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Project PAJ2: Dynamic Performance of Adhesive Bonds

METHODS FOR MEASURING STRAINS AT HIGH RATES.

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Summary

Finite element analysis (FEA) is a powerful technique for the design and analysis of structures sustaining impacts. However, reliable predictions require both a suitable model for the material behaviour and material properties at appropriate strain rates. An aim of one of the tasks in project PAJ2 of the DTI Performance of Adhesive Joints programme was to establish methods for determining such material properties at high strain rates that would be suitable as input for FEA. One particular problem is measuring strains at these high strain rates. Test machines can carry out tensile tests at speeds of around 1 ms^{-1}. These speeds give strain rates of $10s^{-1}$ or more. Conventional extensometry is unreliable at these speeds. As part of project PAJ2, a high scan-rate, linescan camera has been developed to determine strains in the high rate tests. The measurement and analysis procedures for this instrument are complex and it is not yet suitable for carrying out routine measurements. However, it has confirmed that a technique devised for estimating strains from the movement of the test machine crosshead gives a reasonably reliable estimate of the strains. Both of these methods are described in this report.

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CONTENTS

1. INTRODUCTION

Adhesives, like most polymeric materials, have rate dependent mechanical properties. These are of considerable importance when trying to predict the performance of bonded structures under impact loading. Finite element analysis (FEA) is a particularly powerful design tool. However, reliable analyses require accurate input data and the selection of an appropriate materials model [1]. Project PAJ2, in a programme of research on the Performance of Adhesive Joints funded by the DTI, aims to improve methods for obtaining and analysing materials data suitable for use in the prediction of impact performance.

There are several test methods for determining the impact properties of bulk polymers and adhesive joints. However, these either determine fracture toughness [2-4] or energy absorption [5-7] rather than the data required for input to the FE models identified previously [1]. Many of the data requirements for FEA can be satisfied through bulk specimen tensile test data at appropriate strain rates. For prediction of impact performance, data at high rates of strain (greater than 10 s^{-1}) are required. Mechanical test measurements at these strain rates are difficult to perform. One of the biggest problems is measurement of strain. The objective of the current report is to assess methods for determining strain in bulk test specimens in high rate tests and to evaluate an extensometer based on a high speed linescan camera that has been developed for use in high speed mechanical tests.

2. REVIEW OF STRAIN MEASUREMENT METHODS

The measurement of strain discussed in this report concentrates only on the tensile (or axial) strain in the gauge region of bulk tensile test specimens. Lateral strain measurements are also important for accurate characterisation of the mechanical behaviour. However, owing to the small deflections involved in the lateral contraction of tensile test specimens, measurement of lateral strain would be considerably less accurate than that of tensile strain. High rate lateral strain measurements would be difficult to carry out accurately although it may be possible to use some of the techniques discussed here for measuring lateral strains. Test data obtained at lower strain rates suggest that the lateral strain properties of some polymers and adhesives have little strain rate sensitivity. It is probably a reasonable first approximation to assume that the high strain rate behaviour is similar to the low strain rate behaviour. Therefore, high strain rate lateral strain measurements are not discussed in detail in this report.

2.1 COMMERCIAL HIGH SPEED EXTENSOMETERS

Some information was obtained on two commercial instruments that claim to be able to measure strains at high rates. Neither is commonly used in testing labs and these were not evaluated within this work.

2.1.1 Zimmer Electro Optical Extensometer

The Zimmer electro-optical extensometer incorporates two photo cathode tubes which image contrasting marks on the test specimen. When the marks move a feedback voltage is applied to deflecting electrodes to maintain the mark image in the centre of the photo-dectector. This feedback voltage level is then used to calculate the position of the mark. Two photo cathode tubes are used to measure the position of two marks and, through these, strains are determined. The instrument has a high response rate (>100 kHz) and is suitable for high rate measurements. However, the instrument is expensive (>£25k) and has not been widely adopted by UK organisations. No evaluation of this equipment was undertaken.

2.1.2 Schenck Laser Extensometer

The Schenck LEX 20 Laser extensometer is a much simpler instrument. Two corner reflectors are attached to the grips of the test machine. A laser beam is reflected between them, along the axis of the specimen, onto a position sensor. This position sensor measures the change in position of the moving grip. This instrument has a high output rate (100 kHz) which could enable high speed strain measurement. One draw-back of this instrument is that it measures grip separation and not local deflection of the specimen. The advantage of this instrument over the use of the crosshead displacement transducer in the test machine is that any deformations of the components in the test assembly are not included in the measurement.

2.2 STRAIN GAUGES

Strain gauges can have sufficiently high response rates coupled with good accuracy and precision to be useful in measuring strains in impact tests [8-10] for many materials. However, as work [11] carried out on an earlier adhesives project (MTS ADH1) found that for materials such as plastics and adhesives the presence of strain gauges both stiffen the specimens (leading to inaccuracies in the strains determined) and promote premature failure where the gauge is bonded. For these reasons, further investigation of strain gauges for carrying out high rate tests was not undertaken.

2.3 CLIP-ON EXTENSOMETERS

Clip-on, knife-edged extensometers are perhaps the most accurate method for measuring strains [11]. However, there a number of limitations that prevent their use in high speed tests. Often, the response rate of the transducer and instrumentation is too slow for reliable use. A further limitation on their use is their limited measurement ranges and the tendency of the knife-edge contacts to initiate premature failure of the specimen. Within this project, clip-on extensometers were used for test speeds of up to 0.1 ms^{-1} but not for higher speeds.

2.4 CROSSHEAD DISPLACEMENT MEASUREMENT

2.4.1 Calculating Strain from Displacement

One method for estimating strain is to measure the movement of the machine crosshead. Most test machines have built-in linear variable differential transformer (LVDT) displacement transducers. Strain can be taken as the displacement divided by the initial grip separation (taken to be the gauge length). The accuracy of this approach is limited. The shape of the tensile test specimen promotes non-uniform strain distributions The strain in the central parallel gauge section will be greater than in the wider end tabs of the specimen. Further errors are introduced when the material yields and the strain distribution becomes even less uniform. As the specimen yields, the slope of the strain- displacement curve will increase. Local strains may be significantly higher than predicted. There are also gripping effects that, although it is possible to correct for these, introduce errors into the effective grip separation. For these reasons strains determined through crosshead movement can be extremely inaccurate.

In an earlier report [12], a method was outlined for obtaining a function to calculate strain from displacement. At lower and intermediate strain rates (up to ca 2 s^{-1}), displacement measurements were correlated with simultaneous measurements of strain made with clip-on knife-edged extensometers. The relationship between strain and displacement was modelled using a quadratic function. The fitted parameters of the quadratic function depend to some extent on the material, test temperature and specimen dimensions. However, most materials showed little rate dependence and it was reasoned that these could be used to calculate strains from displacement measurements made in high rate tests.

This method appears to work reasonably well as a method for estimating high rate strains. Further validation of the method is discussed in Section 4. However, there are a number of limitations involved in this technique. The function is only valid up to the maximum strain available from the extensometer (around 0.15 for the equipment used in this work). Above this, the strain estimation will become inaccurate as the quadratic function predicts an ever increasing slope of strain against displacement while, in reality this will become constant. A further correction can be made by assuming that after yield the slope of the strain-displacement curve will be constant. This constant can be used in place of the quadratic function at larger strains.

The quadratic function was chosen as compromise between good quality fits (low residuals) and simplicity (few parameters). For materials where there is a rapid onset of yield, the simple quadratic function will not accurately fit the rapidly changing slope of strain-displacement curve near the point where yield occurs. Strains calculated for such materials will contain errors around the point of yield.

The approach for estimating high rate strains from displacement measurements could, in principle, be used with adhesive joint specimens. However, accurate strain determination in bonded joints, even in quasi-static tests, is a complex subject. This was not investigated in the work reported here.

2.4.2 Displacement Measurement Issues

Crosshead displacement measurements may become inaccurate at high speeds. The displacement transducer on the Instron 1343 high speed servo-hydraulic test machine used in this work [13] is designed to be output through an electronic control and conditioning panel. This panel enables output gain settings to be controlled. However, at high speeds, the electronic processing circuits are unable to process the signals sufficiently fast. The unit will then operate in ‘burst’ mode, sending ‘packets’ of information every 200 μs. This builds up the displacement time record as a series of steps, as shown in Figure 1. This occurs at test speeds above 0.1 ms^{-1}. In addition to these steps the signal processing significantly delays the output and the displacement trace lags the load trace considerably. This is also a major reason why clip-on extensometers could not be used at high speeds.

To avoid these problems, it was necessary to use the unconditioned 'analogue' output of the displacement transducer. This could not be scaled and conversion factors in mm V^{-1} needed to be calculated to convert output signal into displacement. Figure 1 indicates that the response rate of the analogue signal is faster than the processed signal. The rise in the analogue displacement leads that of the processed displacement signal suggesting that signal processing delays are shorter.

The output of the displacement transducer appears inherently noisy in the high rate tests. Figure 2 shows that there is sinusoidal noise in the displacement signal with a frequency of approximately 10 kHz even when the machine is at rest at the start of a test. The amplitude of the noise seems to diminish at lower test speeds but this is most likely to be due to the lower data sampling rates that are used for slower speed tests. This wave amplitude of ca ± 0.08 mm leads to an uncertainty of ca ± 0.1 % in the strain which limits the accuracy of measurements at low strains. Reasons for this noise are unclear. However, given the high frequency and the lack of similar noise in the force signal, it is not thought to be due to physical movements of the crosshead.

