

Project PAJ2: Report No 6
Project CAM6: Report No 4

Development of a High Rate Extensometer

B C Duncan

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SUMMARY

This interim report summarises progress on the development of an extensometer for measuring strain at high rates of strain. It details progress on developing a high speed linescan camera system. This work forms part of milestones 2/3 on project PAJ2 and milestones 2/3 on project CAM6 that are concerned with the acquisition and analysis of mechanical design data for impact loading of adhesives and plastics.

The measurement of mechanical data at high rates is a specialised and difficult process. Accurate strain measurements are needed to obtain the accurate materials data required by computer aided design systems. Commercial apparatus to measure strain at high rates is limited in capability and expensive. As part of the MTS project, work has been directed at developing an alternative and less expensive method for strain measurement. A linescan camera, which combines both acceptable linear resolution and high data capture rates, was identified as a potential high speed extensometer. An EG&G Reticon linescan camera with a 2000 element detector and scan rate of up to 10,000 lines per second has been purchased and interfaced with a personal computer. Prototype software has been written to control the camera, analyse and locate the edges of gauge marks and store data.

Initial measurements have demonstrated that the linescan camera can function adequately as an extensometer. Tensile stress-strain curves for polypropylene specimens were measured at strain rates up to 2 s^{-1} , which is the upper rate for conventional extensometers. They are in reasonable agreement with the conventional extensometry data. Some technique development has been performed and further work will be undertaken in these projects with the aim of enabling the extensometer to be used more routinely and reliably as a measurement instrument.

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National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

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

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Interim Report on High Rate Extensometer

B C Duncan

1. INTRODUCTION

Computer aided design methods for impact performance require reliable test data at both high strain rates and large strains [1, 2]. These data are difficult to obtain for polymeric materials such as plastics and adhesives. The aim of the MTS projects PAJ2 and CAM6 is to improve techniques for measuring and analysing such data. This interim report describes development of an instrument to measure strains at high rates.

Measurements of strains at high rates are needed to obtain accurate mechanical test data which are required for predicting the behaviour of structures under impact. High rate tests can be carried out using either servo-hydraulic test machines or impact tests on tensile specimens. Force measurements are straight forward provided that extraneous information, due to shockwaves or resonances, are minimal. These will be described further in the final report. Measurement of strains in the specimen presents more of a problem.

Conventional clip-on extensometers, which give good accuracy [3], are unable to perform reliably at both the large strains and high strain rates required to obtain data for impact modelling. Crosshead displacement can be used to estimate strain and using procedure given in appendix I. Estimates of strain from overall crosshead displacement cannot give local strain behaviour (eg in the formation of necks). This interim report summarises progress to date on the development of a high rate extensometer for use in projects CAM6 and PAJ2 of the DTI MTS programme.

Two high rate extensometers are marketed. The first is an electro-optical extensometer produced by Zimmer. This instrument costs well in excess of £20,000 and the UK supplier could not recall selling any. The second was a system sold by Zwick which works by monitoring the movement of laser reflectors attached to the grips of the test machine. This is slightly more sophisticated than measuring crosshead movement as it eliminates the compliance of the test machine but does not give local strains in the test specimen. Neither of these methods was considered entirely appropriate, the Zimmer instrument because of cost and the Zwick system because it offers little improvement over measuring crosshead movements. It was decided to develop an alternative instrument.

The method selected to measure strains is high rate imaging where the separation of gauge marks applied to the surface of the specimen is determined from the light intensity pattern on a CCD camera. This is the principle of video extensometry. However, traditional video extensometers have relatively slow measurement speeds due to the need to read and process the large amount of information from the rectangular array of light sensitive CCD elements in the video camera. To obtain the high measurement speeds required high speed cameras are needed. High speed film cameras are expensive and large quantities of films would need to be developed leading to high running costs. High speed electronic cameras are very expensive and it is unlikely that they could store or process sufficient images to

capture an impact event. The solution adopted was a linescan camera - where the array of CCDs in an electronic camera has been replaced by a single line of light sensitive elements. Such cameras are relatively inexpensive (ca £7k).

This report summarises progress on the development of a high speed extensometer based on a linescan camera.

2. EQUIPMENT DEVELOPMENT

2.1 HARDWARE

The high speed extensometer is based on a linescan camera supplied by EG&G Reticon.

