual evidence, a valid failure criterion is needed. The criterion proposed earlier (1) is evaluated through calculations of strain distributions at the onset of failure in lap joints (section 3) and scarf joints (section 4). A new criterion is explored in section 5.

2 RESULTS OF FAILURE TESTS ON LAP-JOINT SPECIMENS

Figure 1 shows a diagram of the lap-joint specimen. The radii on the adhesive fillet and the end of each adherend within the bond were included to avoid singularities in the stresses determined using finite element analysis. Figures 2a to 2e show photographs of the edge of the adhesive at time intervals during loading at an average strain rate in the adhesive of 0.003 s^{-1} . The various stages of crack initiation and growth are:

fig 2a, plastic deformation (stress whitening caused by cavitation of the rubber phase) near the region of strain concentration

fig 2b, crack initiation

fig 2c, crack growth around the radius edge of the adherend

fig 2d, crack emerges from the fillet

fig 2e, crack starts to propagate through the thickness of the adhesive layer.

Catastrophic failure follows soon afterwards. These states are correlated in figure 3 with locations on the measured curve of force against the extension of a 25 mm gauge length centred around the adhesive layer.

3 FINITE ELEMENT ANALYSES OF THE LAP-JOINT SPECIMEN

Finite element analyses of the lap joint in figure 1 were carried out in earlier work (3). Further analyses are reported here with the aim of assessing the validity of the proposed failure criterion (1) for predicting the onset of failure. This criterion invokes a critical level and state of strain in the adhesive at crack initiation, so strain contours were calculated in the adhesive at various stages in the loading of the specimen. From previous studies on butt-joint specimens (4), the exponent Drucker-Prager model is considered to give the most accurate predictions of strain. Until recently, this model has only been implemented in Abaqus with the standard solver and this solver was used for the analyses reported here. The accuracy of strain predictions is also considered to be higher if a dynamic analysis is undertaken with rate-dependent hardening data rather than a static analysis. This is because strain localisation, which is caused by enhanced softening of the adhesive in regions of high strain, is mitigated with rate-dependent data. This arises because the regions of high strain are also subjected to high strain rates which increase the yield stress and reduce the strain softening associated with rate independent yielding.

Owing to convergence problems with the standard solver it is not possible, however, to obtain solutions to the lap joint at large extensions using the exponent model with rate-dependent hardening. The analysis will only converge at small extensions that are below the onset of failure. Whilst solutions at large extensions can be obtained using the linear Drucker-Prager model with rate-dependent hardening and the explicit solver, these would take an inordinately long time using the fine mesh illustrated in figure 5. A coarser mesh could be used, but this would lead to larger uncertainties in calculated strains in the region of strain concentration. It was decided therefore to use a static analysis with the exponent model and the standard solver and to use a hardening curve derived at an “effective” strain rate. This “effective-rate” curve was derived using the function developed in earlier work (3) to model the hardening behaviour of the adhesive. The appropriate rate was selected such that the force/extension curve calculated using the single hardening curve at this rate with the linear Drucker-Prager model and the explicit solver was the same as the force/extension curve obtained using a full rate-dependent hardening analysis. A loading speed of 1 mm/s was chosen and the associated effective rate was 3.0 s^{-1} . The other parameters in the

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exponent model were derived from tensile and shear tests on bulk specimens as described in reference (3).

In order to simulate the effect that the crack in figure 2 and its subsequent growth will have on force/extension predictions, the adhesive has been progressively disconnected from the adherend starting at the location of peak strain and moving along the radius of the adherend into the fillet. This was achieved by defining separate, unconnected nodes in the adhesive and adherend along this interfacial region. The effect on predictions of force/extension curves for selected node disconnections is shown in figure 4. Here predictions are compared with the measured curve at the appropriate loading speed. The effect of the crack is seen to progressively reduce the load-bearing capability of the joint and bring predictions in close agreement with experiment. The agreement would presumably be even closer if some plastic deformation were allowed in the adherend by treating this as an elastic-plastic, rather than purely elastic, material. The decreasing load region of the measured curve is associated with crack propagation through the adhesive thickness and has not been simulated in the analysis.

Calculated contours of maximum and minimum principal strain in the adhesive are shown in figure 5 at an extension of 0.1 mm which is close to the region at which the crack is first evident in figure 2. The peak values of the maximum and minimum principal strains in the adhesive here are about 0.075 and -0.045 respectively. These give volumetric and deviatoric strains of 0.03 and 0.06 respectively. These strains lie close to the failure envelop derived in reference (1) from failure tests on bulk and butt-joint specimens and are therefore consistent with the failure criterion. For information, figure 6 shows strain distributions calculated using the linear Drucker-Prager and von Mises materials models and illustrates the sensitivity of predictions to the model chosen to describe materials behaviour. The same single hardening curve data were used as derived for the exponent Drucker-Prager calculations. Values for the other parameters are given in reference (3). It can be seen that the strain levels obtained using the von Mises model are similar to those calculated using the exponent Drucker-Prager criterion but this is coincidental and will not, in general, be the situation.

Figure 7 shows strain maps obtained at an extension of 0.1 mm when a specimen is loaded with 3 nodes disconnected at the bond interface in the region of maximum strain. These strain levels can not be considered quantitatively accurate because no attempt has been made to represent, in the mesh, the shape of the crack fronts. With reference to the strain values derived, the failure criterion is not able to explain why the crack moves towards the fillet before propagation into the thickness of the bond. In order to further evaluate the validity of the proposed failure criterion, measurements and analyses have been carried out on joints of an alternative geometry where stress and strain states at failure are likely to be different from the lap joint. A scarf joint was chosen for this purpose.

4 RESULTS OF FAILURE TESTS ON SCARF JOINTS

4.1 THE SCARF-JOINT GEOMETRY

Butt-joint and lap-joint specimens were chosen for failure studies in the adhesive because they demonstrate behaviour under widely different strain states. In the butt joint, the stress and strain states are predominantly volumetric whilst in the lap joint they are predominantly shear. (Despite this, it is recognised that failure will initiate in regions of stress or strain concentration where the stress and strain states are likely to be quite different). For the scarf-joint specimen, adherends were prepared with an angle of 65° between the bond face and the side of the adherend. This angle was chosen because it produces an average strain state in the adhesive that is composed of roughly equal proportions of volumetric and shear components. A diagram showing the dimensions of the scarf joint and the mesh used for finite element analyses is shown in figure 8. The ends of the adherends are curved with a 1.0 mm radius to remove singularities in the analysis.

Specimens were loaded in the same apparatus used to test butt-joint specimens (5). Split metal collars were manufactured to surround the rectangular section of the adherends to enable them to be rigidly clamped by the circular collets used to introduce load into the butt-joints. The load assembly was therefore very rigid and allowed negligible movement transverse to the load direction.

4.2 COMPARISONS OF PREDICTED AND MEASURED BEHAVIOUR

Some typical load extension curves are shown in figure 9 at a test speed of 0.03 mm/min. The extension refers to the displacement of a 25 mm gauge length centred around the bond line. A predicted curve is also shown using a single hardening curve determined from tensile data at a strain rate of 0.002 s^{-1} . The exponent Drucker-Prager model was again used for this prediction. Values for the model parameters were the same as those used for the lap-joint analyses described in section 3 and reference (3). Contours of maximum principal strain are shown in figure 10 calculated at extensions of 0.018 mm, 0.030 mm and 0.035 mm. These show the development of a localised zone of high strain that initiates close to the radius at the acute angle of the adherend, grows through the thickness of the adhesive and is finally concentrated along the opposing interface. At the extension of 0.035 mm, which is close to that at which joint failure occurs in figure 9, the maximum principal strain reaches a peak value of over 30%. Contours of minimum principal strain at this extension are shown in figure 11 and indicate that the strain state in this zone has a significant dilatational component which peaks at about 25%.

The strain levels within the zone far exceed the strain at which failure of the adhesive is expected from the failure criterion proposed in report (1). Figure 12 shows a photograph of the scarf joint at an extension of 0.035 mm which is just prior to failure. There are no visible signs of premature rupture nor of stress whitening in the zone of high strain. The latter observation is particularly difficult to explain since studies of cavitation promoted by the rubber particles in this adhesive (6) have shown that cavities, and hence stress whitening, should occur at volumetric strains of a few percent at most.

As a further illustration of the sensitivity of strain predictions to the materials model chosen to describe the adhesive, calculated distributions of maximum principal strain are shown in figure 13 at an extension of 0.035 mm using the von Mises and linear Drucker-Prager models. It is interesting to note that no plastic zone through the thickness of the joint is predicted with either of these models, and the regions of high strain at the interface are in slightly different locations from that in figure 10.

Two possible conclusions can be drawn from this work on scarf joints. Firstly, it may be that strain calculations are highly inaccurate using the exponent Drucker-Prager model with this joint geometry. The development of a new materials model has been described in (6) and shows that, although the exponent Drucker-Prager model is generally more accurate than other commonly used elastic-plastic models, there are nevertheless significant errors in the predictions of butt-joint behaviour in tension using this model. Furthermore, it has been emphasised in section 3 that for accurate strain predictions, a dynamic analysis with rate-dependent hardening should be used. Whilst these factors will influence the accuracy of strain predictions, it is unlikely that the error in the strain levels in figures 10 and 11 could be large enough to justify retaining the proposed failure criterion. We now therefore consider other possible criteria.

5 EXPLORATION OF A NEW FAILURE CRITERION

5.1 RESULTS ON SCARF JOINTS

Figure 14 shows a photograph of the joint in figure 12 taken after catastrophic failure. The location of crack initiation is not evident and further work is needed to identify it. It is possible that it has initiated in the plastic zone but, recalling that in the lap joint, the crack initiated at the interface with the adherend, it may be more probable that, in the scarf joint, the crack has initiated at the interface along the radius on the acute-angle corner of the adherend. This suggests that a failure criterion based on a critical state and magnitude of stress at an interface is worth exploring. This is supported by results from the lap joint that are reported in section 5.2.