3. HIGH SPEED LINESCAN CAMERA EXTENSOMETER

3.1 CAMERA OPTIONS

Improving the accuracy of high speed strain measurement requires strain measurement devices with the capability for fast responses and high data output rates. Video extensometry is a useful technique for measuring large strain behaviour but is limited to relatively slow response rates by the large quantities of data to be processed (typically 10 to 20 measurements per second). Higher speed cameras can be used to capture strains and deflections [14]. One of the limiting factors is the time required to read the information from the full screen CCD array in the camera. High speed digital cameras if available tend to be both prohibitively expensive and have relatively low pixel resolution. High speed film cameras have both the resolution and the imaging rates but there is a need to develop and analyse photographs to produce data. Since tensile strain is essentially one dimensional, it is possible to replace the full screen camera with a linescan camera cutting down considerably the number of light sensitive elements to be measured. Linescan cameras with 1000 or 2000 sensitive elements that have output rates as high as 10,000 scans s^{-1} are commercially available and are relatively inexpensive. Such a camera could form the basis of a high rate extensometer.

The linescan camera system (EG&G Reticon LC1912) developed as a high rate extensometer was described more fully in an earlier report [12]. In the current report, the ability of the system to measure strains up to strain rates of 2 s^{-1} (scan rates of 1000 s^{-1}) was demonstrated. Further work has been performed to evaluate the performance of the system at strain rates in excess of 20 s^{-1} (at the maximum set scan rate of 10,000 scans s^{-1}), achieved in 1 ms^{-1} tests.

3.2 MARK DETECTION

The linescan camera software records the position of the gauge marks as the pixel values where the light intensity crosses a pre-set threshold value. At high scan rates, the exposure time, and thus the sensitivity of the light sensitive elements, is low. High contrast between the gauge marks and background is required for detection of the gauge mark edges. Noise in the light intensity signal should be low as only a small number of edges can be recorded (maximum of 16). Therefore, illumination of gauge marks on the specimen is a critical performance requirement for strain measurements. At the fastest available setting (10,000 scans s^{--1}) the camera sensitivity is extremely low and it is difficult even to distinguish black from white. Improved sensitivity would be difficult to achieve with an alternative camera as most photo-detector elements have similar sensitivities. More sophisticated cameras can improve signal-to-noise ratios through cooling the photo-detector.

There are two options for marking and illuminating the test specimen that may allow gauge marks to be detected at the highest scan rates. The first option is to light the specimen using a high intensity light source (minimum of 300 W) and attach highly reflective marks to the specimen. The second option is to place the light behind the specimen. Marks are then attached that protrude from the specimen, shading the camera. These marks show up as 'dark marks' on a light background.

Figure 3 shows a schematic of the set-up used with reflective marks. The reflective material used was adhesive backed foil tape. The alignment of the camera and lamp are critical to obtaining a high level of reflectance from the marks that gives good contrast in the scan. However, since the detected light is due to specular reflection the gauge mark intensity is very sensitive to alignment. This is often difficult to achieve properly. Altering the position of the marks (e.g. during a test) changes the angle of reflection which can have a significant effect on the linescan output. The shape of the mark intensity profile will change, shifting the 'location' of the edges (and the measured position of the gauge mark). There may also be more noise in the edge position data. With sufficient movement, it is possible that the intensity of the mark will diminish below the edge detection threshold resulting in 'loss' of the mark.

Figure 4 shows typical linescan camera outputs. These were measured for a polymer specimen (ABS) tested at 1 ms^{-1} with a set scan rate of 10,000 s^{-1}. The plot shows edge position (as pixel number) versus scan number. The position of the bottom mark increases monotonically with scan number until the specimen ruptured. The top mark is displaced much more than the bottom mark and there were many problems with maintaining a good quality image for edge detection. In the middle of the test there is a discontinuity as the position of the mark seems to move back, possibly due to a sudden change in the shape of the reflected intensity. This shift was reversed a few scans later. The top mark was then 'lost' before the specimen ruptured. The positions of both marks are required to determine strain.

Analysis of this type of data is complex. Figure 5 shows strains derived from the linescan output. These are plotted as a function of time. The discontinuity in the position in the top mark appears as a vertical shift in the strain. It is possible to 'correct' this data by shifting the position of the top mark and, hence, the strains in this region by a constant amount whilst retaining the shape. This corrected data fits smoothly in between the other two sections of data. The agreement between the corrected data and strains estimated from crosshead movement is good.

The set-up for viewing a specimen lit from behind is shown in Figure 6. A high intensity light source is still required to give a sufficient signal to noise ratio (a 10W fluorescent lamp was insufficient). The light intensity should be uniform throughout the field of view of the camera (as represented by the shaded rectangle in Figure 6). The camera lens is focused on the marking rods protruding from the side of the specimen. In this set-up alignment is not critical and imaging the marks to give sufficient contrast is relatively straight forward. The image intensity and contrast do not alter significantly with position over the range of movement of the specimen.

As Figure 7 indicates the marks are detected until (and beyond) specimen rupture. The test data shown were obtained from a polypropylene test specimen at 1 ms^{-1} using a scan rate of 10,000 scans per second. There are no discontinuities in the recorded positions of the edge marks until the specimen ruptures. Using these positions, Figure 8 showing strain as a function of time can be produced. The agreement between the strains determined from the linescan camera and those estimated from crosshead displacement is good.

Lighting the specimen from behind is a far more reliable option than using reflective marks for the measurement of strains in high speed tests. However, it is not free of problems. As the light source needs to be behind the specimen more space around the specimen is required. The use of an environmental chamber may not be possible. The close proximity of the high intensity lamp to the specimen will lead to heat adsorption and the material temperature will be unknown but higher than the environment temperature. This heating problem can be minimised through only using the lamp briefly when measurements are being made. A further source of concern is how closely the movement of the marks correlates to strain in the specimen. These marks can be considered as loosely clamped single cantilevered beams. Inertial effects may deflect the beams and it is also possible that they may slip during the test (introducing spurious strain values). In extreme cases the marks may even detach from the specimen surface.

3.3 MATCHING LOAD AND STRAIN MEASUREMENTS

In theory, stress-strain curves may be calculated from the load vs. time and the position vs. scan number data recorded during the test. Figure 9 shows a schematic of the sources of the data that need to be combined. The linescan data should be converted to strain using the change in the mark positions and the time after test machine activation at each point should be estimated from the time increments between scans. Once strain-time data have been calculated, a polynomial fit can be applied and used to calculate strain at times corresponding to the load data. From this the stress-strain curve can be plotted. Generally, a sixth order polynomial will give a good fit to the strain-time data and will accurately interpolate points up to the end of the strain data. The area most likely to give problems in the fit is the initial part of the curve. This approach requires that the time increment between scans is known and that the start and finish of the data can be matched accurately.

Data records made at a set scan rate of 10,000 scans s^{-1} were initially analysed by assuming that the time increment between scans was 0.1 ms (the reciprocal of the scan rate). The duration of the strain data however appeared to be much shorter than the duration of the load data. Strain rates calculated were far in excess of those estimated from movement of the crosshead. When the data were re-analysed to synchronise significant events in each dataset (start of test, specimen rupture and end of crosshead movement), it was apparent that the actual time increments between scans were considerably longer than 0.1 ms. The value of around 0.25 ms required to synchronise the data suggest an actual scan rate of ca 4000 s^{-1}. Repeating this for slower set scan rates of 5000, 1000 and 100 s^{-1}gave actual rates of 3000, 900 and 100 s^{-1}. The discrepancy is reduced at slower rates. At present, there is no independent method available to determine whether this problem is caused by the camera hardware, the interface card or the analysis software.

These lower scan rates reduce the temporal resolution of the instrument (which at high rates is at least as important as the spatial resolution of the detector). This leads to worse strain resolution of the extensometer than had been anticipated. The 10,000 scans s^{-1} rate should have given a resolution of 0.1 % strain at a strain rate of 10 s^{-1}. The actual scan rate of 4000 s^{-1} suggests a resolution of 0.25%.

There are further problems with trying to match up the load and strain data. All the files recorded contain a significant quantity of points measured before the test machine is activated (these are used to determine the initial gauge length and loads). As the crosshead has to accelerate to the test speed, the initial rates of increase of load, displacement and strain are low. It is difficult to determine the precise point at which the test starts. The linescan camera has poorer resolution than the other two transducers and the start of the test is more difficult to define precisely. By the time that an increased strain is apparent from these data, the initial part of the load curve has been missed.

An alternative method of matching the data is to use a later feature of the test such as specimen rupture or end of crosshead travel. This ought to be easier to define in the test record. This time is then defined according to the time in the load record and all the times in the linescan record are determined by subtraction of the scan period. When this is done, the zero time point appears to occur a one or two scans before the strain is seen to increase. As the time increments in the linescan data are relatively large, there will still be some uncertainty over precisely synchronising the load and time data. To improve the match, the time value at the defined point can be adjusted (by a maximum of ± 1 time increment) to more precisely match the initial shapes of the strain-time and displacement-time plots. There still is some degree of subjectivity in this matching process. Further development of the test instrumentation to improve control over the scan interval and to incorporate simultaneous triggering of the force, displacement and scan recorders to synchronise the data would help to reduce the uncertainty involved in the matching procedure. These improvements would be required if the extensometer was to be commercialised.

4. COMPARISON OF STRAIN MEASUREMENT METHODS

4.1 BACKGROUND

Two methods of determining strains in high speed tests have been considered in this work - estimates from crosshead movement and measurement using a high speed linescan camera. Crosshead movement is generally a standard feature in test machines and measurements are straightforward to make. However, the accuracy of this method for determining strain is open to question. As part of this work, a procedure for estimating strain from displacement has been proposed. One of the aims for the high speed extensometer was to confirm whether this method can be used with sufficient confidence in the generation of design data.

Using the linescan camera to measure strains is not a routine operation. The actual measurement method presents a number of challenges that have been described in a previous section. The analysis of the data requires considerable effort and the technique, at present, is not suitable for routine data acquisition. Mechanical properties data have been measured on a number of polymers and adhesives using the linescan camera to provide a basis of comparison with data generated from the movement of the crosshead.