The basic elements to this linescan camera are:

Reticon LC1912 Linescan Camera	2048 light sensitive elements in a linear array; 20 MHz maximum clock frequency; 10,000 lines per second maximum scan speed.
Reticon RS1910 Camera Controller	Powers the camera; Enables manual control.
Reticon SB1956 Linescan Processor Board and Software	Interface board enables the camera to be run from a PC and data storage; Basic operating software and library of board functions supplied.
Macro lens	Magnifies image of specimen.
Through the lens viewer	Used to align and focus the camera.

The linescan processor board and software supplied were installed in a 33 MHz 486 Elonex PC. Both the board and software date back a few years and it was not possible to install the system in a more modern pentium PC.

The camera is connected directly to the RS1910 controller that is in turn connected to the SB1956 interface board. The basic software supplied enables basic control of the camera and can display single scans. It does not allow for the storage of multiple scans (at any scan speed).

The macro lens and extension tube give high magnification images of the specimen (up to 1:1) but with the extension tube the focal length is small. To work with the camera further than 300 mm from the specimen (normally the case particularly if an environmental chamber is fitted), the extension tube was removed. This reduces the magnification but should still give acceptable resolution.

2.2 SOFTWARE

To convert the linescan camera into a functioning extensometer it was necessary to write software (in C language) to carry out the following functions:

1. load configuration files and look-up tables which contain camera control settings;
2. calibrate gain control to maximise contrast;
3. set test parameters (scan rate, etc);
4. set a threshold intensity to detect marks through changes in contrast (edges in the scan);
5. scan continuously, recording locations of edges on each scan;
6. save edge locations to a file for later processing.

The software to run the camera as an extensometer was written by the Centre for Information Science and Engineering at NPL. To minimise the quantity of information to be transferred through the computer bus (which could limit the rate of data acquisition), the software utilises the edge detection facility of the processor board. In essence, each scan is analysed and the element numbers are recorded where the intensity detected passes a pre-set threshold (either direction). This greatly reduces the amount of information to be processed within the computer. For two gauge marks with optimum contrast, the information from 2000+ light sensitive elements can be reduced to just 4 numbers (representing the locations of the edges of the marks).

There are a number of bugs in the software that prevent the extensometer from being used reliably.

2.2.1 Known Problems with the Software

1. Memory allocation problem: The total number of scans requested (particularly if large i.e. >1000) may not all be recorded. In some tests, very few scans are recorded and the test can be missed - this may be associated with noise creating too many 'edges'. There seems to be no warning of when a problem will occur and little difference between the contrasts of good and bad tests. The limit to the number of scans recorded is also a problem at high rates where the scan will be over in fractions of a second - during which the test machine needs to be activated.
2. The intensity calibration function, used in stage 2 above, will not run. At present, gain factors are set using the calibration functions in the original software supplied by Reticon. It is inefficient to need to run two separate programs to set-up and make measurements.

3. MEASUREMENT TECHNIQUE

3.1 ILLUMINATION AND SPECIMEN MARKING

It is critical that the contrast between the gauge marks and the specimen surface is as large as possible to give clearly defined edges. At fast scan speeds, the amount of light falling on the photo sensitive elements is low and the sensitivity of the camera is poor. Under normal room illumination it is impossible to pick out marks from the specimen background at scan

rates above ca 100 scans per second. Directly illuminating the specimen with an angle poise lamp makes little difference.

More intense illumination is possible with a floodlight (300 W bulb) which provides a uniform field of illumination over the specimen. But even with this, contrasting marks on the specimen surface are only visible at scan speeds of a few hundred scans per second. The only method that allowed mark detection at high scan speeds was to attach reflective marks to the surface of the specimen. By angling the camera and the light source so that the light was directly reflected off the marks onto the active array of the camera, it was possible to obtain sufficient intensity to distinguish marks up to the fastest scan rate of the system (10,000 lines per second).

One possible drawback of the requirement for a bright light source is that the specimen may be heated up by the lamp. If at all possible, the specimen should be enclosed by an environmental chamber and illuminated through a window. This should absorb some of the infra-red component of the illuminating light and the test environment can be actively controlled. Care also needs to be taken when interpreting strain data as the reflective marks made on the specimen may slip during a test (which would appear as a 'strain').

3.2 RESOLUTION

The resolution and accuracy of the extensometer are limited by both spatial and temporal considerations. These need to be considered when assessing the accuracy of the instrument.

3.2.1 Spatial Resolution

The absolute resolution of the extensometer is determined by the number of elements between the gauge marks. The larger the number of elements between the marks the higher the resolution. However, the field of view has to be large enough to accommodate the movement of the marks during the test. The camera has a 2048 length array of photosensitive elements. A gauge length of around 1000 elements gives a resolution (smallest detectable change is 1 element) of 0.001 but should still be able to cope with strains of around 0.25-0.3.

