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Project PAJ2 - Dynamic Properties of Adhesive Bonds

Report No 9

COMPARISON OF IMPACT AND HIGH RATE TESTS FOR DETERMINING PROPERTIES OF ADHESIVES AND POLYMERS NEEDED FOR DESIGN UNDER IMPACT LOADING.

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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 a suitable model for the material behaviour and material properties at appropriate strain rates. An aim of this project PAJ2 was to establish methods for determining such material properties at high strain rates that would be suitable as FEA input. In this report, the abilities of high speed servo-hydraulic test machines and instrumented falling weight impact apparatus for generating high strain rate, tensile test data suitable for design have been assessed. The data generated by these tests are less accurate than from conventional test equipment operating at lower strain rates. If this limitation is born in mind then the data can be used for design purposes. The data generated from falling weight impact tests are inherently noisier than data from the high rate test machines. However, where strains to failure are reasonably large (ca. 0.1), and the signal to noise ratio is acceptable, it should be possible to extract design data from the tensile impact test.

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1. INTRODUCTION

The increasing use of light weight materials such as plastics and adhesives in structural applications necessitates the use of alternative design philosophies. Toughened adhesives are visco-elastic, and exhibit non-linear behaviour prior to failure. Their load response is strongly influenced by the rate of applied strain and the stress history of the sample. One of the most powerful design tools for evaluating structures containing plastics or adhesive bonds is FEA, Finite Element Analysis [1,2]. FEA can be used to predict the deformation of a structure under load to assess its rigidity and resistance to impact loading. FEA may also be used to perform stress analyses to identify areas in the adhesive where stress concentrations, which are sites for failure initiation, will develop. Alternative designs may be evaluated using FEA thus avoiding the expense of building or testing prototypes.

The performance requirements of the material will relate the application, e.g. energy absorbent interior trim in cars or adhesive bonds that retain integrity in the event of a crash. However, materials property data at high strain rates will be required for use in the FE analyses. The behaviour of visco-elastic, polymeric materials may be approximated through elastic-plastic models. Many of the data requirements for implementing elastic-plastic analyses can be satisfied through tensile stress-strain measurements [1].

Accurate mechanical properties at appropriate strain rates are critical for reliable modelling of structural adhesives and polymers under impact. An objective of project PAJ2 of the Materials Metrology Programme Performance of Adhesive Joints was to develop methods for determining these properties. This report compares two methods, high speed servo-hydraulic test machine and falling weight impact, for determining the mechanical properties of adhesives at high strain rates (up to 100 s^{-1}). These devices are capable of generating test speeds in excess of 1 ms^{-1}. Impact instruments are less expensive and more widely available than high speed test machines. However, it is thought that there may be more problems with interpreting data measured in impact tests. Strain measurement at high strain rates is a further challenge. Other project reports describe techniques for determining strain [3, 4].

2. TEST MACHINES

Polymers have rate and time dependent properties. They may be used in applications where the applied rate of strain varies from very low (creep) to extremely high (impact). There are no test machines currently available that will span the range of strain rates (from $< 10^{-6}$ s^{-1} to $> 10^{2}$ s^{-1}) required for full characterisation (even if creep is ignored).

2.1 LOW RATE TEST MACHINES

Low and intermediate strain rate data (up to ca. 10^{-2} s^{-1}) can be measured with high accuracy on standard electro-mechanical test machines such as an Instron 4500 series machine. Measurement methods were established in an earlier project [5, 6].