4.2 POLYMERS

Three representative types of polymer are being studied as part of the DTI Characterisation of Advanced Materials project CAM6. These are summarised in Table 1. Since preparation of polymer test specimens is considerably simpler than preparation of adhesive test specimens, the initial development work on the linescan extensometer concentrated on these materials.

Table 1: Engineering Polymers

Material	Type	Supplier	Grade
Polycarbonate	amorphous	Bayer	Macrolon 293
Polypropylene	semi-crystalline	BASF	Novalen 2300LL
ABS	rubber toughened	BASF	Terluran 967K

Stress-strain curves determined simultaneously from both linescan and crosshead data for the three polymers are shown in Figures 10-13. All the tests were performed at a test speed of 1 ms^{-1} giving a strain rate of ca 30 s^{-1}. Figures 10 and 11 show data determined from tests on ABS using both the linescan measurement set-ups (reflective marks and back lighting respectively as outlined in Section 3). In Figure 10, the agreement between the points calculated using the corrected linescan data agree well with the data derived from crosshead measurements. By estimating a strain rate from the last few points in the linescan data record an extrapolation can be made to estimate the strain to failure. This is shown by the dashed line where the product of strain rate and time increment were used to calculate strain increments from the last measured point. Figure 11, also shows good agreement between the linescan and crosshead data. These data were obtained using back lighting. Figure 12 shows a similar good match for stress-strain curves of polypropylene. The strains represented in the dashed lines in Figures 11 and 12 were calculated from the polynomial function fitting strain to time in the linescan record. There may be some uncertainties in the strain values due to the fit.

The mechanical behaviour of polycarbonate differs qualitatively from the other polymers. There is a distinctive peak in the measured stress values around 6 - 10 % strain followed by a ‘plateau’ stress at higher strains. This reduction in stress is due to the formation of a local neck in the specimen which then ‘travels’ (at a constant force and cross-section through the gauge section of the specimen). This necking behaviour makes it difficult to determine local strains in this material. During the test shown in Figure 13 a neck formed in the specimen between the two gauge marks. Once this occurred, the local strain increased in this region by a much greater extent than was estimated from the overall extension of the specimen (which gives an average strain). There is quite a large discrepancy between the strain at failure measured using the linescan camera and estimated from crosshead movement as the camera is measuring strain over a different gauge length than the displacement transducer. However, as the stress-strain curve is flat at large strains, both methods give roughly the same shape.

A brief comparison of the maximum stresses determined in the tests described above revealed that these stresses are around 10 % lower than stresses determined in measurements made without the linescan extensometer on these materials at the same nominal temperatures and strain rates. The most likely reason for this is that the high intensity light used to illuminate the specimen also heats the specimen. The higher temperature would lead to lower yield stresses. Considerable changes would need to be made to the test arrangement to separate the light source and specimen.

4.3 ADHESIVES

The linescan camera has been used to measure tensile stress-strain behaviour of three of the adhesives being studied within the Performance of Adhesive Joints project PAJ2. These tests were carried out at 1 ms^{-1}. Measurements on a fourth adhesive (a toughened acrylic) were not made owing to a shortage of suitable test specimens. This material has very similar tensile behaviour to the ABS discussed above although the strain at failure is very much smaller (around 5 %). The three adhesives are detailed in Table 2.

Table 2: Adhesives

Adhesive	**Type**	**Supplier**
AV119	1-part epoxy	Ciba
LMD1142	1-part toughened epoxy	Ciba
DP609	2-part polyurethane	3M

Figure 14 shows the test data measured for AV119. This adhesive has a relatively small strain at failure (ca 2.5 %). The low resolution of the extensometer is more of an issue in testing materials such as this as there are few data points measured before failure. The ability to match the load and strain records accurately is critical to determining the stress-strain curve with any degree of confidence. In this example, the fracture of the specimen was assumed to occur midway between two points representing a discontinuity in the position-scan plot. This was used to calculate the effective time of each point in the linescan record and these were matched with the load data to give the stress-strain curve. Both the actual points and the modelled strain curve agree very well with the curve determined from the crosshead displacement. This is to be expected as no extrapolation of the fit parameters was required.

Figure 15 shows stress-strain behaviour measured for the epoxy adhesive LMD1142. This adhesive is much tougher than AV119 and the strain at failure is significantly higher (>14%). Agreement between the linescan and the crosshead data is generally good although the low resolution of the linescan extensometer causes difficulty in matching the two sets of data. In the region after the specimen has yielded, the strain rate is at a maximum (ca. 35 s^{-1}), and the strain increments between successive points are approximately 1 %. Failure was assumed to occur midway between the points where a discontinuity occurred in the linescan record. This gives rise to a degree of uncertainty in the strain at failure.

The stress-strain curves determined for the polyurethane DP609 adhesive shows good agreement between the linescan and the crosshead except at high strains. The properties of DP609 have significantly greater rate dependency than the properties of any of the other polymers or adhesives used in this work. It may be that, in contrast to the other materials, the fit parameters used to calculate strains from displacement are also rate sensitive. The larger strain to failure of this material (around 35 % strain) masks the problem of the linescan extensometer resolution.

4.4 DISCUSSION

In tests on materials with large strains at failure where necking does not occur (polyurethane, ABS and polypropylene), the agreement between the stress-strain curves determined from the two techniques is generally good. There are some discrepancies in the strains at failure, around 2-3 % difference for strains of around 30 %. This is most likely because the clip-on extensometers used to measure the strains for fitting to the displacement data had limited ranges (maximum of 15 %). Over this range of strain, the agreement between strains appears good. Any strains estimated above this value have to be extrapolated from the small strain data. There is scope for error in these extrapolations. The sign of the deviation from the linescan data is dependent on the material. The sizes of these discrepancies were repeatable when further specimens were tested. This suggests that the parameters used to model the relationship between strain and displacement could be further refined to improve accuracy. The linescan extensometer offers a potential method for improving the reliability of the relationship between displacement and strain at high strain rates and large strains.

For materials that have lower strains at failure, such as some epoxy adhesives, the agreement between the crosshead measurements and the linescan extensometer are reasonable. There are uncertainties in the strains at failure due to the low resolution of the extensometer. A faster linescan camera system (e.g. one that operated correctly at the 10,000 scans s^{-1} setting) would significantly reduce these uncertainties.

The 'dips' seen in the stress-strain curves at larger strain are a consequence of the inability of the servo-hydraulic test machine to maintain a constant velocity. In addition to the acceleration period at the start of the test at high speeds, fluctuations in the hydraulic pressure lead to fluctuations in the crosshead speed. These fluctuations in the crosshead speed are shown as inflection points in both the displacement-time and linescan strain-time curves. These inflection points coincide with the 'dips' in the force trace which are due to the reduced strain rate lowering the plastic flow stress.

5. METHODS FOR DETERMINING STRAINS IN IMPACT TESTS

An alternative method to a high speed servo-hydraulic test machine for generating mechanical test data for design is the falling weigh impact test. These tests can be carried out on the same tensile test specimens that are required for the high rate tests. The data produced are force against time that require subsequent analysis in order to produce stress-strain data. A more general evaluation of falling weight impact tests for producing design data is covered in another PAJ2 report [13]. This section gives a brief overview of techniques for estimating the strains.

5.1 LINESCAN EXTENSOMETER

One of the aims of developing the linescan camera was to give a method for measuring strains in falling weight impact tests on bulk tensile specimens. There were significant problems with achieving this. The falling weight impact stage uses a twin striker to impact the lower anvil grip of the tensile test frame (Figure 17). When the striker is in place it blocks visual access and therefore the camera will see very little of the specimen. As has been discussed above, it is extremely difficult to image gauge marks on a fully visible specimen and the additional difficulties prevent the use of the linescan camera with the falling weight impact apparatus.

5.2 CALCULATIONS FROM GRIP DEFLECTION

The deflection of the grips is not measured directly but calculated from the impact velocity and subsequent deceleration. The simplest method of estimating grip movement is to multiply the time by the initial velocity. This neglects the deceleration of the striker due to the reaction force applied to the specimen. However, if the fracture energy of the specimen is low compared to the kinetic energy of the striker then the change in velocity will be small. Thus, the test can be assumed to be at a constant velocity. A more sophisticated analysis involves integrating the force signal to calculate changes in velocity. This can be carried out through the analysis software of the impact apparatus or off-line using a spreadsheet macro. In the materials tested in this work the correction to the velocity was less than 5-10 % at fracture which is not a significant error. Small errors may also creep in at the beginning of the trace. Some of the impact may be taken up by deformation of a 'soft' contact (e.g. a cushion used to damp noise in the trace). This material deformation will retard the initial movement of the anvil that will then lag the movement calculated using a constant or corrected velocity assumption. This error will be small if the contact between striker and anvil is relatively 'hard'.

The approach taken for estimating strain from displacements on the high rate machine was investigated in the impact tests. It was assumed that the compliance of the servo-hydraulic test machine and the tensile impact test frame were both negligible in comparison to the test specimen. The same design of grips was used in each apparatus and, hence, grip effects should be similar. The strains applied in response to movement of the grips should be approximately the same in each machine. Thus, the quadratic function and parameters used to analyse the high rate machine tests should be suitable for impact test data.

As Figure 18 shows, the stress-strain curves for polycarbonate specimens determined from tensile impact and high strain rate tests show essentially the same shape as the low strain rate data. Polycarbonate shows a peak in the stress-strain curve around 6%-10% strain and, therefore, is an extremely useful material to use in the evaluation of test methods. The data suggest that calculating grip displacement from the initial velocity and time followed by applying the quadratic conversion function determined from the high rate test machine gives a reasonable approximation to the strain.