The uncertainty in the position of an edge is normally a maximum of ± 1 element. By the time the averaged mark positions are used to calculate gauge lengths the uncertainty is typically of the order of ± 1 element (or 0.001 for 1000 element gauge length).

3.2.2 Temporal Resolution

As the exposure time of the scan is long relative to the interval between scans and the number of scans recorded in the duration of the test may be small then there will be limitations on the resolution of the extensometers due to the resolution in time. As an example, if the strain rate of the test is 100 s^{-1} , the strain to failure 0.1 and the scan rate is 10,000 scans per second then the resolution of the extensometer is limited by the following:

duration of test = 10^{-3} s;
number of scans = 10;
interval between scans = 10^{-4} s which is equivalent to 0.01 strain;
strain change during each exposure < 0.01.

Thus the temporal resolution of the extensometer will be at best 0.01 that is significantly worse than the nominal spatial resolution. In such a case it may be worthwhile to reduce the active area of the array (which can be set in the control programme). This would increase the scan rate (and thus improve the temporal resolution) but decrease the spatial resolution. The best resolution of the extensometer would then occur when the temporal and spatial resolution are comparable. At slower strain rates (below 10 s^{-1}) the temporal resolution should be no worse than the spatial resolution provided that a sufficiently fast scan rate is chosen.

3.3 METHOD OF STRAIN DETERMINATION

The principle of strain measurement is to determine change in the distance between two contrasting marks on the specimen surface. For a flat field of view, the gauge length is simply the number of elements between contrasting edges in the scan. As the specimen is deformed, this distance (d) increases. Strain (ϵ) is then calculated using the increase in distance divided by the initial mark separation (d_0):

$$e = \frac{d - d_0}{d_0}$$

In Figure 1, an idealised scan for a dark specimen with two light coloured gauge marks is shown. Four element values (M1, M2, M3 and M4) where the intensity crosses the threshold value will be returned by the edge detection function.

If there is noise in the scan then the mark position may be given by several element values. The mark position then should be calculated as the mean of these element values. Typically, the stability of the edge location is to within ± 1 element. Strain is determined from the separation or gauge length of the two gauge marks. The average position of the two marks G_1 and G_2 are given by $(M1+M2)/2$ and $(M3+M4)/2$ respectively. The gauge length ($G(t)$) is therefore $G_2 - G_1$. As the specimen is deformed then the positions of both G_1 and G_2 will increase as will the gauge length. Figure 2 shows the positions of two gauge marks recorded during a test. The data recorded before the start of the test define the initial gauge length G_0 . The values for G_0 will normally be within ± 1 of the mean value for G_0 . The current gauge length $G(t)$ is calculated from the separation of the two marks. The strain as a function of time ($\epsilon(t)$) is thus:

$$e(t) = \frac{G(t) - G_0}{G_0}$$

The calculated values of strain can be plotted against time (from start of the test). As shown in Figure 3, a best fit line can be fitted to the strain vs time plot. This fitted line enables

strains to be interpolated at any time. This is important as the strain data has to be combined with a record of load vs time to give a stress-strain curve. It is not possible to simultaneously record strain and load on the same recording device. Two data recording devices are needed which record the strain and load from the same test separately. These have to be combined during the data analysis phase. The fitted function that relates strain and time can be used to calculate strains at each time interval in the load vs time record and, from this, the stress-strain curve can be derived.

It is important that the start times of the load and strain records are synchronised. It is likely that both records will contain 'pre-trigger' data before the test machine is activated. The actual start of the test on each record may not be precisely defined and normally must be estimated from the beginning in the rise in the values measured. Where this rise begins slowly and accelerates, the start of the test may be difficult to pick out, particularly if there is low instrument resolution or noise. Typically, resolution in the force signal or crosshead displacement will be greater than that of the linescan extensometer. One method of synchronising the two records is to determine the duration from the activation of the test machine to failure of the specimen using the load or displacement data. This defines the time at which the specimen is seen to fail on the linescan record (assuming this is obvious from the trace). The entire strain-time trace can then be generated by subtracting successive time increments from this time at failure until the time value reaches zero. This should coincide with the part of the record where the strain starts to increase.

4. ILLUSTRATIVE DATA

Measurements have been made to illustrate the use of the linescan camera as an extensometer. Two tests are illustrated. One was made at a low strain rate using a low speed electro-mechanical test machine. The second was performed at a high strain rate (for which clip-on extensometer data was available) using the high speed servo-hydraulic machine.