2.2 HIGH RATE TEST MACHINES

2.2.1 Servo-Hydraulic Test Machines

Servo-hydraulic test machines, such as an Instron 1343, can be used to carry out intermediate and high strain rate tests (from c.a. 10^{-2} s^{-1} to c.a. 100 s^{-1}). The crosshead is driven by forcing high pressure hydraulic fluids into a piston. Depending on the size of the actuator valve system, crosshead speeds up to several ms^{-1} can be achieved. A schematic of this type of test machine is shown in Figure 1. These machines are less readily available in test labs than low-speed electro-mechanical machines. Often development of computer control or data analysis systems has lagged that of the electro-mechanical machines making the acquisition and analysis of test data more complicated. In this work an Instron 1343 servo-hydraulic test machine (with an upgraded 8500 digital control panel) with an obtainable top speed of ca. 2 ms^{-1} was used. The outputs of the force, strain and displacement transducers were captured using a Gould Data Systems 840 digital storage oscilloscope that records 5000 data points at 16 bit resolution. The data were transferred to a PC for analysis using Gould Transfer Acquisition (v 2.10.12) software.

2.2.2 Force Measurement

Force measurements were made using a Kistler 50 kN piezo-electric load washer that fixed into the load assembly. The load washer was between the rigid base of the test machine and the lower specimen grip. This force transducer and signal conditioning amplifier system have the high response rate needed to measure forces at high test speeds. This high speed capability is at the expense of longer term stability and it is noticeable that the force transducer output will drift with time. This precludes the use of this load cell in quasi-static tests. The drift is more significant at non-ambient temperatures.

The hydraulic system driving the test machine can be a source of noise in the measured data. Vibrations (which can be felt in the load train) are transmitted via the crosshead to the specimen and load cell. In order to compensate for these vibrations and the drift of the force transducer, zero force was defined from the force transducer output after failure (provided that the force trace was flat). This was used to determine the initial stress (and strain through the assumption of an appropriate modulus). Vibration and drift typically gave stress offsets of between -2 MPa and +2 MPa.

2.2.3 Application of Deformation

The movement of the crosshead is driven by forcing high pressure hydraulic fluid into a piston. There is a period of acceleration of the crosshead as the flow pressure increases. The speed of the crosshead will not be constant during the test but will accelerate until a constant velocity is achieved. At relatively slow test speeds there should not be any significant effects on the test data. The acceleration will take place in a relatively short period of time and is likely to be over whilst the material is still in the low strain elastic region. At high speeds, the period of acceleration is a greater proportion of the test duration and variation of strain rate during the test will be more significant. Furthermore, at high speed settings the profile of the pressure pulse in the hydraulic fluid within the machine may cause variations in the crosshead speed. An example of this is shown in Figure 2. The instantaneous crosshead speed (determined from the slope of displacement against time) both overshoots (1.4 ms^{-1}) and undershoots (0.4 ms^{-1}) the nominal set speed (0.83 ms^{-1}). The fluctuations in the crosshead speed are reproduced in the measured load trace. The yield behaviour of the adhesive shown (polyurethane DP609) is very sensitive to strain rate.

One method of reducing the acceleration effect is to use a ‘loss motion device’ (LMD) between the moving and stationary parts of the test machine. LMDs allow some travel of the crosshead before the load is picked up and applied to the test piece. During this travel, the crosshead should reach the test speed and, hence, the test piece should experience a constant rate of deformation. However, LMDs will not remove the longer time fluctuations in the crosshead speed shown in Figure 2. One disadvantage of using a loss motion device is that the ‘impact’ at the end of the travel of the LMD can introduce shock waves in the specimen causing noise in the measured force data. This can significantly reduce the accuracy of the measurements.

Variations in strain rate during tests may occur even if the crosshead speed is constant. This is simply because the compliance of the test piece will fall relative to that of the test machine as the material yields. This will lead to a higher proportion of the applied displacement being applied to the specimen as strain and, thus, an increase in strain rate occurs. It has been observed that, typically, the rate of strain will increase by a factor of ca. 2 between the elastic and yield regions due to this effect alone. It is unlikely that the speed of the crosshead can be controlled (particularly at high speeds) sufficiently to compensate. The acceleration in the rate of strain will be more pronounced if a neck forms in the specimen. For these reasons, LMDs were not used for testing bulk test pieces. Where data were determined as a function of strain rate, the practice was to quote the local strain rate in the specimen in that section of the stress-strain curve. LMDs need to be used when testing adhesive joints where the displacements are much smaller.