Contours of the 3 components of principal stress in the scarf joint are shown in figure 15 at an extension of 0.036 mm. The stress has reached a maximum here and is constant at larger extensions. It is necessary to emphasise, as just explained in section 4.2, that although the exponent Drucker-Prager model is believed to be more accurate than other commonly used models, significant errors in predicted stress and strain levels may still be present. Until the new cavitation model has been successfully implemented in an FE system, the accuracy of stress predictions is

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uncertain. Despite this, it may be possible to draw some broad conclusions regarding criteria for failure.

It can be seen from figure 15 that, whilst the maximum principle stress is highest in the adhesive away from the radius, the hydrostatic stress (the mean of the 3 principal components) is highest in a local region at the interface around the radius. This region is consistent with the location of failure initiation proposed from figure 14.

5.2 STRESS PREDICTIONS IN THE LAP JOINT

Contours of the 3 components of principal stress in the lap-joint are shown in figure 16 calculated at an extension of 0.1 mm. The maximum principal stress peaks at the interface with the adherend but slightly further around the radius on the adherend than the location of the maximum principal strain in figure 5. The other components of principal stress reach their peak even further around the radius. This means that the maximum component of hydrostatic stress occurs on the interface slightly further into the fillet region than does the maximum tensile component of stress. Both of these locations are close to the point of crack initiation as shown in figure 17. With this joint specimen, greater emphasis was placed on surface preparation than with the joint in figure 2. The location of crack initiation is therefore more well-defined but still insufficiently precise to stipulate whether this is in the region of maximum tensile stress or hydrostatic stress.

5.3 STRESS ANALYSIS OF THE BUTT JOINT

The butt-joint test used for this work has been reported elsewhere (5). Some load/extension curves obtained with this test using the toughened epoxy being studied here are shown in figure 18. The loading speed was 0.03 mm/min. The extension here refers to the adhesive thickness of 0.5 mm since the deformation of the adherend has been subtracted by simple calculation. The mesh used for finite element calculations is shown in figure 19. The adherends are circular cylinders, and the figure shows the region of the adhesive close to its circumference. The mesh shows only half the adhesive

thickness. Use of a finer mesh gave problems with solution convergence at extensions above 0.01 mm.

The predicted force/extension curve at a mean strain rate of 0.002 s^{-1} is compared with experimental results in figure 18. As with the analyses of other joint geometries, the exponent Drucker-Prager materials model was used. A value for the parameter a in the model was chosen to give the best fit to the data. This was larger than the value used for the scarf and lap-joint analyses and again illustrates the limitation of the exponent Drucker-Prager model for describing the behaviour of toughened adhesives under different stress states. Contours of principal stress are shown in figure 19 at an extension of 0.029 mm. Except near the circumference of the adhesive layer, the stress state is uniform and the radial and circumferential components are nearly the same as the axial component. This means that the calculated stress state is almost pure hydrostatic. As explained in section 4.2, preliminary analyses using the new materials model (6) that includes the influence of cavitation on yielding indicate that this prediction is wrong and that the transverse stresses are typically half the axial component. This means that the hydrostatic component of stress is not as high as predicted using the exponent Drucker-Prager model and this conclusion presumably also applies to the other joint geometries. It is also worth noting that, in contrast to the predicted stress distribution in the scarf joint (figure 10), there is no indication of a zone of high strain established through the thickness of the adhesive. This may be real and result from the different stress distribution in the butt joint or it may indicate poor accuracy in the scarf joint calculations that leads to a false prediction of the zone of high strain.

6 CONCLUSIONS AND FURTHER WORK

Premature and localised failure at the interface with the adherend in the lap-joint specimens has been shown to be responsible for a reduced load-bearing capability of the specimens. This explains the observed departure of predicted load/extension curves, in the absence of a crack, and measured curves.

The predicted strain state in the adhesive near the location and at the extension where the crack is observed to initiate is broadly consistent with the failure criterion proposed in earlier work.

With the scarf-joint geometry studied here, there are no indications of premature failure either from observation of the joint surface or from comparisons of measured and predicted force/ extension curves. Prior to failure, finite element calculations predict large strains localised near a radius on the adherend. The strains predicted are significantly above the level at which failure is expected with the strain-based failure criterion proposed in earlier work. It can be concluded therefore that either the strain predictions are grossly in error or the failure criterion is invalid.

An alternative failure criterion has been explored based on a critical level and state of stress at the interface with an adherend. Whilst stress predictions using the exponent Drucker-Prager model are more realistic than those obtained with other models in ABAQUS, comparisons with some preliminary calculations using the new cavitation model reveal that stress predictions using the exponent model may be significantly inaccurate. It is therefore not possible, at this stage, to propose an alternative failure criterion.

In order to assist the development and evaluation of an alternative failure criterion, stress analyses should be carried out on the lap, scarf and butt joints using the new cavitation model when this has been successfully implemented in an FE system. In addition, further photographic studies are needed on the lap and scarf joints to identify the precise location of failure.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution to this work from Mr R Mera with the testing and photographic observation of some of the joints. The work was funded by the Department of Trade and Industry as part of the Performance of Adhesive Joints programme.

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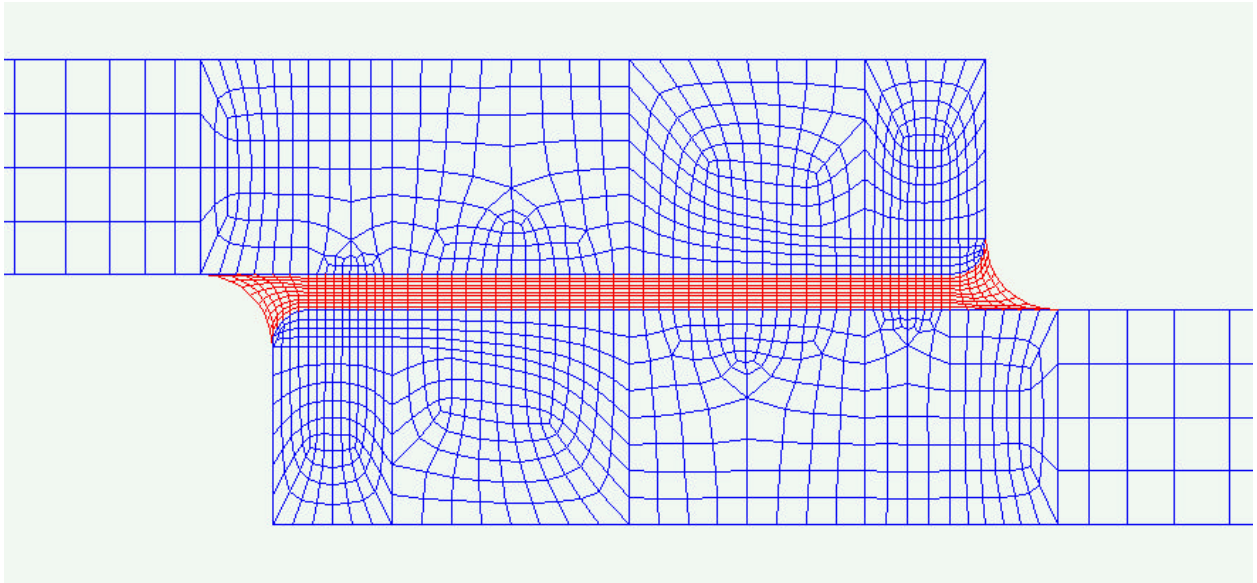
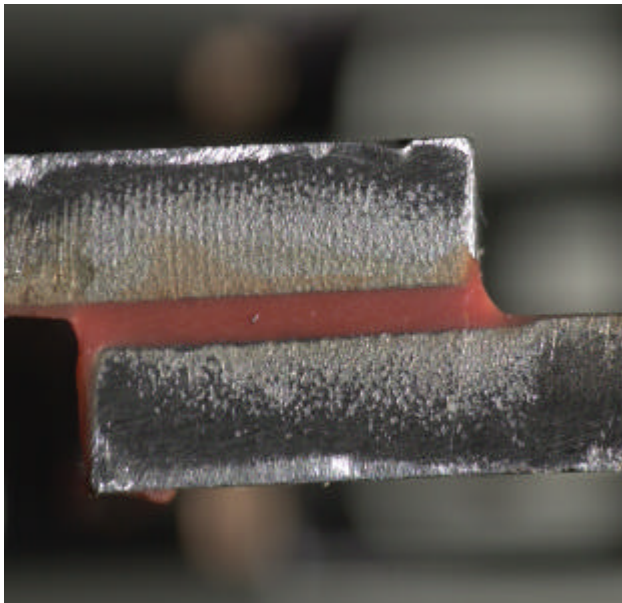
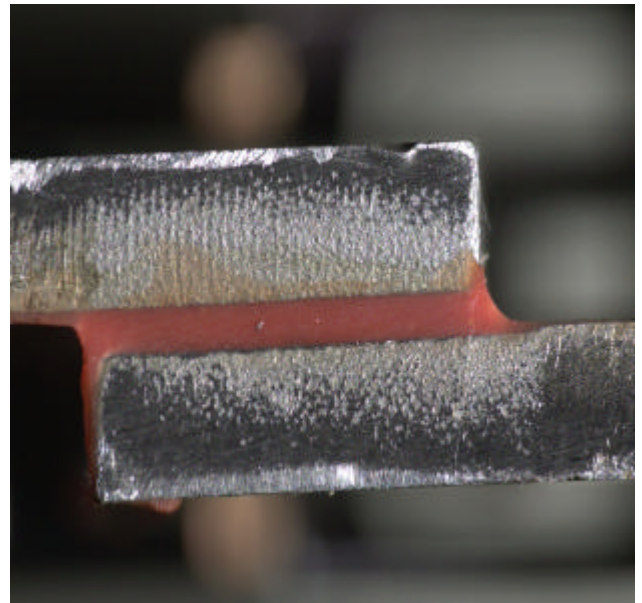


Figure 1. The lap-joint specimen showing a coarse mesh used in exploratory analyses only. The refined mesh is shown in figure 5.