6. CONCLUSIONS

- The linescan extensometer that has been developed in projects PAJ2 and CAM6 has been used successfully to generate stress-strain curves for adhesive and polymer specimens tested at high speeds (1 ms^{-1}).
- The data generated from the linescan extensometer demonstrate that the technique for estimating strains from crosshead movement being used in the project is reasonably reliable.
- It is recommended that further refinements to the technique for estimating strains from crosshead movement are carried out in conjunction with data from the linescan extensometer.
- This technique has been shown to give reasonable estimates of strains in falling weigh impact tests.
- It was not possible within the project to develop a sufficiently user-friendly system to enable the extensometer to be used for routine measurements as the measurement and analysis procedures are complex.
- The lower than expected output rates of the linescan system compromise the resolution of the extensometer.
- The low sensitivity of the photo-detectors make recognition of the gauge marks a problem. The sensor elements in camera employed have typical sensitivity for this type of equipment but more sensitive systems (where the photo-detectors are cooled to reduce noise) could be used but would likely lead to a significant increase in instrumentation costs.

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8. REFERENCES

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List of Figures

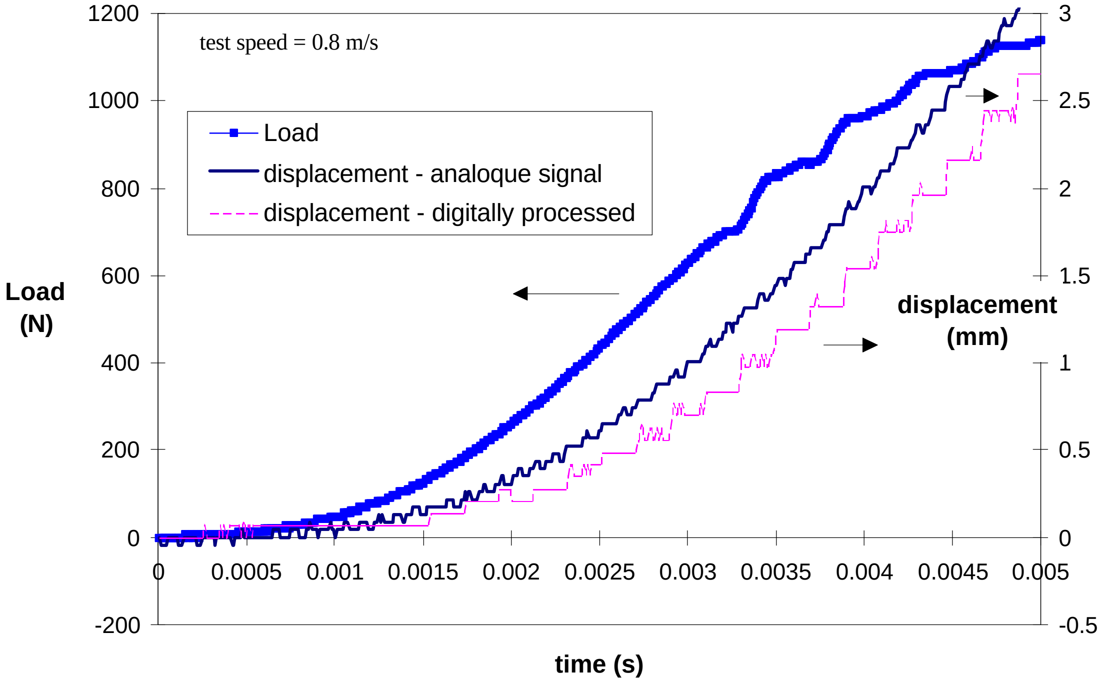

Figure 1: Output signals from the high rate test machine

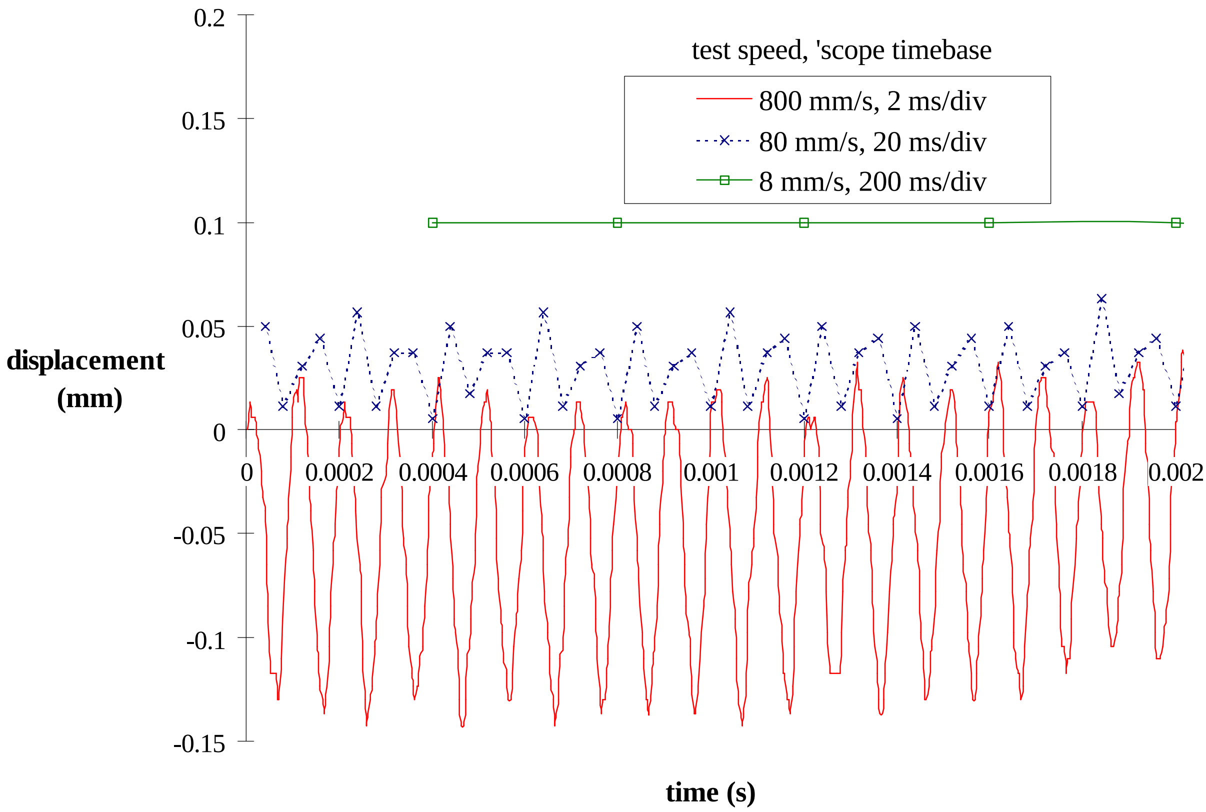

Figure 2: Noise in the displacement transducer signal

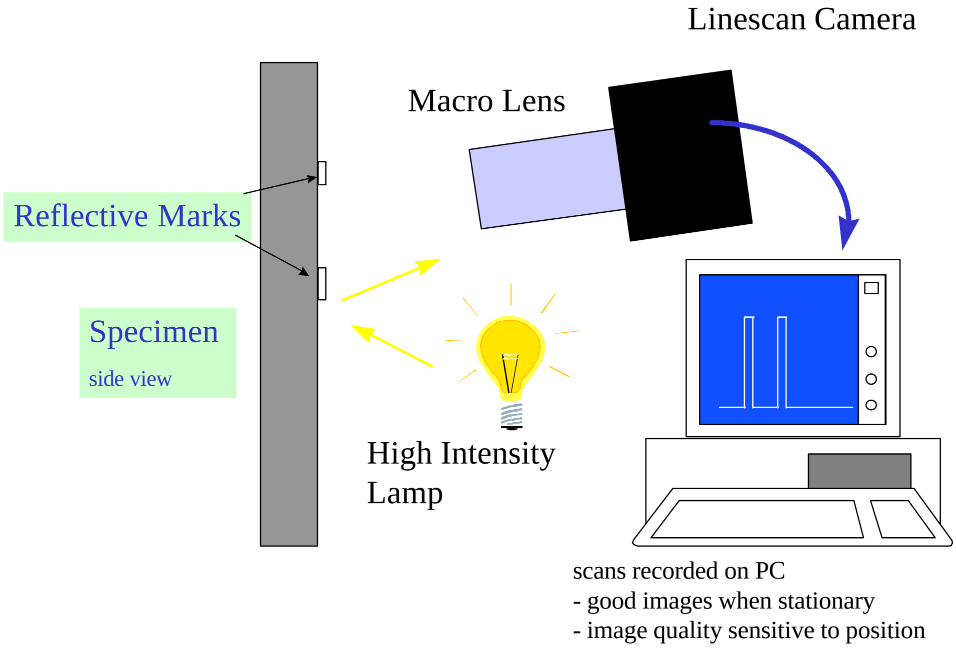

Figure 3: Set-up for measurement of strain using the linescan extensometer and reflective marks