2.3 FALLING WEIGHT IMPACT APPARATUS

Impact tests can be used to generate test speeds from upwards of about 1 ms^{-1}. Two types of apparatus, pendulum and falling weight, are commonly used for impact measurements. For extremely high rate work, split Hopkinson’s bar and explosive driven apparatus have been used [7]. These techniques were not used in the current project. Pendulum machines often have limited striking energies that are often not sufficient to break modern, tough adhesive specimens. These instruments are not considered in this report. In falling weight tests extra kinetic energy can be obtained by increasing the drop mass or by increasing the drop height (which also increases impact speeds).

Modern impact apparatus is typically instrumented with an accelerometer or force gauge but some older instruments only determine the energy lost in breaking the specimen. Impact energy alone may be suitable for ranking adhesives for impact strength (in the particular specimen geometry used) but is not suitable as general purpose design data [8]. To measure data suitable for design calculations, the test must be instrumented and provide at the very minimum a trace of force against time from which stress-strain data can be determined.

There are a number of standard impact test methods for bulk test specimens, such as Izod [9], Charpy [10], falling dart [11] and tension pendulum [12] which give impact energies. However, none of these provides stress-strain data that are suitable for designing adhesive joints. Impact strengths for adhesive joint specimens can be measured directly using methods such as block shear [13, 14, 15], tensile lap joint [15, 16] or the 'Boeing' impact wedge test [15, 17]. Data from these joint tests are generally not applicable to other bond configurations as the stress states are ill defined and the adherends have a considerable influence on the results. Another approach is through fracture mechanics where considerable work has been done [18]. This approach requires the presence of a notch, whereas designers often need to predict the onset of fracture. With suitable adapters, standard test specimens, such as the bulk tensile, can be tested to give stress-strain data under defined stress states.

2.3.1 Apparatus

The falling weight impact tests were performed on a Rosand IFW5 machine with a tensile test frame. This frame used the same specimen grips as the high rate machine and used the same size of test specimen. It could also accommodate adhesive joint specimens. The frame used for performing falling weight impact tests is shown in Figure 3. The test specimen was clamped into a rigid frame that fitted to the bottom of the test machine. The falling mass strikes the freely-hanging lower grip. The reaction force transmitted through the specimen was measured by the force transducer attached to the top of the specimen frame and the fixed upper grip. This force signal is recorded onto a computer that controls the impact apparatus.

The instrument was controlled, and data logged, using Rosand IFW5 (v1.08) software supplied with the apparatus. Recordings were triggered when the striker passed an optical detector just before impacting on the anvil.

2.3.2 Force Measurement and Noise Reduction

Significant noise can be generated when the test duration is close to the period of a natural resonance frequency of the system. To reduce the effect of this on the load signal the lowest resonance frequency should be as high as possible. The resonance frequency depends on the stiffness of the system (where the load cell is the most compliant part) and inversely on the moving mass in the resonant mode. The stiffness of the load cell should therefore be as large as possible. However, since stiffness is linked to the load capacity, a high stiffness means lower force resolution. In the work reported here a 50 kN load cell was used which gave a compromise between stiffness and acceptable resolution (the maximum forces measured for some materials were around 500 N). To minimise the mass of the system, titanium grips, with low mass but high stiffness, were employed. The connections between the various parts of the tensile test frame should be as tight as possible to minimise dynamic vibrations during the test.

A further problem is that the impact will generate shockwaves that will travel through the specimen. From the test piece length and the speed of sound in the material it is possible to estimate the frequency of such shockwaves. The speed of sound (c_s) in a solid is related to its modulus (E) and density (ρ).

$$c_s = \sqrt{\frac{E}{r}}$$

Taking polycarbonate for example, E is approximately 2700 MPa and the density is approximately 1200 kg m^{-3}. Thus, c_s is approximately 1500 ms^{-1}. As the length of the specimen is around 75 mm, the time for a wave to travel a round trip through the specimen is ca. 10^{-4} s. Therefore, standing waves with a frequency of ca. 10 kHz would be produced. This agrees with the frequency of the ripples observed in the load-time traces such as Figure 4. Most noise generated in this way will be close to this frequency although the exact frequency is material dependent. The magnitude of the noise due to these reflected shockwaves will depend in part on the damping properties of the material.