2.1 Local plastic deformation



2.2 Crack initiation

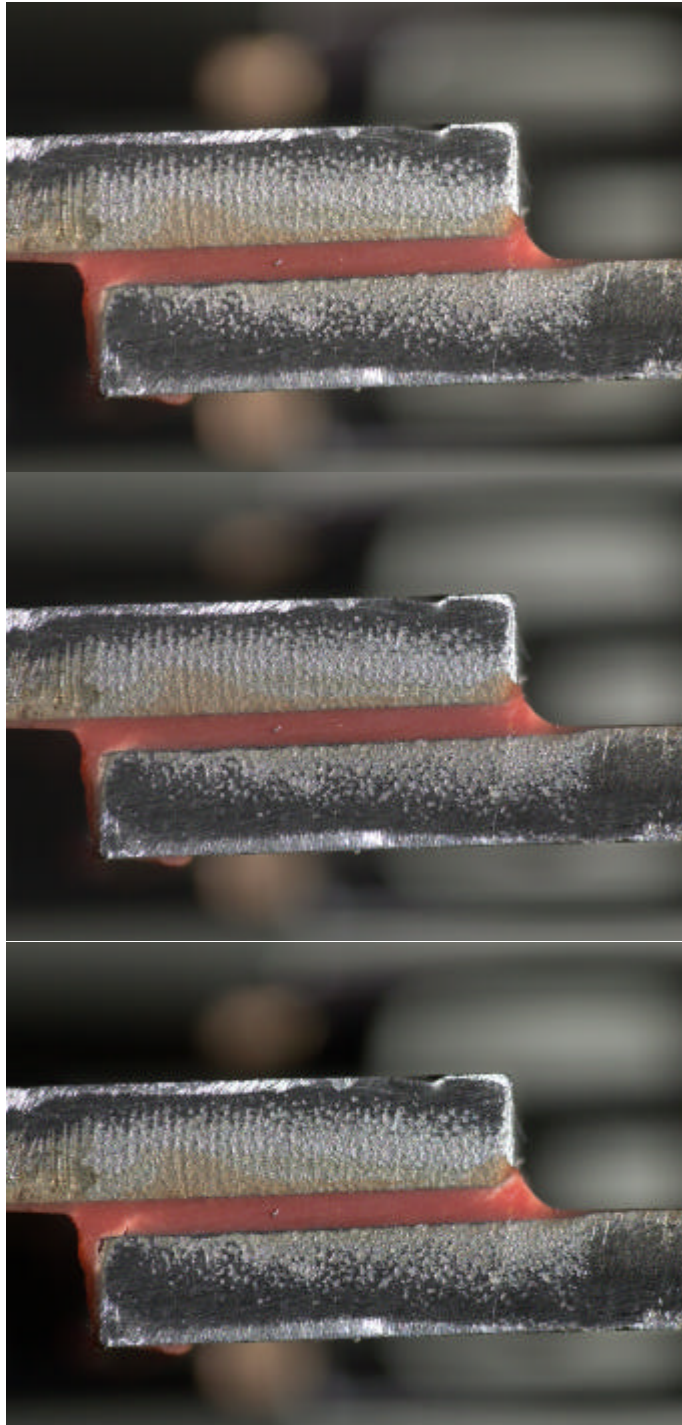


Figure 2. Sequence of photographs of the edge of a lap-joint specimen showing stages of failure before rupture.

- 2.3. Crack growth
- 2.4 Crack through fillet
- 2.5 Crack starts through thickness

Figure 2 cont. Sequence of photographs of the edge of a lap-joint specimen showing stages of failure before rupture.

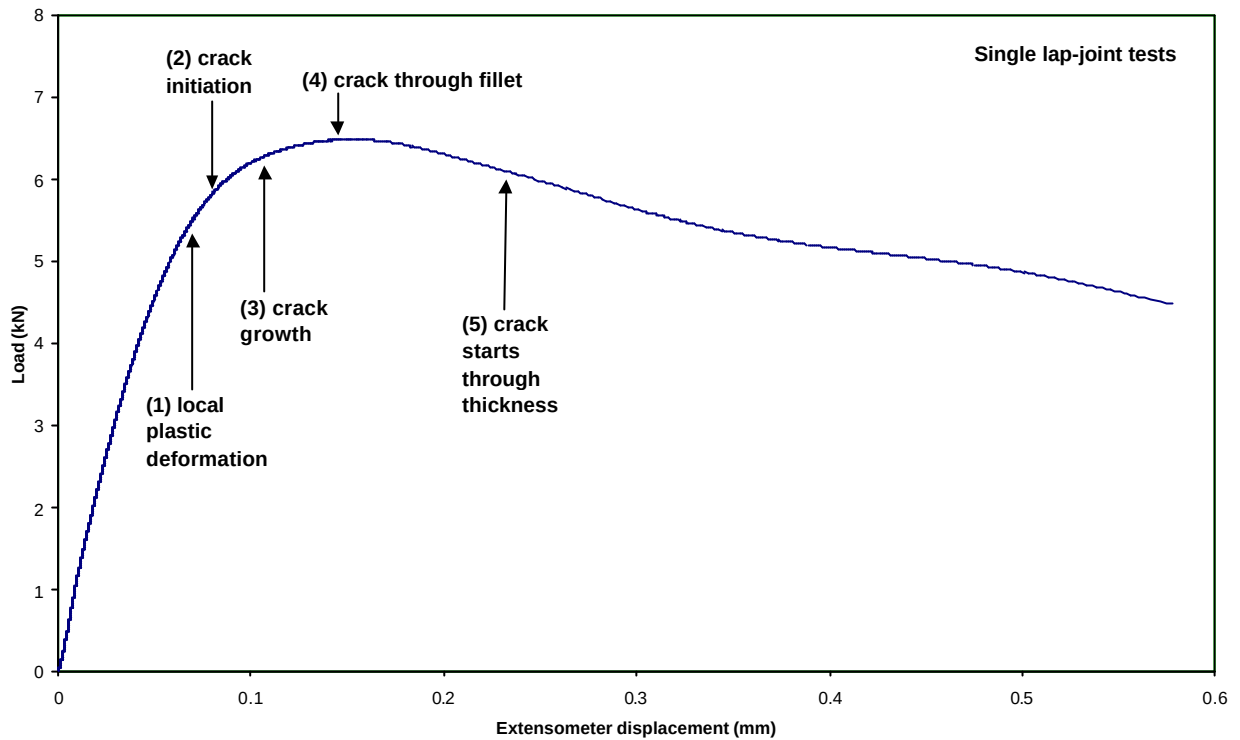


Figure 3. Locations on a force/extension curve at which the photographs in figure 2 were taken. Lap joint loading speed was 0.4 mm/min.

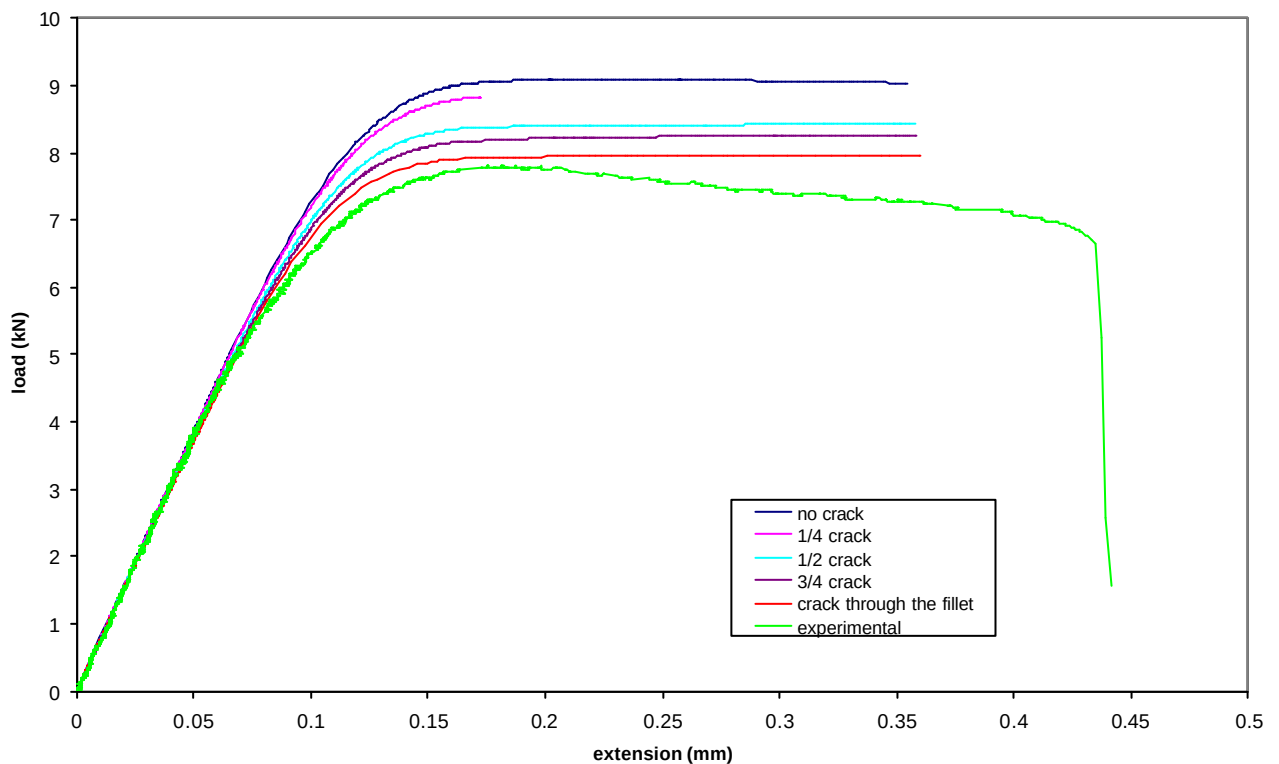


Figure 4. Comparison of a measured force/extension curve for a lap-joint specimen tested at 1 mm/sec with predicted curves for different lengths of an interfacial crack near the ends of the bond.