A stress-strain measurement was made on a sample of polypropylene tested at room temperature at a speed of 100 mm/min (strain rate $\sim 10^{-2} \text{ s}^{-1}$). This is a relatively slow speed test made on an electro-mechanical test machine where data acquisition is relatively straight forward. The linescan camera was run at a relatively slow 100 scans s^{-1} . As the scan rate is low conventional lighting (fluorescent tubes mounted by the window on the test chamber) could be used. Figure 4 shows a comparison between a stress-strain curve for polypropylene derived from the data generated from the linescan camera (and a recording of load against time) and data measured using a conventional video extensometer. There is very good agreement between the two techniques. It is generally recognised that the accuracy of video extensometers is relatively poor at low strains where elastic moduli are measured (0.0005 to 0.0025 strain). The modulus of polypropylene at this rate and temperature (measured by clip-on extensometers) is approximately 1680 MPa. The value for the modulus determined using the linescan extensometer was 1865 MPa which is within 10 % of the actual value. This level of accuracy is typical of video extensometers (the conventional video extensometer gave a value of 1750 MPa).

Figure 5 shows a stress-strain measurement made on polypropylene at a faster speed of 5000 mm/min ($\sim 0.1 \text{ ms}^{-1}$) which is the highest speed at which clip-on extensometers were used. The strain rate in this test is around 2s^{-1} . The scan speed was 1000 scans per second. This high speed required an intense illumination source and reflective marks were attached to the specimen to give bright 'targets'. The data generated by the linescan are compared with two other stress-strain curves. The first curve was generated from the force and displacement data measured in the test (where displacement data were converted into strains using the procedure in Appendix I). The second curve is an earlier test where clip-on extensometers were used. The repeatability of test data measured on the servo-hydraulic machine is not as good as the electro-mechanical machine as is shown from the differing values of stress at the high strain plateau region. The stress-strain curve measured using the linescan camera shows the same general shape as the other stress-strain curves. There is a small difference between the strains measured but in general the curves are close. The differences between the strains may be due to a problem in synchronising the 'start' of the different records. There is also a need to check the time difference separating individual scans on the linescan camera to confirm that the period between scans is exactly equal to the reciprocal of the scan rate as assumed here.

5. CONCLUSIONS

The initial phase of development has been completed. The linescan extensometer has been assembled and software for data acquisition written. A technique for determining strains from the output has been outlined. The test data show that the linescan camera can function as an extensometer with reasonable accuracy.

The next steps are to further refine the software to eliminate the bugs present. Measurement procedures need to be developed to improve reliability.

6. FUTURE WORK

1. Further software development to eliminate bugs in the software.
2. Develop methods for illuminating and marking specimens so that reliable data can be obtained routinely. Particular attention needs to be paid to illuminating the specimen within an environmental chamber where reflections may cause problems.
3. Use the camera to validate at high strain rates the function used to obtain strain data from displacements.
4. Assess accuracy and repeatability of the high rate extensometer.
5. Determine whether strains can be measured in impact tests.

There may be some potential for commercially developing this instrument for high rate strain measurement. As the instrument stands, it is complicated to set up and use and is not yet suitable for routine work. Experienced and skilled staff would be needed to run it. The following points would need to be addressed before it could be commercialised.

- User friendliness of software.
- Triggering of extensometer automatically with the test.

- Illumination issues - supply a light source with the instrument?
- Automation of the conversion of edge locations into strain.

7. REFERENCES

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3. Duncan B.C., Dean G.D. and Tomlins P.E., Tensile testing of bulk and thin film adhesives, Proceedings of EURADH'96, Published by the Institute of Materials, September 1996.