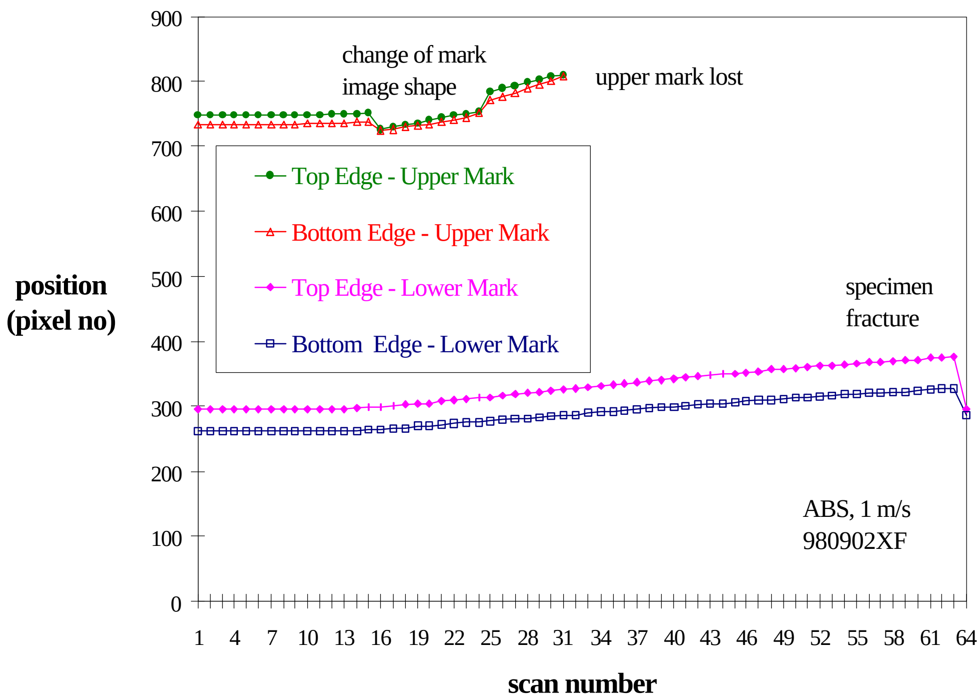

Figure 4: Typical linescan extensometer output when using reflective marks

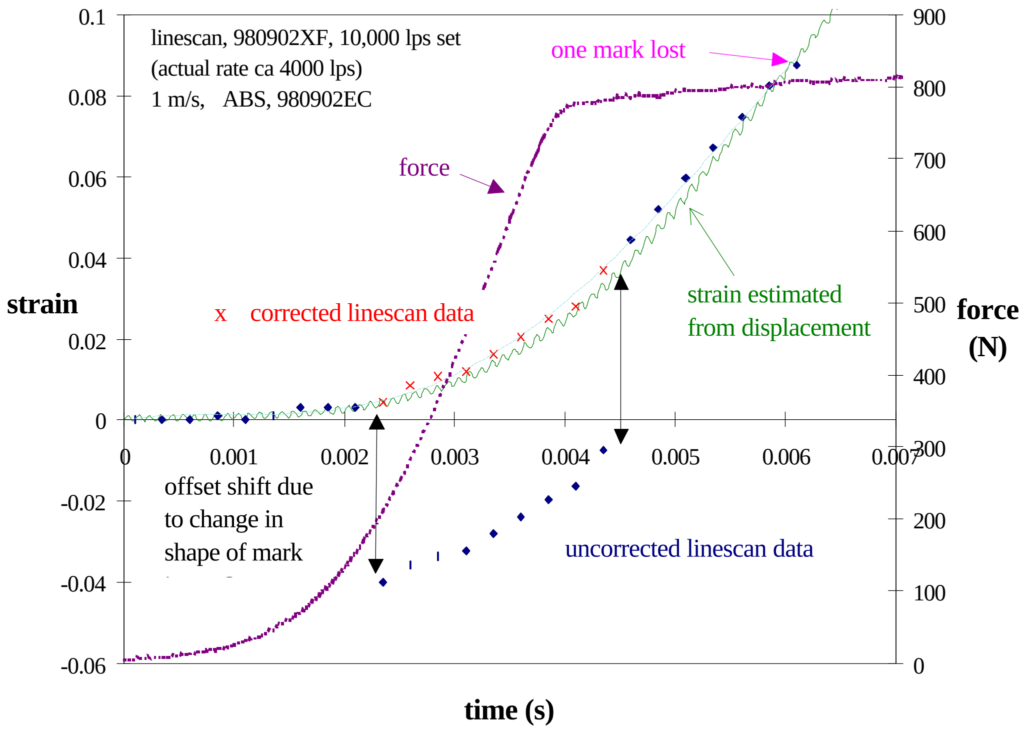

Figure 5: Strain data derived from linescan output in Fig. 4

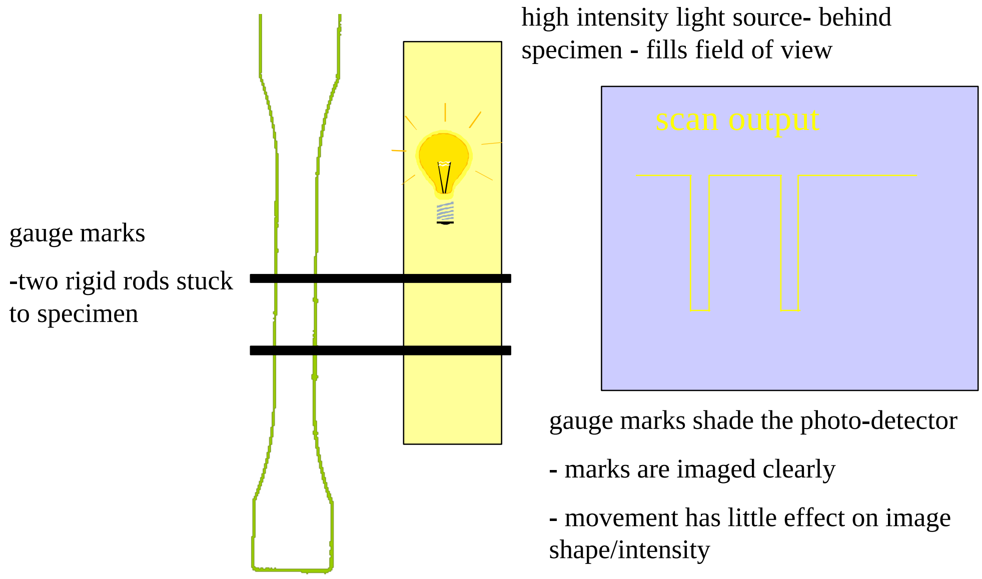

Figure 6: Camera view when set up for back-lighting specimen and gauge marks

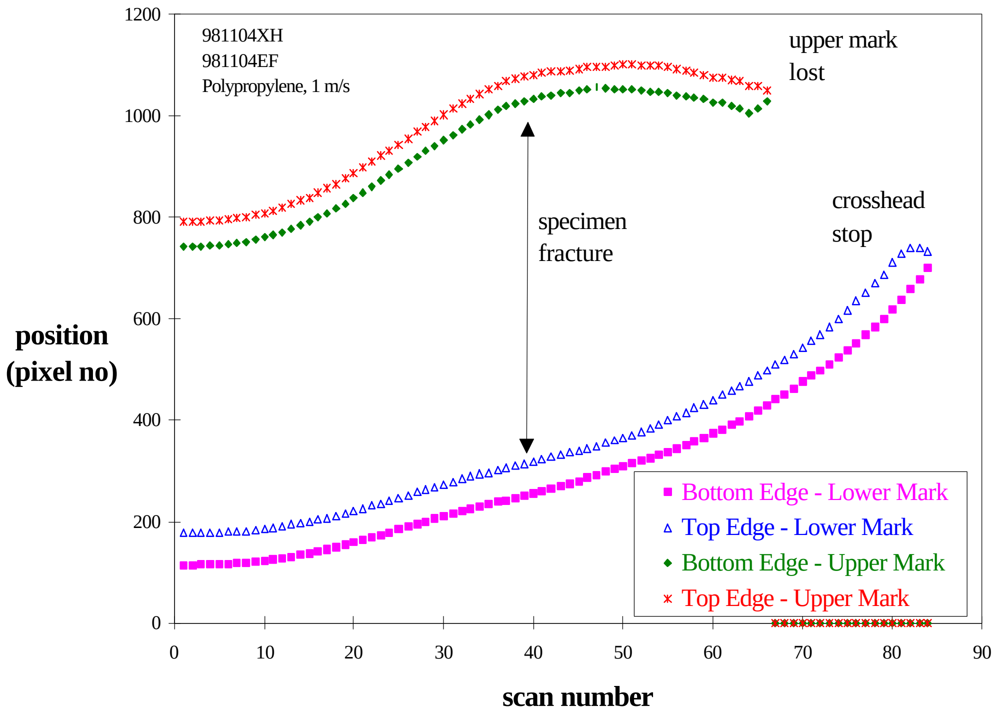

Figure 7: Typical linescan extensometer output using the back-lighting procedure