It is possible to reduce the severity of these shockwaves in the data trace but such measures may affect the data gathered. The magnitude of the waves may be reduced by introducing a softer material between the striker and the anvil which 'cushions' the impact. Figure 4 shows the effect of using a variety of different methods to reduce the ripples seen on the data. Generally, the more effective the damping, the slower the 'pick-up' in the load values and the larger the shift on the location of the 'peak' in the force-time curve. The results suggest that a thin sheet of rubber gives a reasonable degree of damping but does not introduce too large a shift at the beginning of the trace.

A further method of reducing the magnitude of the noise is to filter the force cell response (either electrically or numerically). Figure 5 shows the effect of applying numerical filters in the Rosand software to an impact test measurement on a polycarbonate specimen. Reducing the filter frequency can lower the mean stress level at the peak and can shift the location of the peak. Filtering introduces the risk that some features of the data may be removed.

2.3.3 Crosshead Travel

Since the weight is freely falling and the kinetic energy is absorbed in the deformation of the specimen, there will be a steady reduction of velocity throughout the duration of the test. However, if the kinetic energy of the striker is much greater than the failure energy absorbed by the specimen then this deceleration of the striker will be small. For most practical purposes, the test will take place at a constant speed. To maximise kinetic energy, the mass of the striker was large and impact speeds were set by the drop height. The mass of the striker used was 12.5 kg and the drop height of 1 m gives an impact velocity of 4.4 ms^{-1}. The initial kinetic energy was 122.6 J. A typical specimen fracture energy of 20 J implies a final velocity of 4.05 ms^{-1} which is approximately 10% lower than the initial velocity. The reduction in rate is unlikely to significantly effect the material properties of the polymer. The rate of strain will still increase as the specimen softens.

Strains can be estimated from the movement of the grips if a suitable model is available to relate strain and displacement. The impact test data described in this report were analysed using the quadratic strain-displacement functions derived from the high rate test machine data [3, 4].

3. MATERIALS

Producing bulk test specimens of adhesives is relatively expensive. Thus, much of the initial assessment of the impact test was carried out using plastic test specimens produced for the Characterisation of Advanced Materials project CAM6. These are summarised in Table 1.

Table 1: Engineering Polymers

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

The adhesives studied in this work are summarised in Table 2.

Table 2: Adhesives

Adhesive	**Type**	**Supplier**
AV119	1-part toughened epoxy	Ciba
LMD1142	1-part toughened epoxy	Ciba
Plexus MA310	2-part toughened acrylic	ITW
DP609	2-part polyurethane	3M

4. LOW STRAIN (ELASTIC) PROPERTIES

For any design analysis the low strain, elastic properties of the material are usually required. These are normally satisfied through the determination of the Young's modulus and Poisson's ratio. As these properties are determined at small strains, accurate strain measurement is critical. Strain measurement at high speeds is unlikely to have sufficient accuracy to supply reliable data on modulus and Poisson's ratio [4].

4.1 MODULUS

The measurement of tensile modulus is specified in ISO 527-2 [19] by the determination of the slope of stress against strain in a tensile test between strains of 0.0005 and 0.0025 (0.05% to 0.25%). The standard, waisted specimen should be used for tensile measurements [20]. In the low strain region where moduli are determined the transverse contraction of the specimen is negligible and can be ignored in stress calculations.

Moduli can be accurately determined at low strain rates [5,6]. These seem to depend (linearly) on the logarithm of strain rate. Increases in modulus are typically 5% per decade of rate. These data can be extrapolated to estimate the modulus at high speeds.