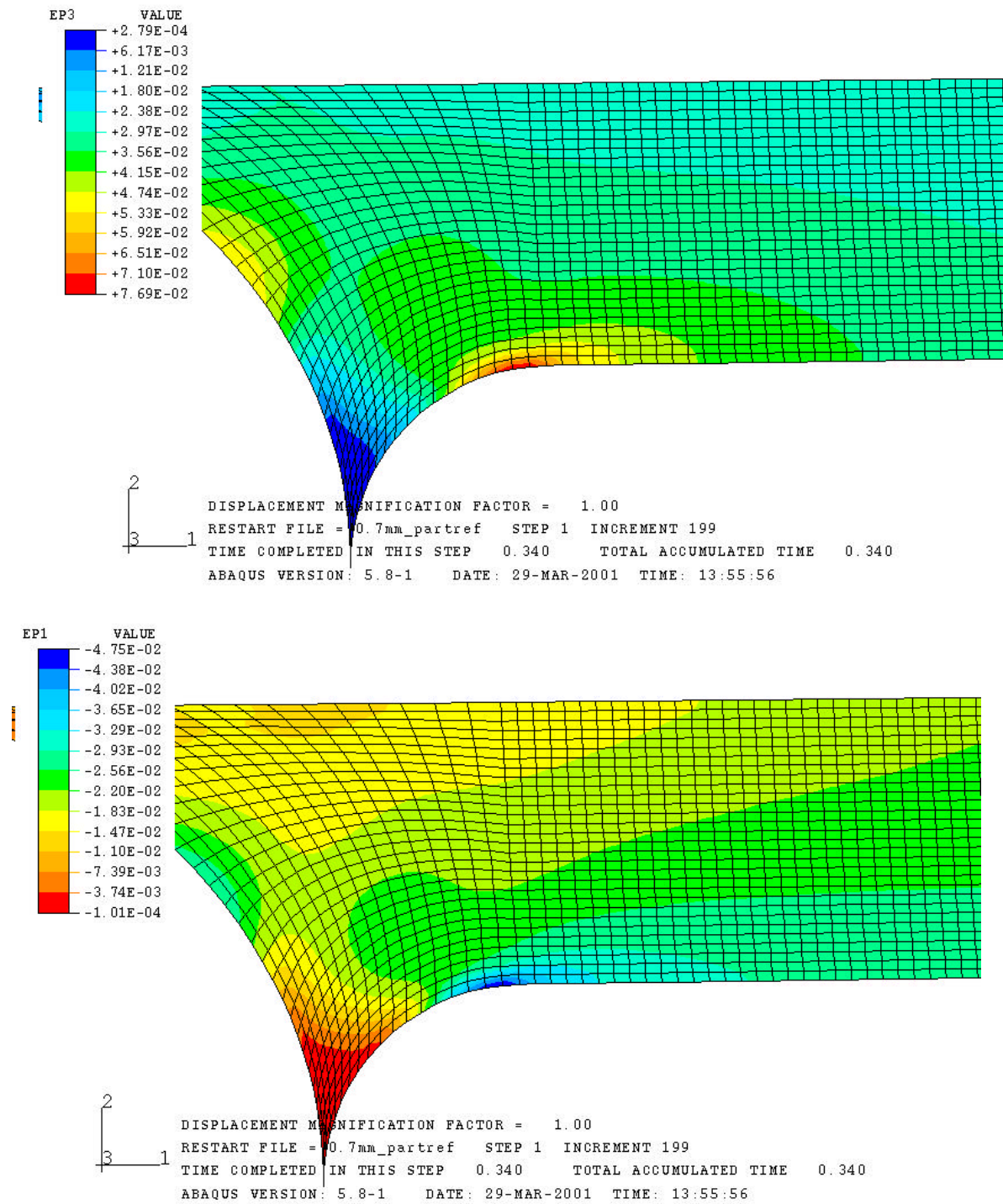
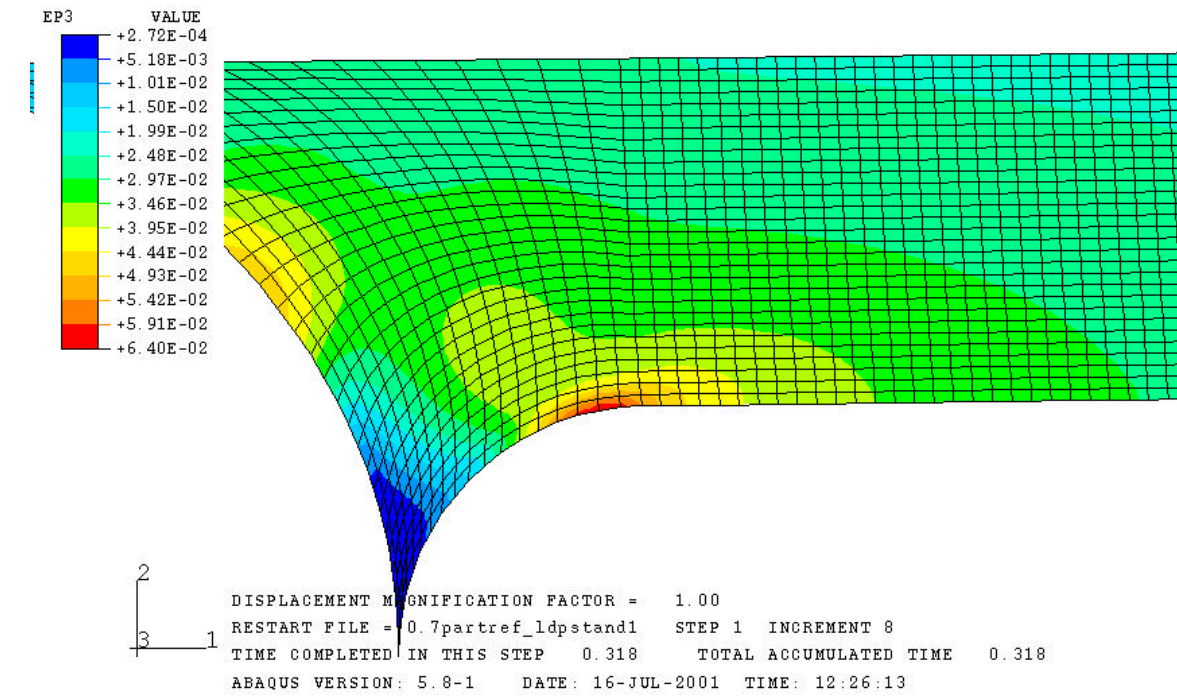
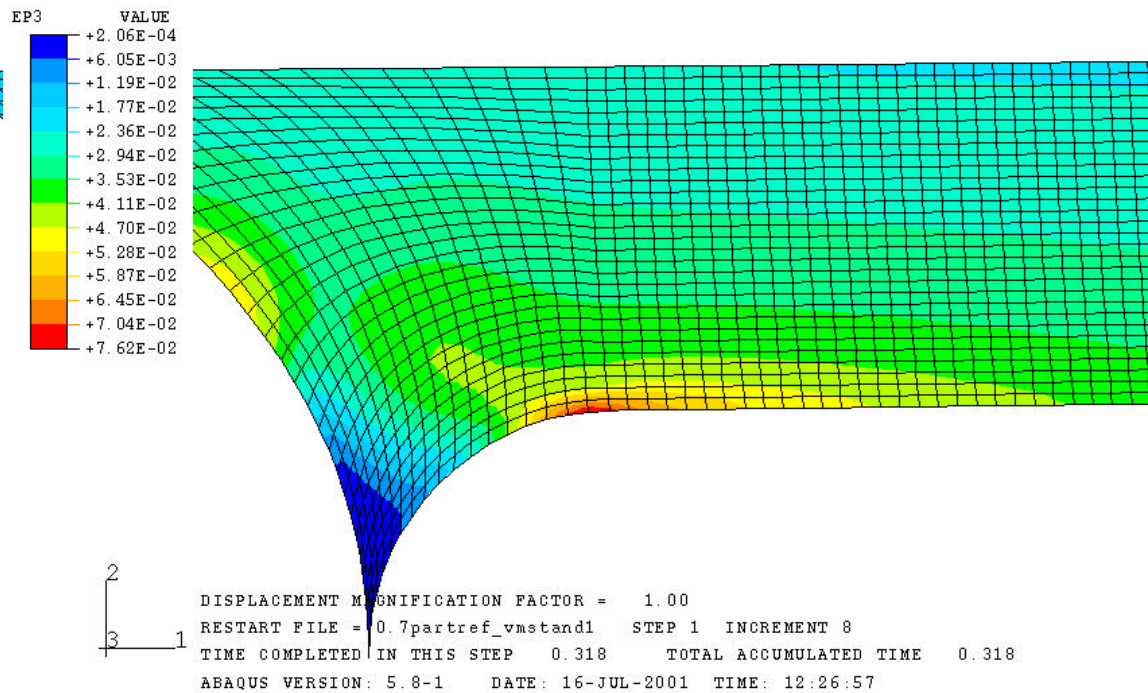


Figure 5. Predicted distributions of maximum and minimum principal strain in the lapjoint at an extension of 0.1 mm.