8. ACKNOWLEDGEMENTS

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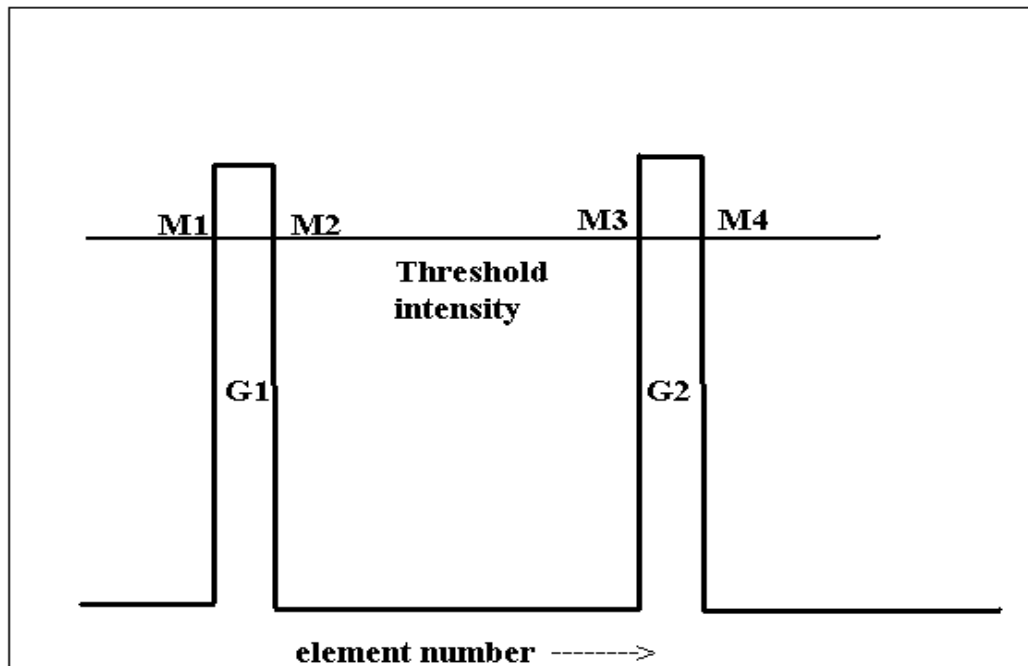


Figure 1: Linescan for two light coloured marks on a dark specimen used to determine gauge mark positions (G_1 and G_2) used for strain measurement.

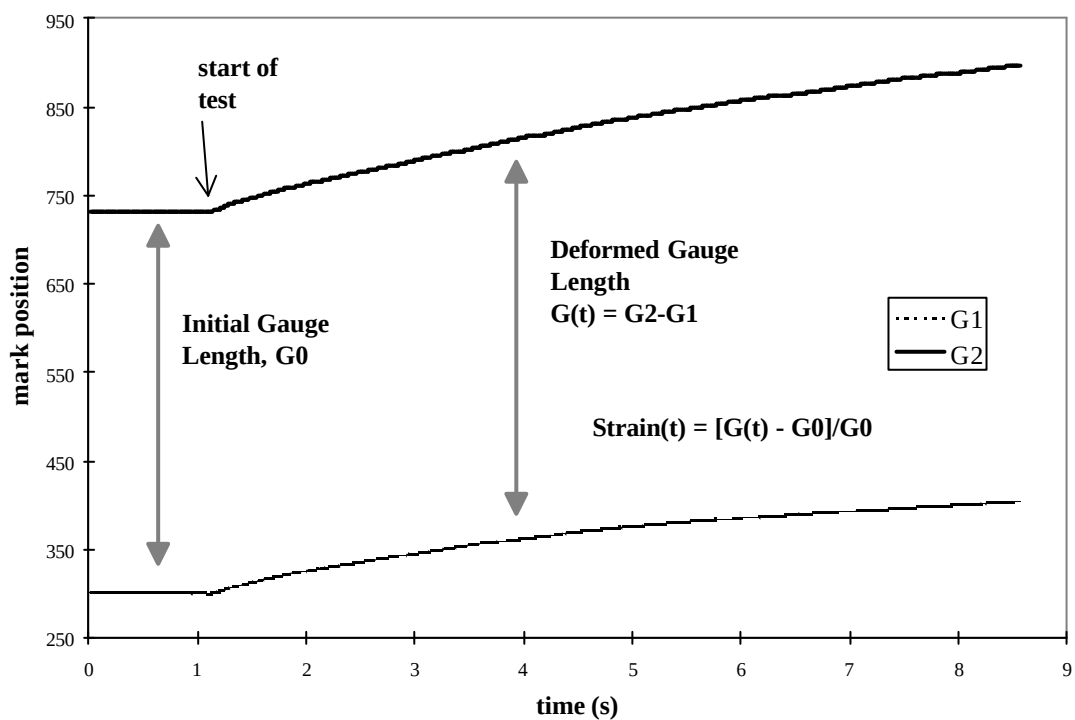


Figure 2: Plot of mark position against time used to calculate strain as a function of time.