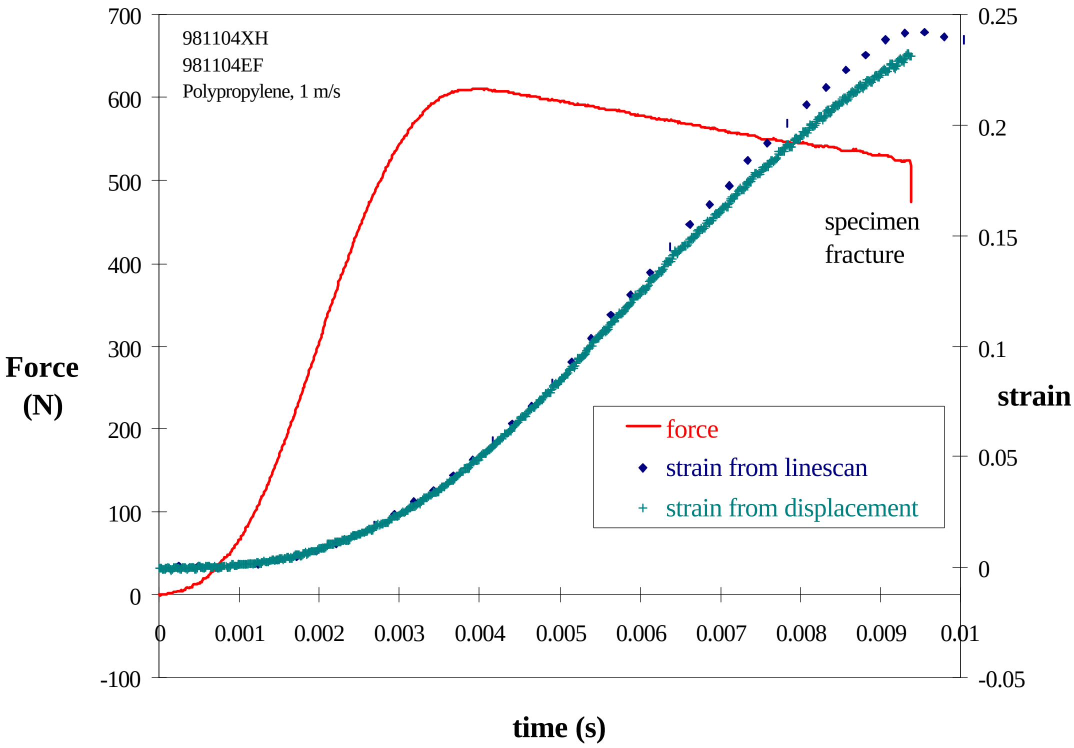

Figure 8: Strain data derived from Fig. 7

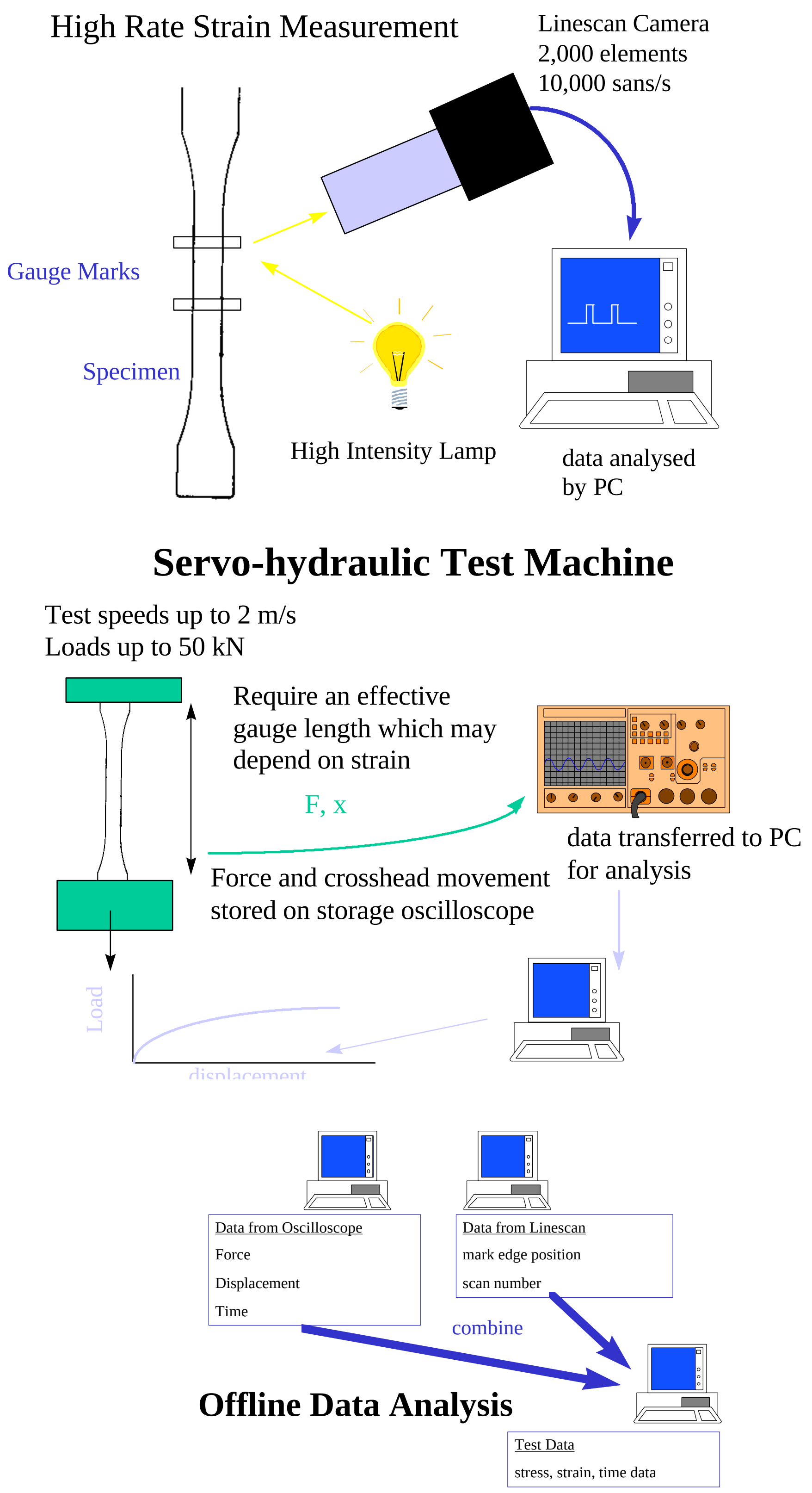

Figure 9: Schematic for combination of stress and strain data

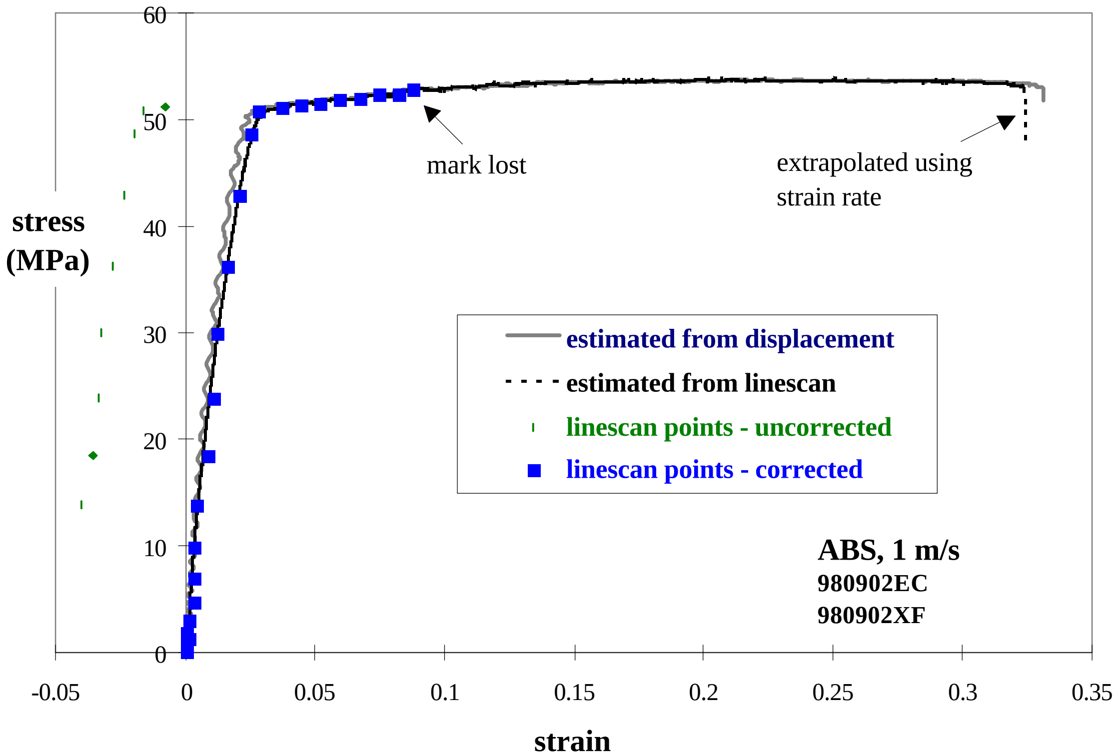

Figure 10: Stress-strain curves measured for ABS at 1 m/s using reflective marks

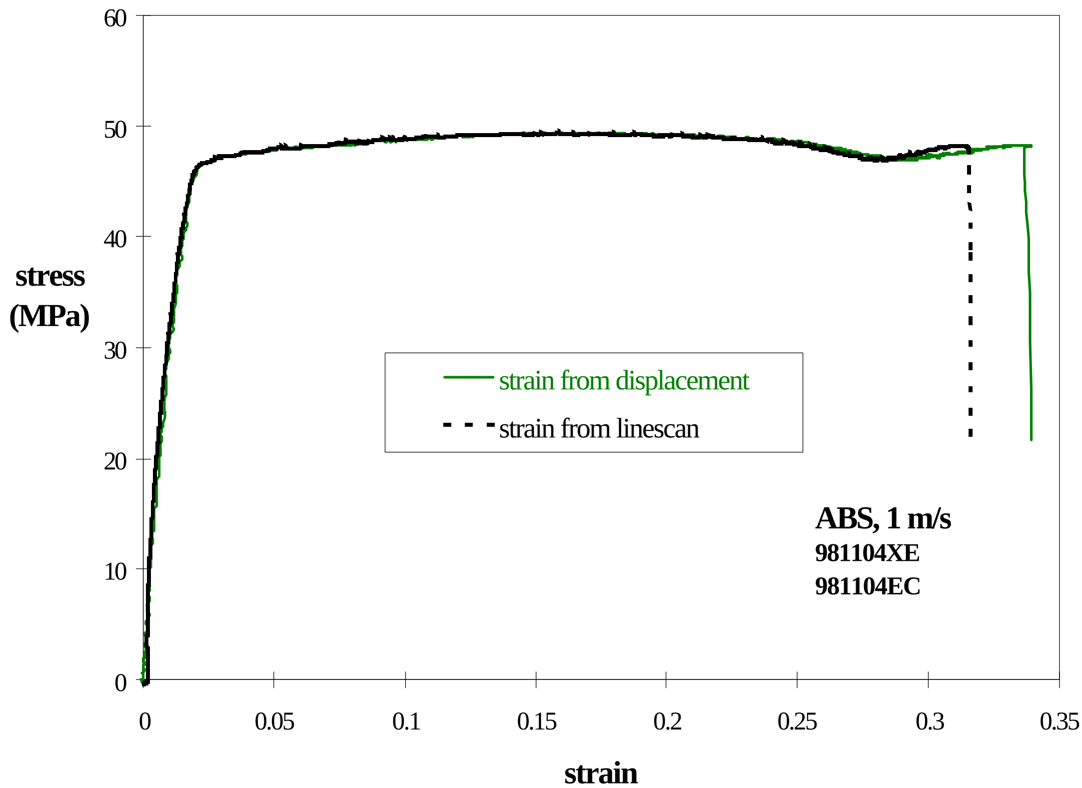

Figure 11: Stress-strain curves measured for ABS at 1 m/s by back-lighting the specimen