(a)



(b)

Figure 6. Predicted distributions of maximum principal strain in a lapjoint at an extension of 0.1 mm, using (a) Linear Drucker-Prager (b) von Mises analyses.

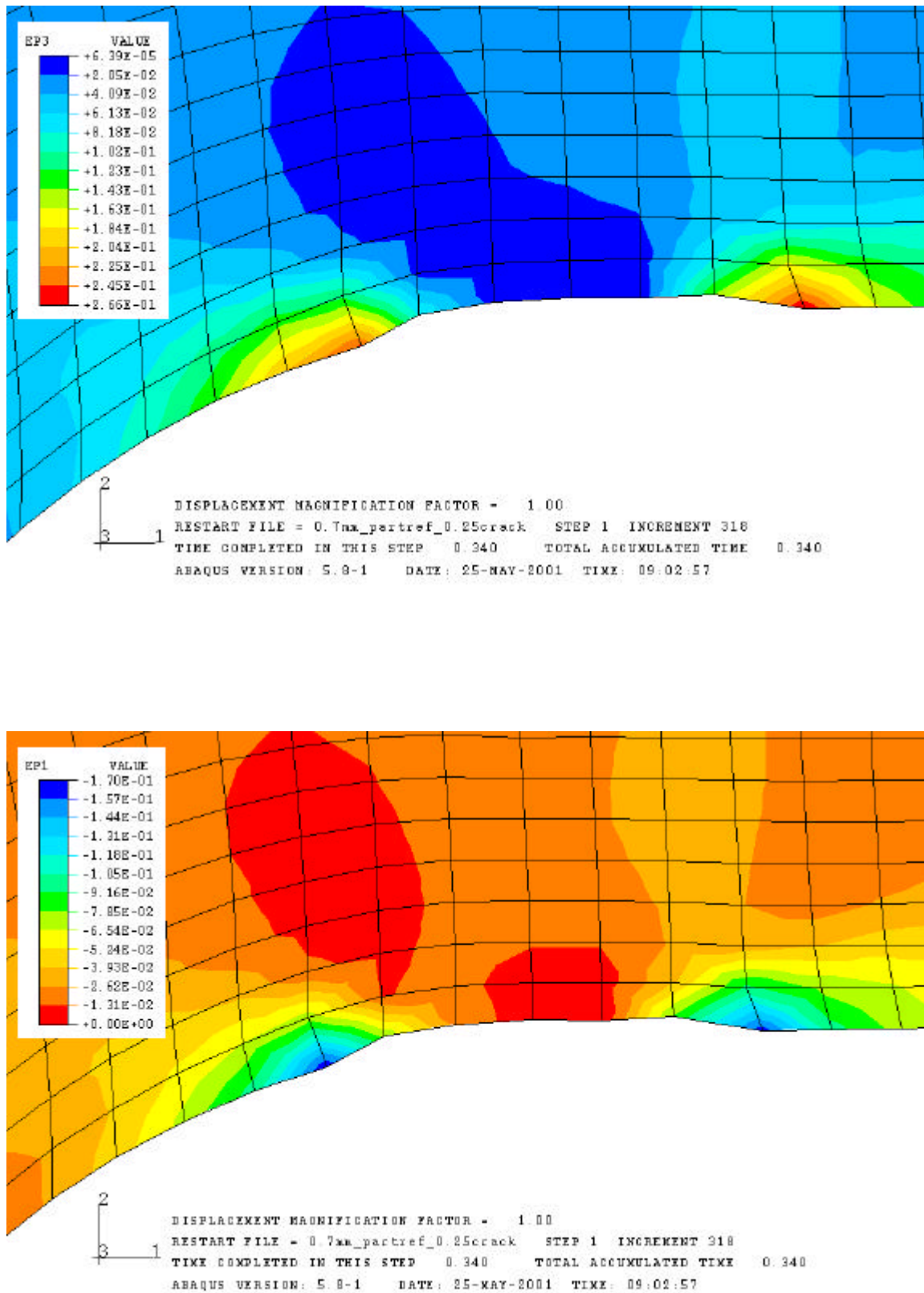


Figure 7. Distributions of maximum and minimum principal strain predicted at either end of a short interfacial crack in the lap joint (the $\frac{1}{4}$ length crack in figure 4).

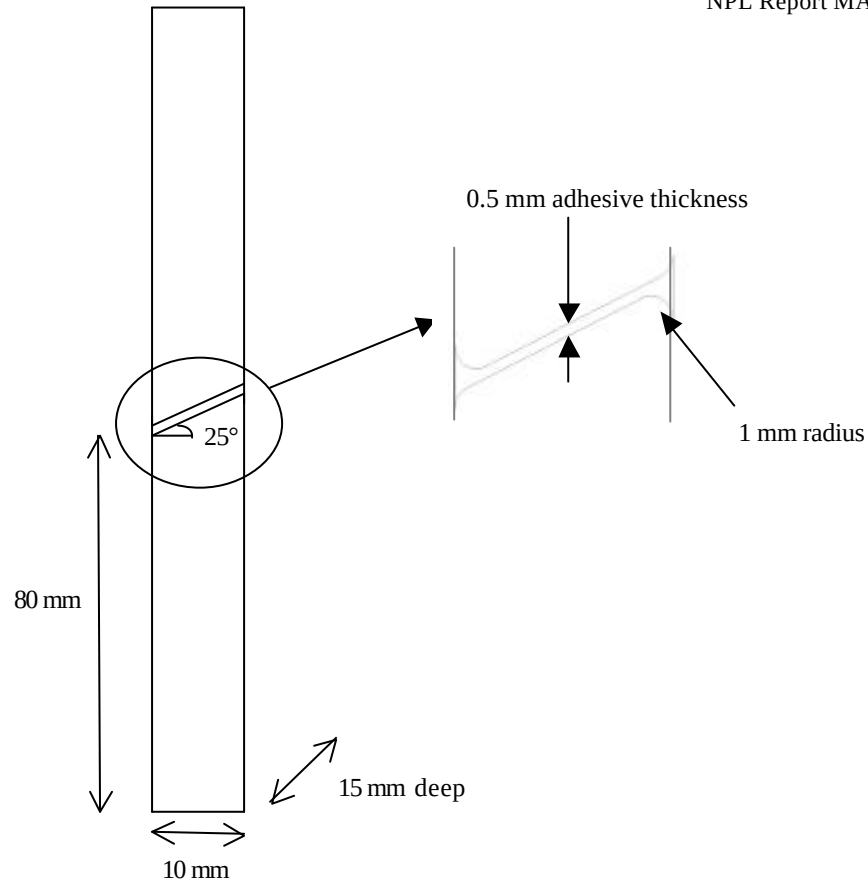


Figure 8. Schematic diagram of the scarf-joint specimen showing the dimensions and the geometry of the adherends.

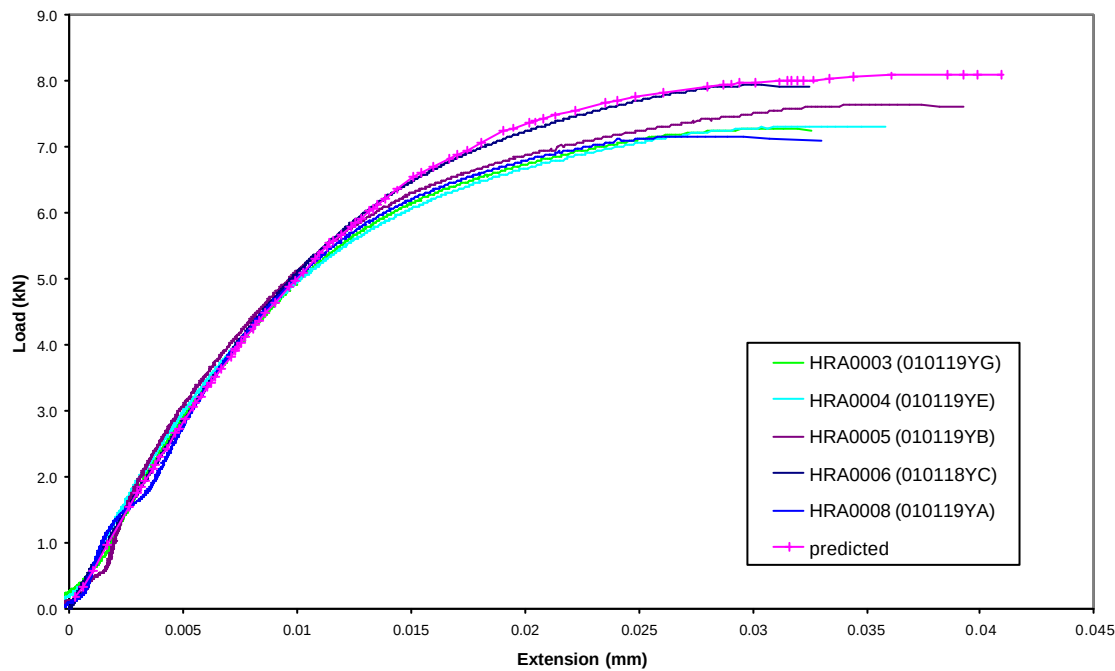


Figure 9. Comparison of the predicted load/extension curve for the scarf joint at a mean strain rate of 0.002s⁻¹ with some experimental curves measured at a test speed of 0.03 mm/min.