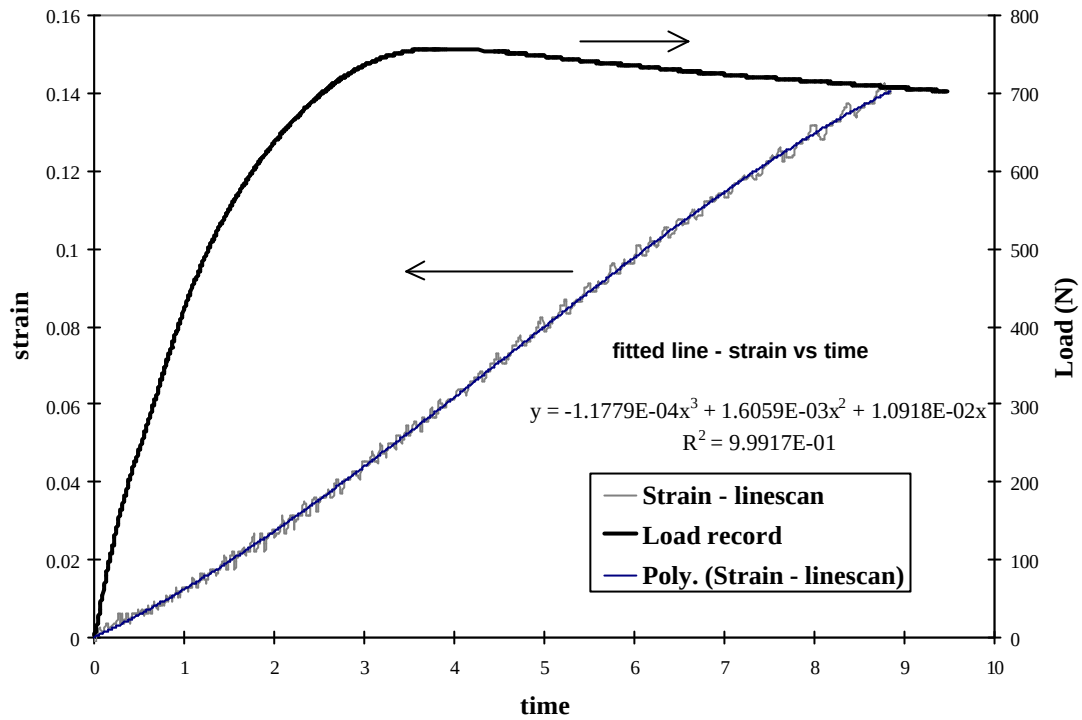


Figure 3: The records of strain vs time and load vs time need to be combined to produce a stress-strain curve.

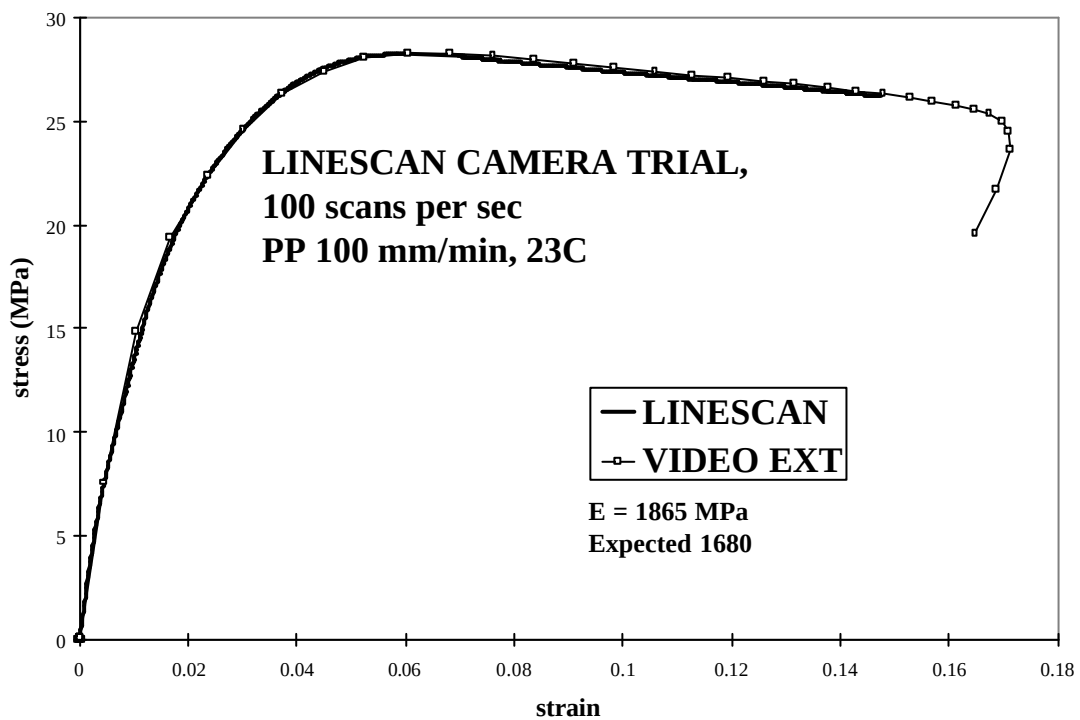


Figure 4: Comparison between linescan camera and conventional extensometer at low strain rate.