4.2 ACCURACY OF HIGH RATE TEST APPARATUS

Earlier work has shown that clip-on, contacting extensometers give the most accurate measurements of strain at low strain rates [5]. These typically give values that are repeatable to within ± 2 %. Accuracy is maintained at the fastest speeds available (around 100 mm min^{-1}, strain rates ca. $1x10^{-2}$ s^{-1}). The modulus of glassy polymers typically increases by around 5% per decade of strain rate.

Tests made using the high rate apparatus were almost all tests to failure. Hence, experiments to establish the repeatability of measurements on single specimens have not been performed. Through reference to tests carried out on the low rate machine it is possible to estimate expected values. At the strain rates where the capabilities of the two test machines overlap ($1x10^{-2}$ s^{-1}), modulus values can be compared directly.

Moduli were determined for a number of adhesives and polymers using, clip-on extensometers and displacement measurements. These are compared with measurements from the low speed machine in Table 3. For each material the variability of modulus measurements is generally much greater from the high rate machine than from the low rate machine. This is most noticeable where more measurements have been made. The mean value may be comparable but the standard deviation of the data is larger. Where fewer measurements have been made, the standard deviation may be small but the mean modulus is not comparable with the low rate machine value. The clip-on extensometers are generally more reliable than using strains calculated from displacement measurements. One reason for this is that the parameters for the functions relating displacement to strain are the mean values determined from strain-displacement plots up to relatively large strains (ca. 10%). These fit parameters will not have good accuracy in the low strain region of the curve.

The variability of the moduli determined seems to increase as the test speed is increased. At the higher speeds, modulus values are so scattered that meaningful moduli determinations are difficult to make with any degree of confidence. This increase in scatter with rate is illustrated in Figure 6. It may be possible to use time-temperature superposition to derive moduli at the higher rates from tests at lower rates and lower temperatures.

4.2 MODULI FROM HIGH RATE AND IMPACT TESTS

The resolution of the high speed linescan extensometer developed within PAJ2 [4] was too poor for accurate modulus determinations to be made for strain rates greater than ca. 1 s^{-1}. Estimations of moduli can be made if strains are estimated from the movement of the grips through a relationship derived between strain and grip displacement. The strain-displacement fit parameters used to produce stress-strain curves in high rate tests were used to analyse the FWI tests.

Table 4 shows moduli estimated from room temperature tests carried out on the high rate machine (speeds between 0.8 and 2 ms^{-1}) and the FWI machine (4.4 ms^{-1}). The strain rates in the initial parts of the high rate machine tests (2-8 s^{-1}) are much lower than the mean rates in these tests (20-35 s^{-1}). This is because the low strain portion of these tests occurs during the period of acceleration of the test machine. In contrast the initial part of the impact data records is assumed to occur with the velocity at its maximum. The strain rates in these tests are 50-60 s^{-1}, a factor of 10 higher than the high rate machine tests.

However, when these impact data are used to estimate moduli, the values are very inaccurate. Where no damping is used, the initial impact test moduli determined are around 2 to 3 times the values expected (2000 MPa becomes 5000 MPa) The degree of scatter is large. Where a 'cushion' is used, the slow pick-up of load leads to a significant underestimate of the modulus (typically around 50% of the values expected). Improvements to the accuracy of moduli determinations from impact tests can only be made with a suitable high rate extensometer.

Table 3: Comparison of Moduli Determined at Comparable Strain Rates

Material & Temperature	Low Rate Machine Clip-On Extensometers 50 mm Gauge Length (number of tests)	High Rate Machine Clip-On Extensometers 25 mm Gauge Length	High Rate Machine Crosshead Displacement
Polycarbonate 23C	2450 ± 20 (10)	2480 ± 130 (10)	2400 ± 365 (10)
ABS 23C	2308 ± 23 (9)	2225 ± 10 (3)	2642 ± 55 (3)
Polypropylene 23C	1661 ± 31 (9)	1605 ± 125 (5)	1576 ± 150 (6)
Epoxy LMD1142 23C	1734 ± 10 (3)	1755 ± 110 (4)	2015 ± 100 (4)
Epoxy AV119 23C	3190 ± 85 (6)	3267 ± 10 (2)	3820 ± 240 (3)
Epoxy AV119 50C	2832 ± 55 (4)	3290 ± 160 (3)	3470 ± 140 (3)