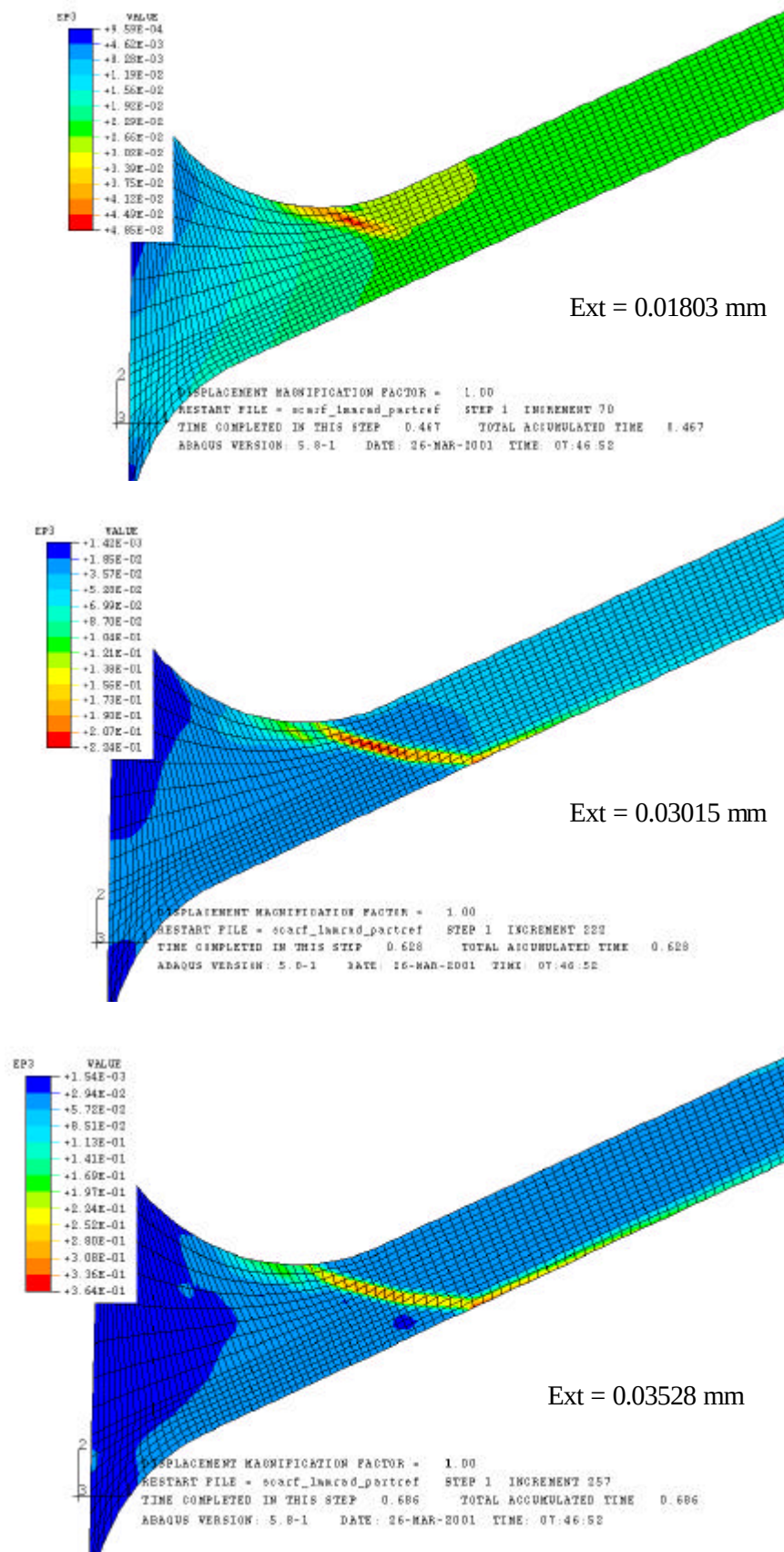


Figure 10. Contours of maximum principal strain in the scarf joint calculated at selected extensions prior to the measured extension at failure.

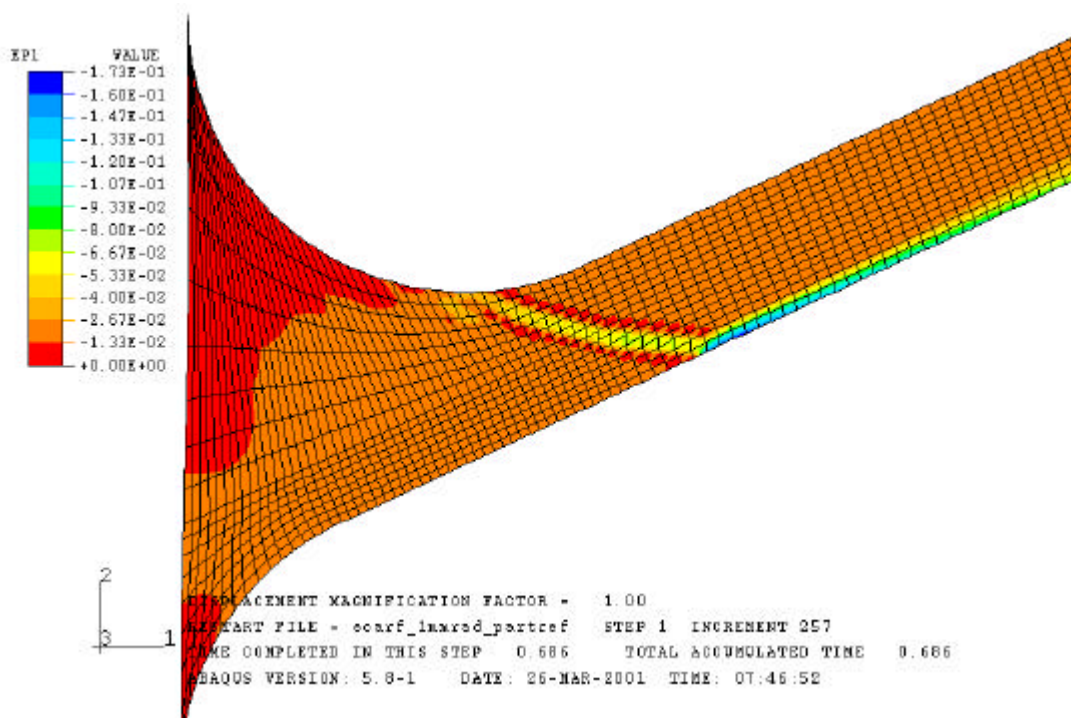


Figure 11. Contours of minimum principal strain in the scarf joint calculated at an extension of 0.035 mm.

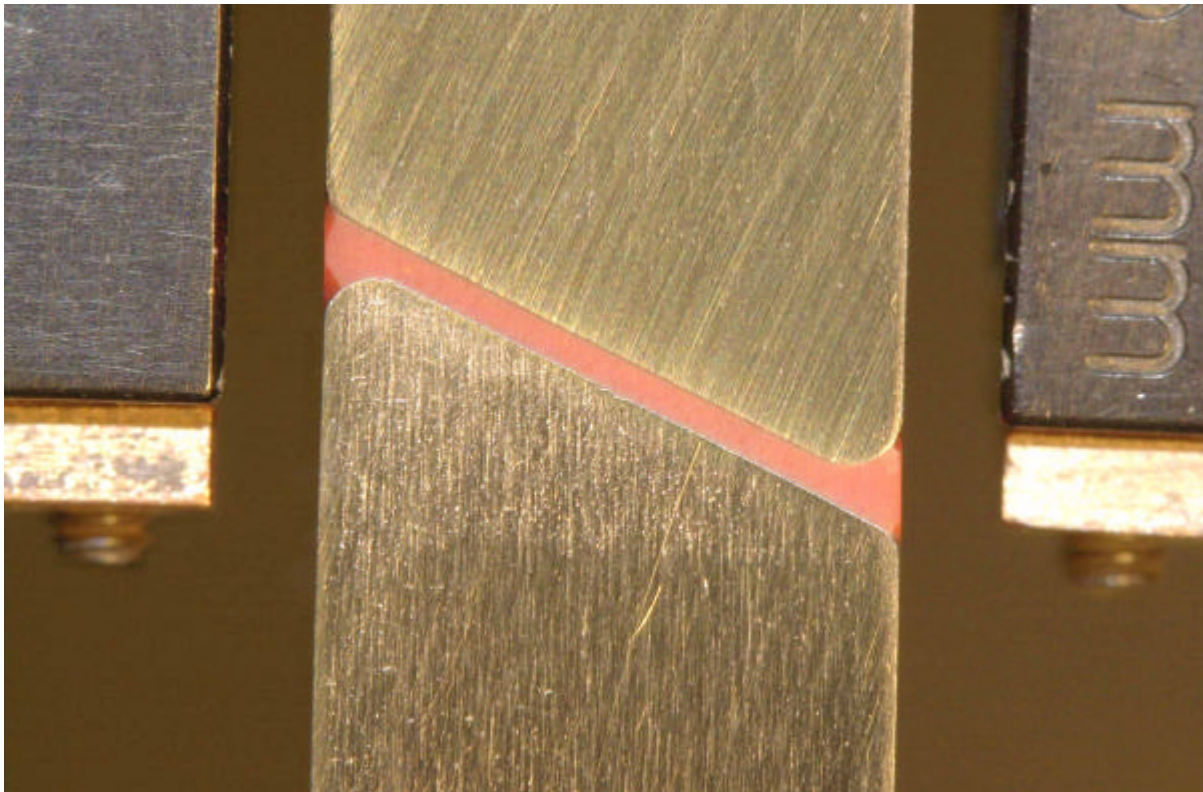


Figure 12 Photograph of the face of a scarf joint at an extension just prior to failure.