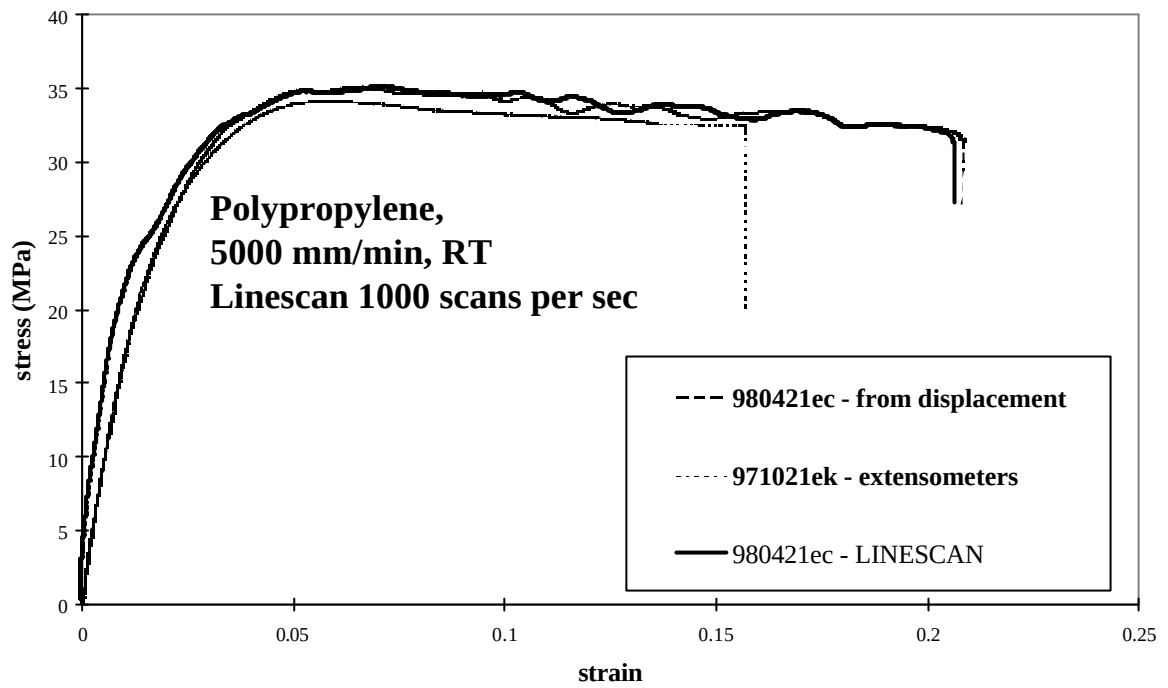


Figure 5: Comparison between linescan and alternative strain determination methods at a high strain rate.

APPENDIX I DETERMINING STRAINS FROM CROSSHEAD DISPLACEMENT

It is possible to estimate strains in the gauge section of the tensile specimen from the movement of the crosshead of the test machine. One means of doing this is to simultaneously measure displacement of the crosshead and strain using clip-on extensometers simultaneously. The relationship between strain and displacement is then modelled using a polynomial function. This relationship needs to be extrapolated to high strain rates. One disadvantage of this method is that strains can only be estimated with confidence up to the limit of the extensometer travel.

The following section explains how a relationship between strain and displacement was determined for specimens tested using the Instron 1143 high rate servo-hydraulic test machine.