Table 4: Moduli from High Rate Tests (> 0.8 ms^{-1})

Material	High Rate Machine	Impact Machine
AV119	4025, 3717, 3299, 3580, 2571	5775, 6179, 8461, 3763, 5783
LMD1142	2687, 2655, 2574, 2862, 2428, 2644	5701, 6650, 4997, 4645, 3601
ITW MA310	4286, 4881, 4969, 4668	3203, 4592, 6200
Polyurethane DP609	1882, 1856, 1976, 2051, 1827	2928, 2369, 1875

5. STRESS-STRAIN TO FAILURE

5.1 HIGH RATE TESTS

Tests performed on the high rate machine at low strain rates give similar shapes of stress-strain curves to those performed (at comparable rates, on the same material) on the low rate test machine. However, noise may be higher and repeatability is slightly worse. Figure 7 shows stress-strain curves for polycarbonate obtained using high rate and low rate tests apparatus. At a comparable strain rate ($10^{-2}s^{-1}$), the peak stresses are similar but those obtained from the low rate machine (67.6-68.1 MPa) have less scatter than those obtained from the high rate machine (64.6-68.7 MPa). Differences between the shapes of the stress-strain curves after the peak are attributable to the difficulty in measuring strains in a specimen where a neck forms. For all the materials tested, the spread of 'reference' stress values was greater for tests performed on the high rate machine than it was for tests performed on the low rate machine

5.2 IMPACT TESTS

Tensile impact stress-strain curves show the same basic shapes as the stress-strain curves measured using test machines. Figure 8 illustrates the similarity between the stress-strain curves obtained for polycarbonate. This is despite having to use a displacement-strain function to estimate strain which was not specifically determined for the apparatus. The results shown in this work suggest that it is appropriate to use the same model relationship between displacement and strain that was used for the high rate test machine. This is a far more reliable method than assuming a nominal gauge length for the specimen. The noise in the impact tests is generally far greater than in the high rate tests. This may be due to the shockwaves mentioned earlier that are produced on impact

The size of these shockwaves may be reduced by introducing a softer material between the striker and the grip which 'cushions' the impact. Tests that were carried out using polycarbonate specimens to study the effect of a number of different 'cushions' are shown in Figure 4. The noise is reduced most when a soft material is used. This causes problems with the estimation of strain as the initial load increases more slowly and there is a long tail at the beginning of the load-time record. As displacements are estimated from the impact speed and the time from impact, strains are significantly overestimated.

The peak stress values exhibit a similar spread as the peak stress values determined from high rate tests. For example 20 tensile FWI tests performed at 4.4 ms^{-1} (using a variety of methods to cushion the impact) gave a range of peak stress values between 82.9 and 86.0 MPa. This is a similar scatter to that seen in high rate tests at speeds around 1 ms^{-1}. The values of the peak stresses measured are slightly greater than would be expected from extrapolation of the peak stress against rate curves measured using the test machines, Figure 9. Part of the reason may be that the 'peak' stress determined may be the peak of a ripple in the force trace and that the actual peak stress should be lower. However, the data also include results from tests where effective cushioning has been applied to remove most of the noise. It may be that the simple proportionality between stress and log(strain rate) used is not an accurate model for the material. Models for the rate and temperature dependent behaviour of polymers are discussed elsewhere [21].

5.3 TEST DATA

Tensile stress-strain curves to failure were obtained using high speed servo-hydraulic and impact tests. They are presented as plots of engineering stress versus nominal strain. No filtering was applied to any of the data.