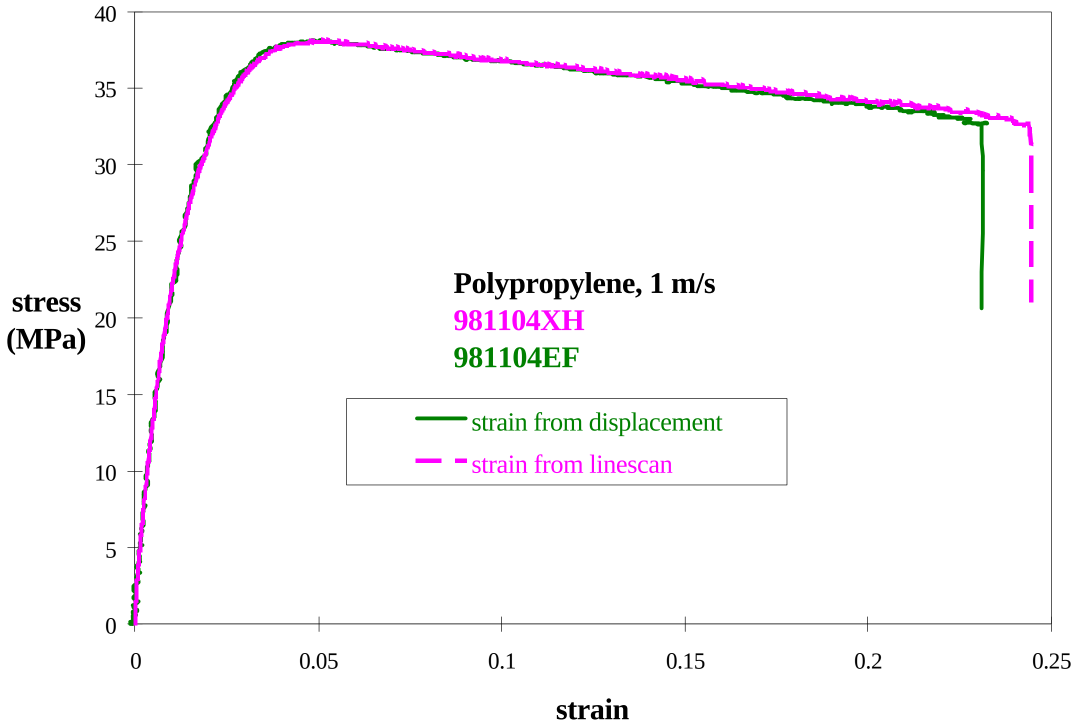

Figure 12: Polypropylene measured at 1 m/s using the back-lighting method

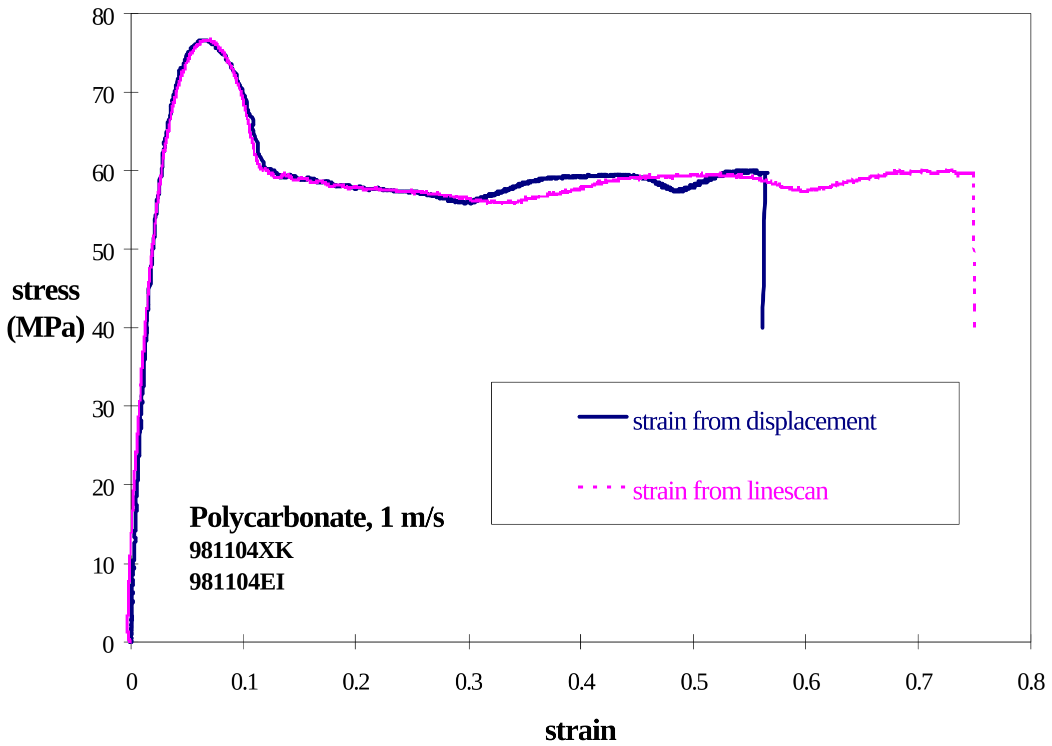

Figure 13: Polycarbonate measured at 1 m/s using the back-lighting method

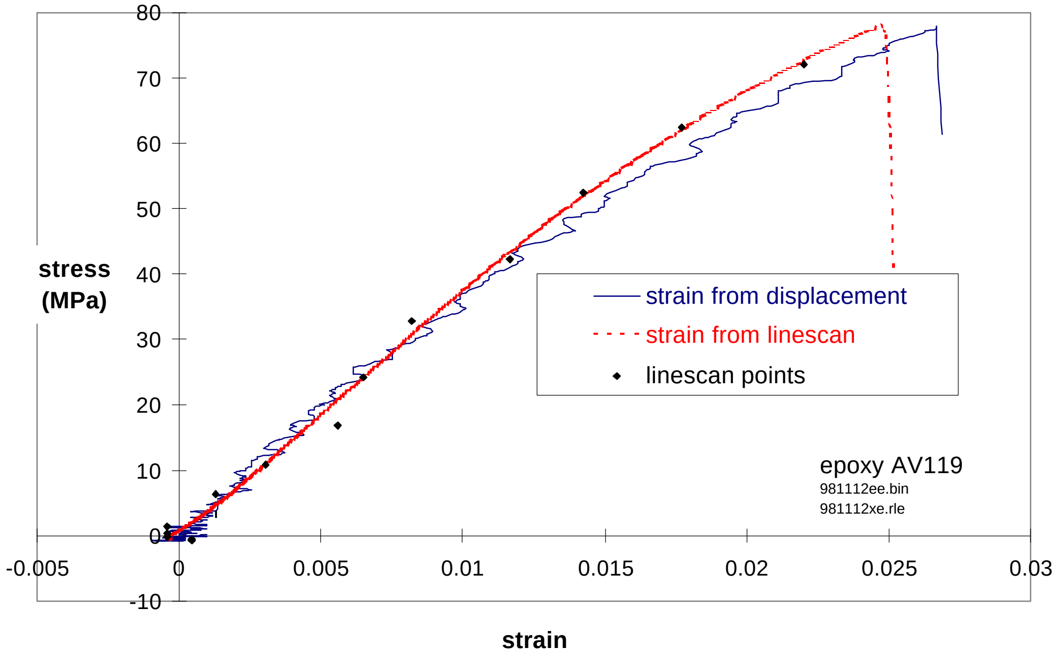

Figure 14: Tensile stress-strain measurement for epoxy AV119 at 1 m/s

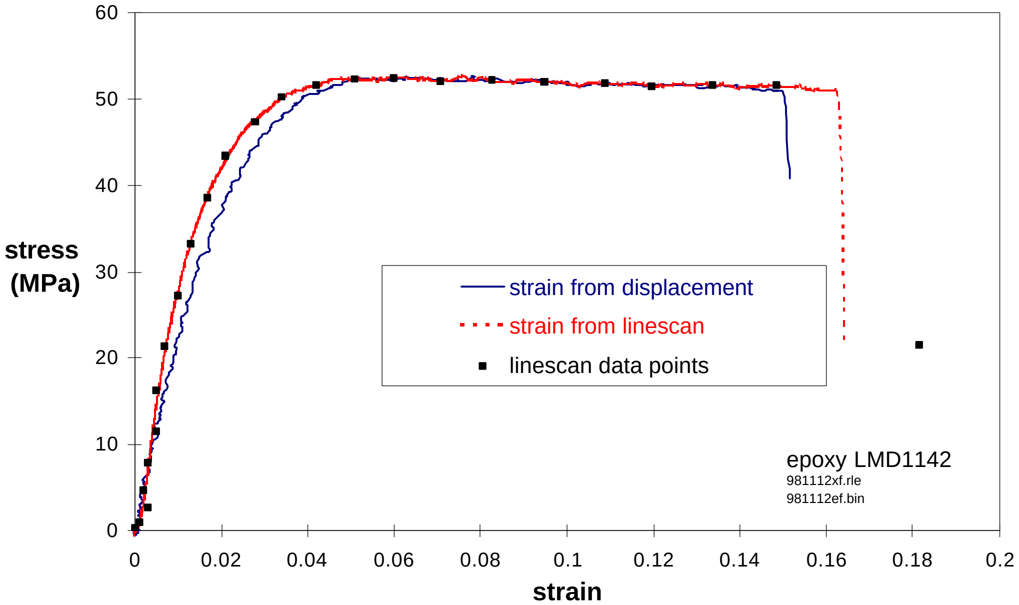