Equipment Used

Instron 1143 servo-hydraulic test machine with 8500 control panel	Maximum speed $\sim 2 \text{ ms}^{-1}$ Grip separation = 65 mm Displacement transducer outputs available direct and through 8500 panel
Pair of Instron clip-on extensometers conditioned through 8500 panel	Gauge length = 25 mm Travel $\sim \pm 2.5 \text{ mm}$ Maximum strain ~ 0.1
Digital storage oscilloscope	
Digital voltmeter	

The 8500 control panel digitises the measured signals (displacement, extensometers, load). There is a maximum rate at which this system can operate and above that the data are sent as single values in 200 μs 'bursts'. For high speed tests, where the test duration is a few ms, this gives very poor resolution. There is also evidence that suggests that this digitised signal is 'delayed' in the processor and lags the actual response. This problem limits the reliable use of these digitised signals to crosshead speeds of 0.1 ms^{-1} or less. It is possible to take an analogue output directly from the crosshead displacement transducer, bypassing the 8500 panel. This has a much faster response rate and is more suitable for the highest speeds. Using the voltmeter it is possible to determine a calibration factor for this transducer in Vmm^{-1} . The extensometer signals can only be accessed through the 8500 panel. Hence, the highest speed for which simultaneous measurements of strain and displacement can be made is 0.1 ms^{-1} .

The procedure for determining the strain-displacement relationship is to perform tests using the same material, shape of specimen and crosshead separation at different rates (normally 50, 500 and 5000 mm/min). Strains are measured using a pair of clip-on extensometers and the crosshead displacement from the displacement transducer. The average strain (ϵ_a) from the extensometers is plotted against displacement (d) as shown in Figure 1a. A quadratic best fit line, of the form $\epsilon_a = A_1 d + A_2 d^2$, is fitted to the data. The values of the fit

parameters A_1 and A_2 are then plotted against $\log(\text{strain rate})$ to determine if there is any significant rate sensitivity. In practice, rate dependence is low and the mean values of the parameters A_1 and A_2 can be used to estimate strains from displacement measurements where extensometers are not used (eg at high rates). The values of the fit parameters A_1 and A_2 are related to the stiffness of the specimen and will change with material, specimen thickness and temperature. They must be re-evaluated when any of these change significantly. Figure 1a shows strain-displacement relationships for 3 different polymers.

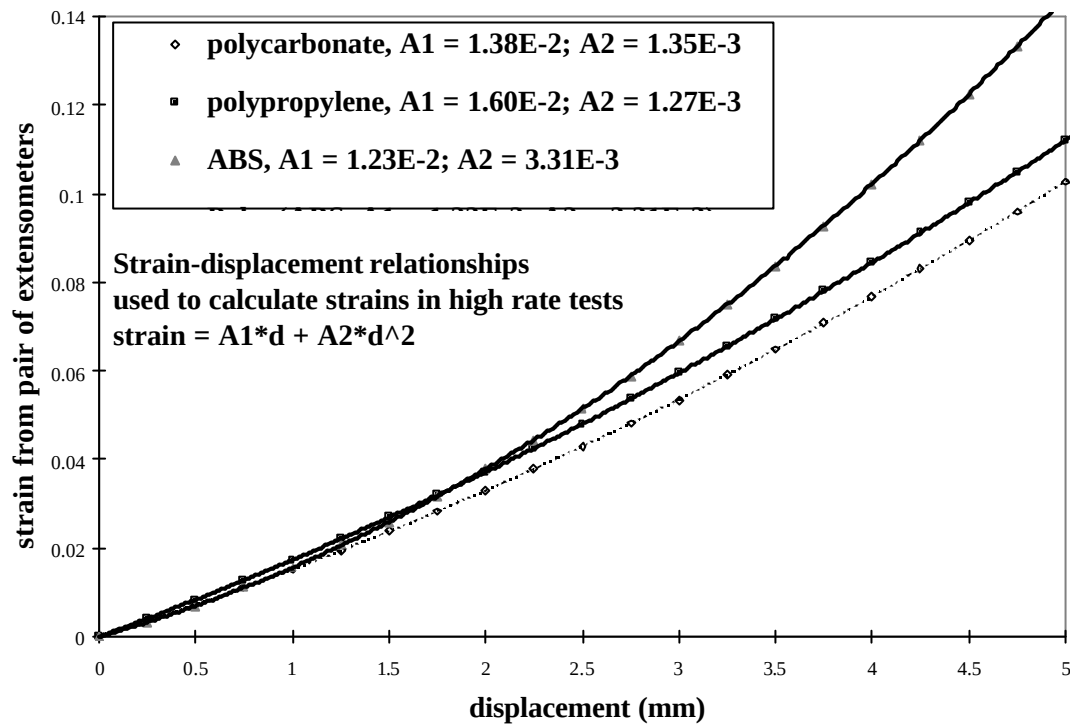


Figure 1a: Strain-displacement relationships used to determine strains in high rate tests.