5.3.1 Polymers

Figures 8, 10 and 11 respectively show high rate and impact data measured for the three polymers; polycarbonate, polypropylene and ABS. In general, these materials have large strains to failure. There is little difference between failure strains in high rate tests and failure strains in impact tests. For all three materials the impact and the high rate test curves are in reasonable agreement. Stresses are larger in the impact tests as the strain rates are higher. As discussed earlier, the levels of noise are significantly less in the impact tests where damping, in this case a thin sheet of rubber, was used. However, as the test data show, the shape of the stress strain curves in the undamped impact tests is in much better agreement with the high rate machine test data. Figure 8 shows that the shape of the stress-strain curve for polycarbonate (including stress peak around 6-8 % strain) is little changed over several decades of strain rate. The undamped impact data are much closer to this shape than the damped data where the peak in stress seems to occur at roughly 3-4 % higher strain. For all the materials, the initial slopes of the damped-impact stress-strain curves are lower than the lower rate tests. For some materials, such as ABS (Figure 11), the shape of the stress-strain curve changes significantly with rate.

5.3.2 Adhesives

Figures 12 to 15 show stress-strain curves measured for the four adhesives that were studied. Figures 12 and 13 show the data for the epoxy LMD1142 and the polyurethane DP609 respectively. Both of these adhesives are relatively tough and, typically, have strains at failure larger than 0.1. Failure strains differ little between the impact and high rate tests. The general shape of the stress-strain curves produced by the two methods are similar. The main area of difference is that the dip in the polyurethane stress-strain curves at large strains in the high rate data is not present in the impact data. This is because the impact apparatus maintains a more constant (although decreasing) speed than the servo-hydraulic system especially at large displacements when the accumulator in the servo-hydraulic mechanism has discharged much of its pressure reserve. The polyurethane has particularly rate dependent mechanical properties so the fluctuation in speed is reflected in the flow stress. With care in sampling the data to avoid the peaks and troughs of the noise, impact data could be used for input design data.

Figure 14 seems to indicate good agreement between high rate and impact data for the epoxy AV119. Although low, failure strains are in reasonable agreement. However, the low strains at failure mean that only a few resonance wave lengths are present in the impact stress-strain curves. Potentially, this could lead to severe errors in the determined design data.

For materials such as the acrylic, Figure 15, the combination of low strain to failure and yield leading to a sudden change of slope of the stress-strain curve gives significant problems with the impact test. The resonance vibrations in the force signal lead to major differences in the shape of the stress-strain curves especially at low strains. This is also evident in traces for the other rigid adhesives.

5.4 GENERAL CONSIDERATIONS

5.4.1 Lateral Strain Measurement

Although not addressed explicitly in this work, lateral strain properties are important in the accuracy of predictions of material behaviour. In this section some of the issues of lateral strains at high rate are discussed.

Lateral strain measurement is required in order to correct the cross-section area of the specimen to determine the true stress that is required for FE input. Furthermore, for most of the adhesives tested, Poisson’s ratio at large strains tends to be lower than in the elastic region and the assumption that material volume is constant in many material models does not hold. However, most material models in FE packages assume that the Poisson’s ratio is constant for all strains and so only the elastic Poisson’s ratio is used as input. This may be a source of error in the analyses.

Since strain dependent lateral strains are not handled in most material models, lateral strain measurements were not made at high rates. Measurements at low strain rates tended to indicate little rate sensitivity in the relationship between lateral and tensile strain. For some materials, such as ABS or the acrylic adhesive, plots of lateral strain against strain, such as Figure 16, show two regions with different slopes. At low stains, the elastic Poisson’s ratio is around 0.4 but after yield (where crazing/cavitation occurs leading to an increase in volume) the slope of lateral strain against strain is ca. 0.1. This is significantly lower than assumed. Estimating true stress using the elastic Poisson’s ratio alone will give a significant error at large strains.

To estimate lateral strains at high rates, it is suggested that low strain rate data are used. Lateral strains can be described as either linear functions of strain (where Poisson’s ratio was reasonably constant) or bi-linear models (where there was a significant decrease in Poisson’s ratio).