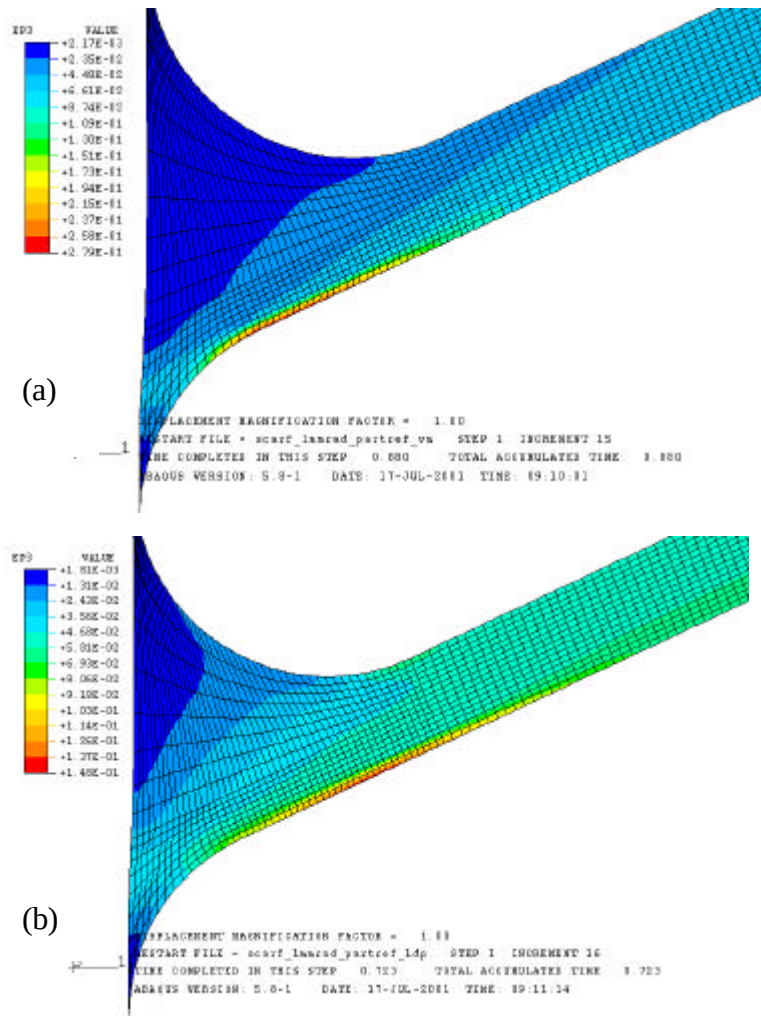


Figure 13. Contours of maximum principal strain in the scarf joint at an extension of 0.035 mm using (a) Linear Drucker-Prager and (b) von Mises analyses.

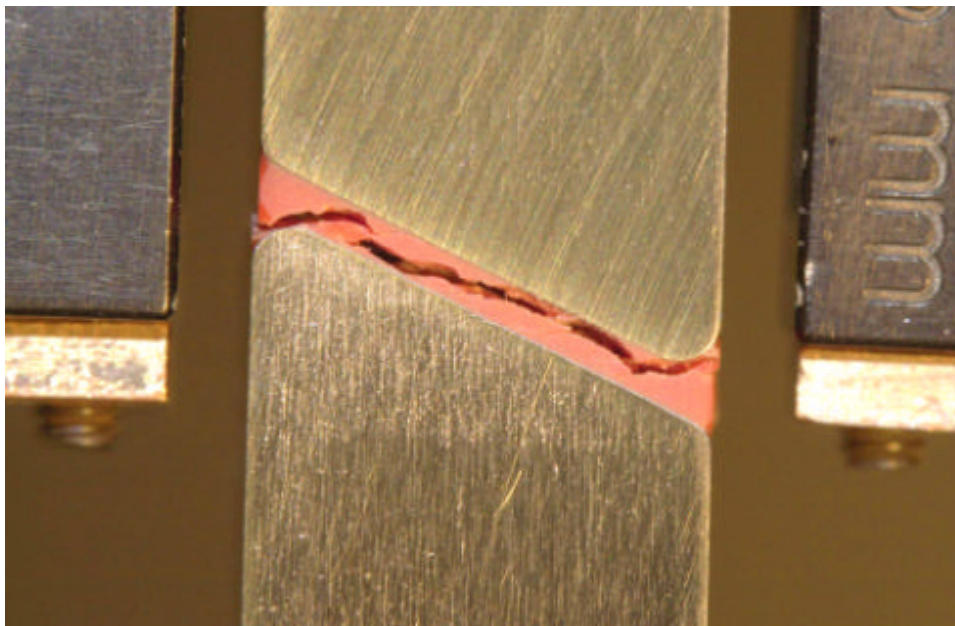


Figure 14. Photograph of the same joint as that shown in figure 12 after failure.

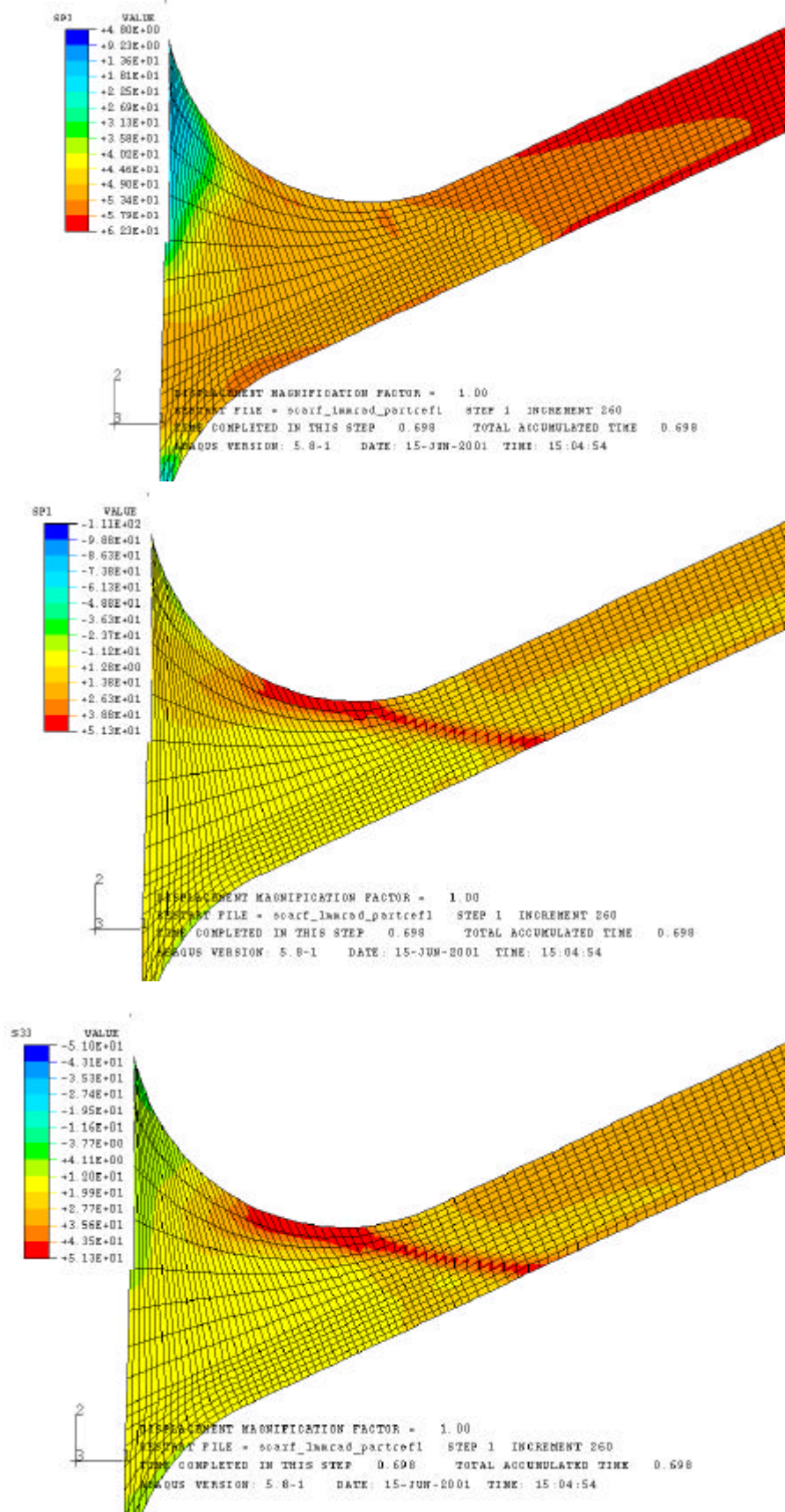


Figure 15. Contours of principal stress in the scarf joint at an extension of 0.036 mm.