Figure 15: Tensile stress-strain measurement for epoxy LMD1142 at 1 m/s

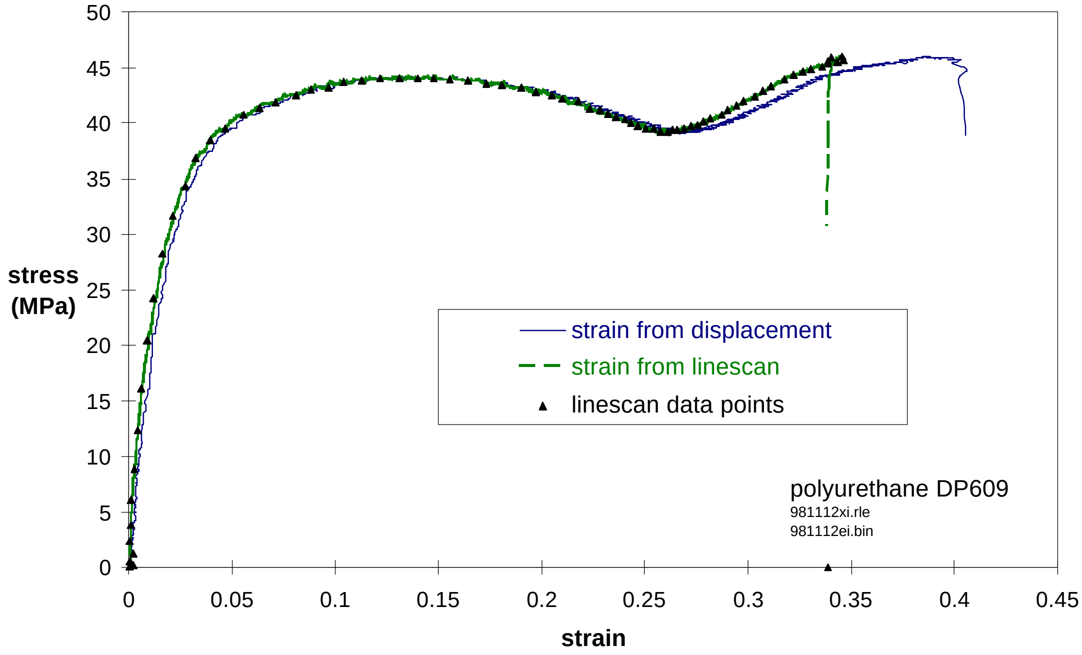

Figure 16: Tensile stress-strain measurement for polyurethane DP609 at 1 m/s

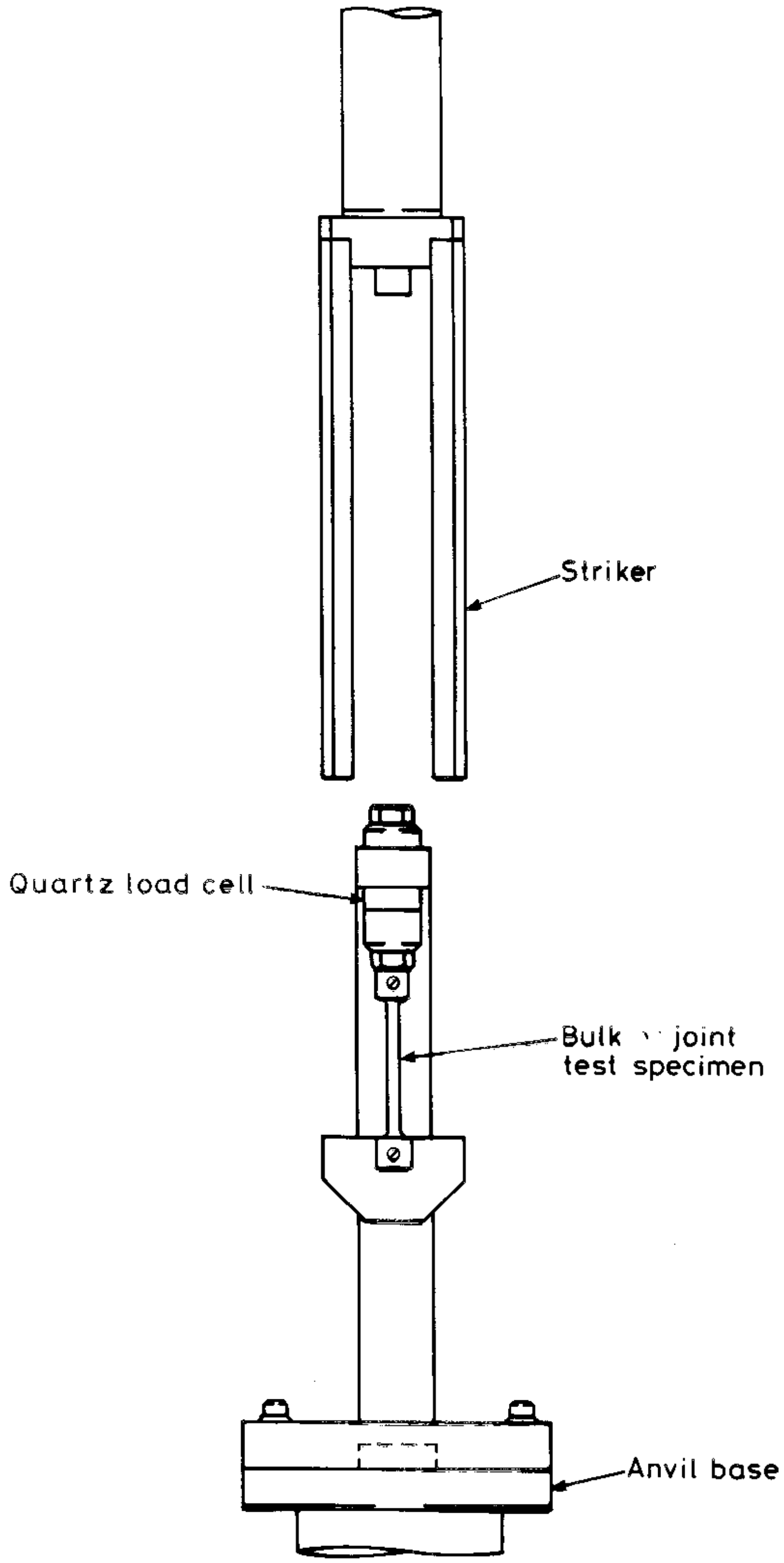

Figure 17: Tensile impact apparatus

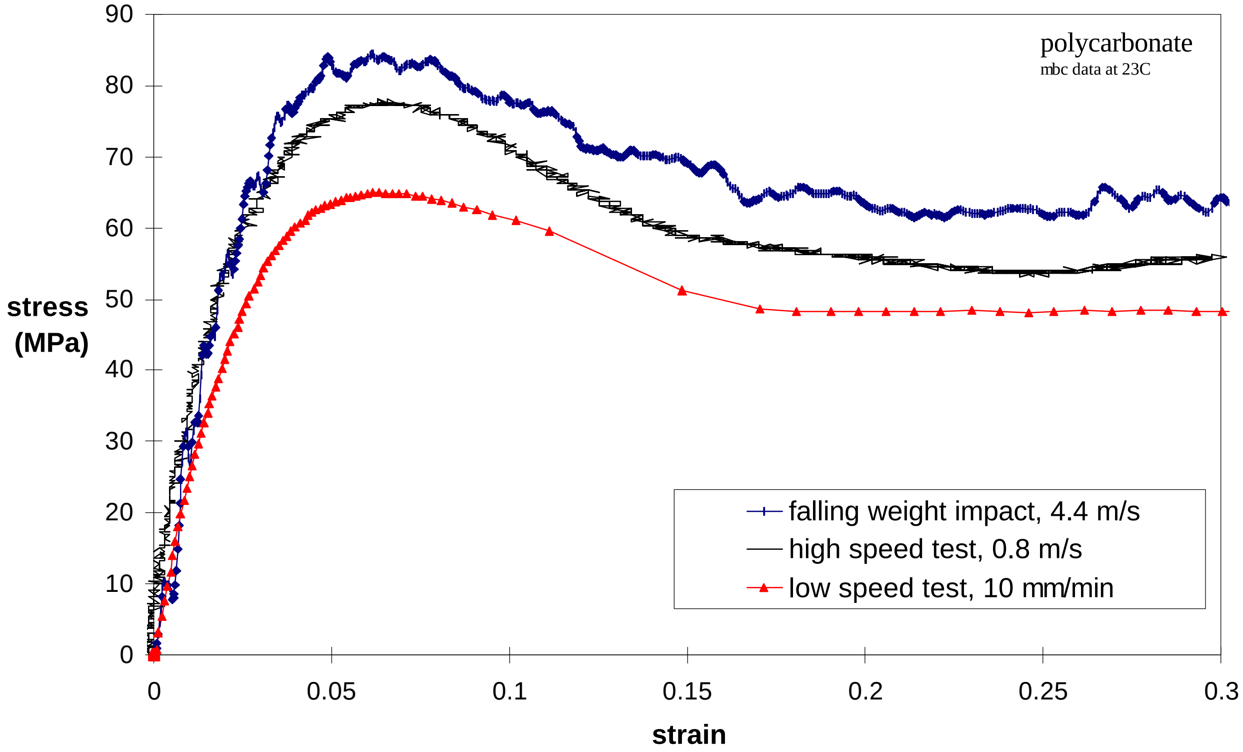

Figure 18: Stress-strain curves determined in tensile impact and constant displacement rate tensile tests