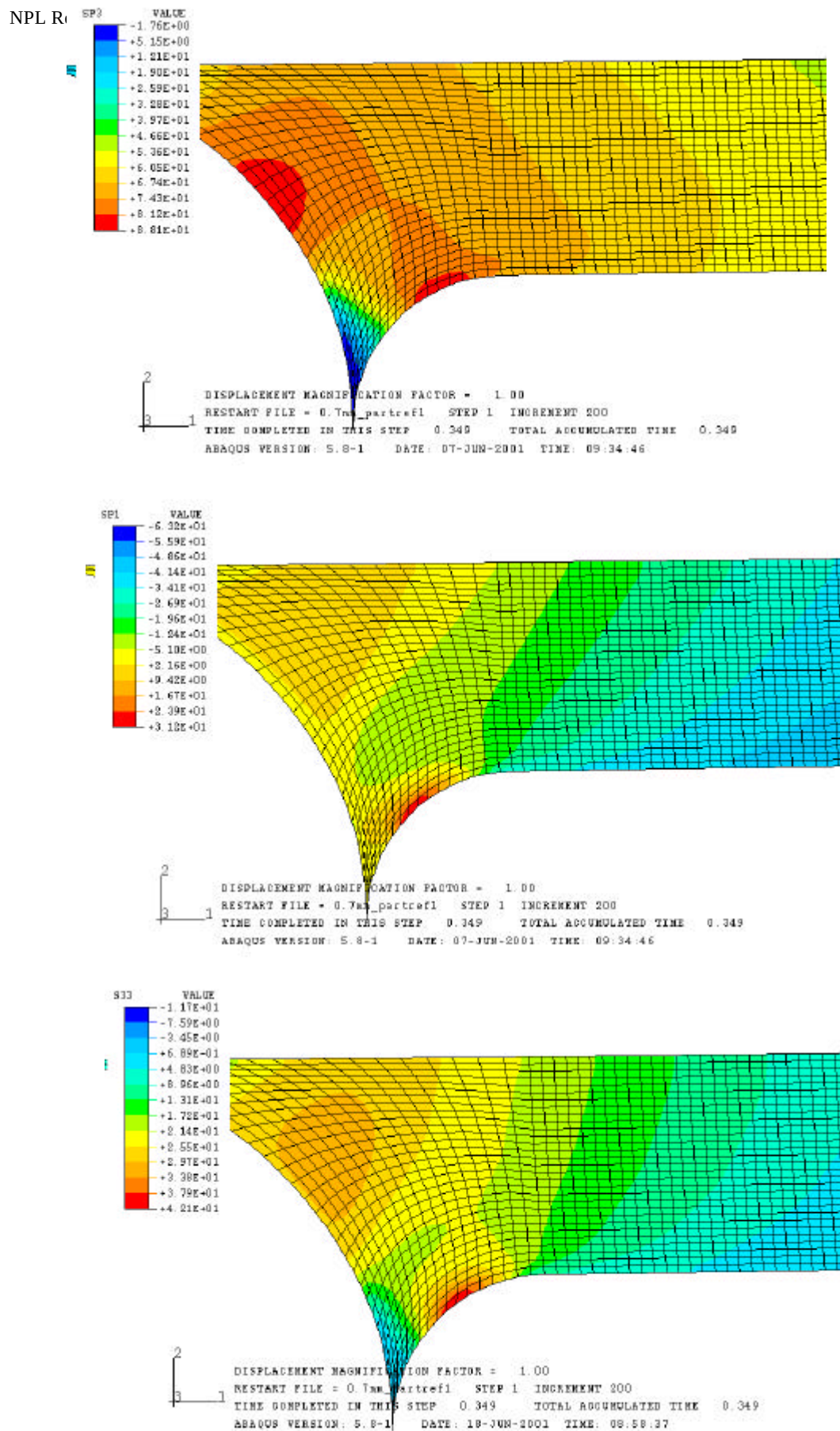


Figure 16. Contours of principal stress in the lap joint at an extension of 0.1 mm.



Figure 17. Photograph of a lap-joint specimen, after careful preparation of the side face, showing the interface crack prior to propagation through the thickness of the adhesive.

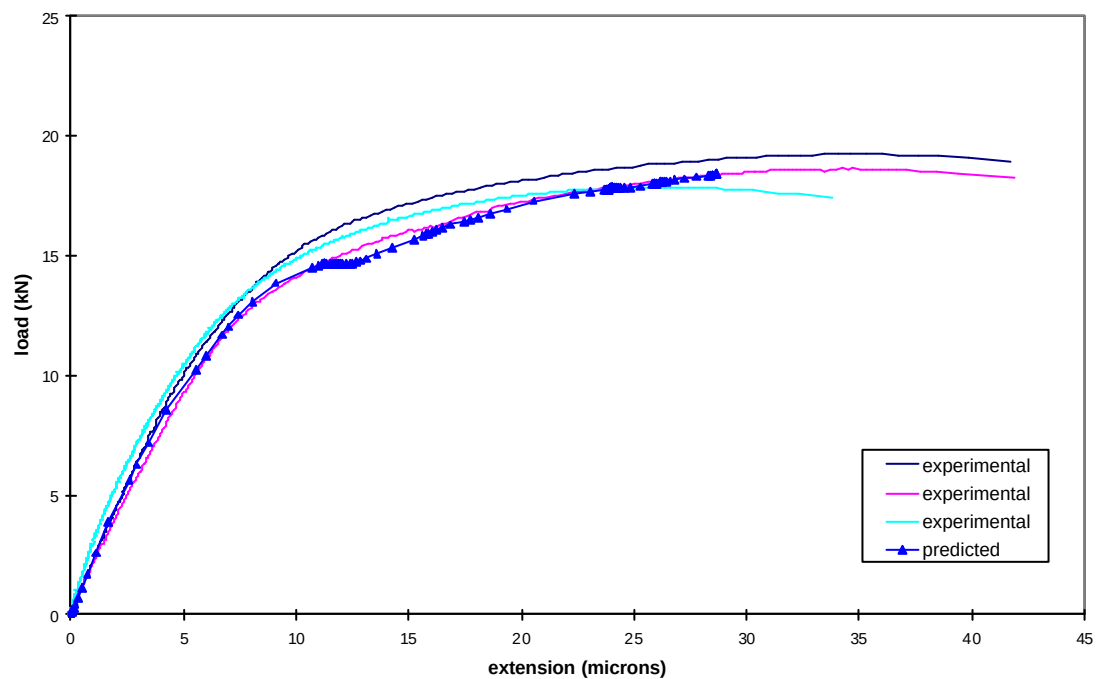


Figure 18. Comparison of the predicted load/extension curve for the butt-joint specimen at a mean strain rate of 0.002s^{-1} with experimental curves measured at a test speed of 0.03 mm/min .

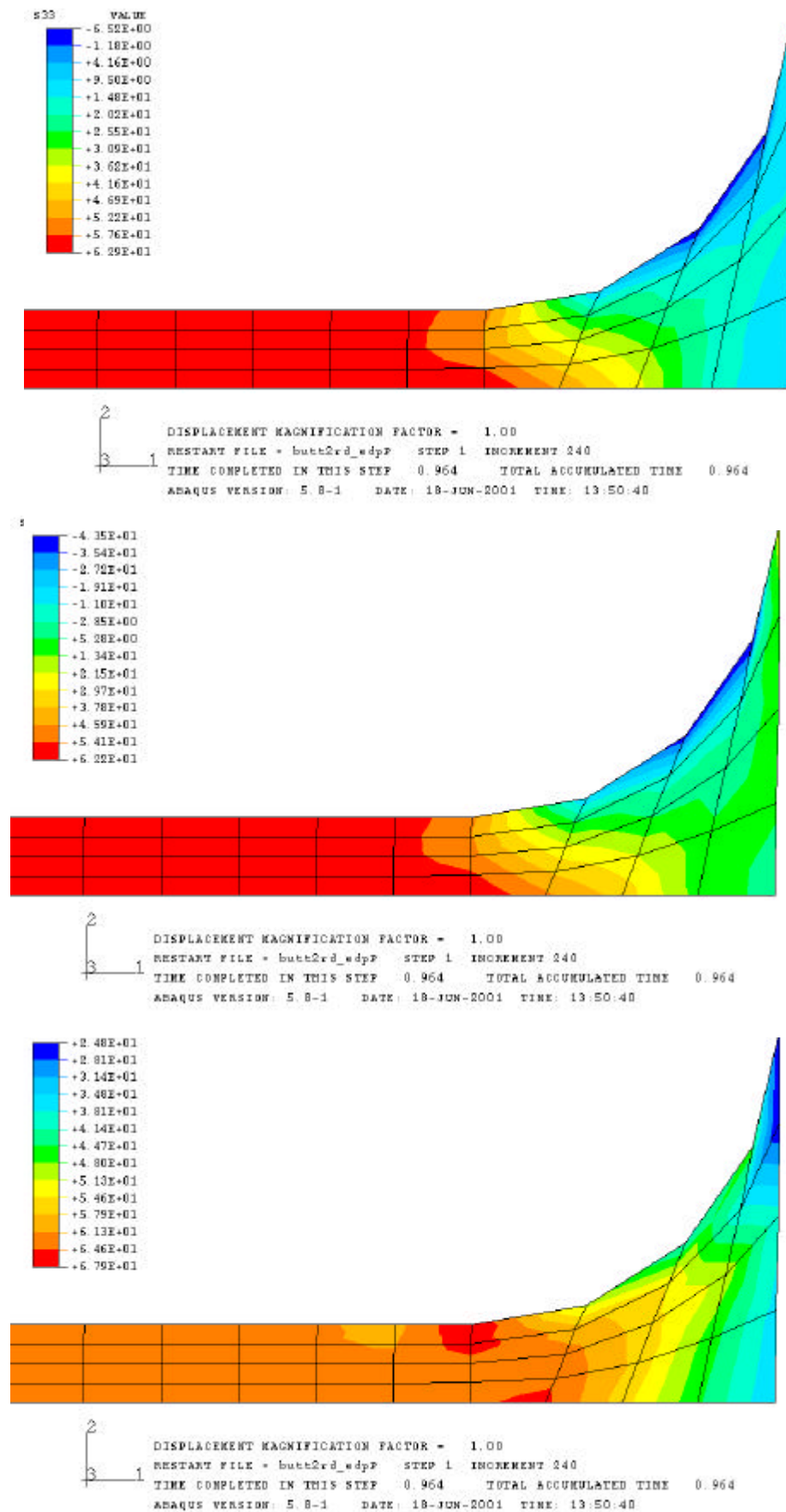


Figure 19. Contours of principal stress in the butt joint at an extension of 0.029 mm