Interpretation of lateral strain data is complicated by the observation that, for some materials, lateral strains differ across the two lateral dimensions of a rectangular test piece. Figure 17 shows lateral strains determined simultaneously across the width and thickness of a test specimen. The lateral strains (after yield) in the thickness direction are larger than in the width direction. Further evidence for a difference in the directional behaviour of the lateral strains comes from measuring the dimensions in the necks of polycarbonate specimens with a micrometer after tests were completed. The lateral strains are reasonably constant (even though a wide range of strain rates were used) and those in the thickness direction were significantly larger than those in the width direction (Figure 18). There was not the opportunity to investigate this further with different geometries of test specimen to determine whether this observation was a real material property, due to process variables or an artefact of the measurement. For the sake of consistency, the lateral strains determined from width measurements (the larger dimension) were used in any subsequent analysis.

5.4.2 Specimen Temperature

It is well known that the mechanical properties of polymers and adhesives are influenced by temperature as well as rate. Doing work on a material will increase its temperature. The elastic-plastic model of materials assumes that the extension of the material can be split into elastic (recoverable) and plastic (permanent) strains. Another way of considering this is that work energy applied to the specimen is stored in an elastic process but dissipated as heat in a plastic process. Therefore, plastic strains are associated with an increase in the temperature of the material.

In low speed tests, the plastic strain rate and, hence, the heating rate will be low. Heat exchange with the surrounding environment will help to reduce these temperature rises. In higher speed tests, the plastic strain rates and the heating rates will be correspondingly higher. Heat exchange will have less of an effect on maintaining a constant specimen temperature. Significant temperature rises could influence the properties of the material being measured. A simple formula relating the change in temperature (ΔT) to applied stress ($\sigma(t)$), plastic strain ($\varepsilon_p(t)$), material density (ρ) and heat capacity (C_p) can be derived:

$$\Delta T = \frac{1}{r C_p} \int_0^{e_p} s\left(e_p\right) de_p$$

Assuming that there is no flow of heat, this can be used to estimate temperature rises in the material during tests. Typically, ρ will be around 1200 kg m^{-3} and C_p will be 1500 to 2000 J kg^{-1}°C^{-1}. Assuming that the peak stress occurs with a plastic strain (ε_p) of 0.05 at a constant stress of 75MPa (both larger than for many materials in this study), then the expected temperature rise will be about 2°C. Therefore, the temperature increase will not be significant. However, if the plastic strains experienced by the material during the test are large then temperature increase may be greater. This may account for the gradual drop in flow stress seen in some of the high rate tests and lead to inaccuracies in determining the isothermal hardening behaviour.

When a material necks, very large local strains occur rapidly. These may induce large temperature rises in the neck. Using the example above, and making an assumption that the local strain increases by 0.5 in the necked region, then the formation of a neck may be associated with temperature rises of 20°C or more.

6. CONCLUSIONS

Provided that sufficient care is taken with the testing, it is possible to produce mechanical test data at high rates (> $10s^{-1}$) on bulk specimens of adhesive that are suitable for input for FE design.

The most accurate mechanical properties data, especially in the low strain, elastic region, are obtained using a low speed electro-mechanical test machine. However, the maximum speed of such machines is far below the speed required to give strain rates required to model impact events ($10s^{-1}$ or higher).

Tests can be performed at higher rates through the use of a high speed servo-hydraulic test machine. The data obtained from such a machine are less accurate than those available from low speed machines. Strain measurement is more difficult and there are significantly higher levels of noise in both the strain and force measurements. As a result, the accuracy in modulus measurement is impaired but the overall stress-strain curves are in reasonable agreement. This technique allows measurement at different (high) strain rates for investigation of the rate dependence of the mechanical properties.

Tensile tests can be carried out at high strain rates (ca. 100 s^{-1}) using falling weight impact apparatus. However, the accuracy of data produced can be poor. This is a particular problem where the strain to failure is low and the trace may be dominated by resonance vibrations. Methods for removing noise from the data run a risk changing important information from the test. Where damping is necessary the methods have to compromise between reducing vibrations and preserving the shape of the stress-strain curves. Of the systems investigated, thin (ca. 0.6 mm) sheets of rubber seemed the most appropriate.

The lateral strain behaviour of adhesives and polymers is difficult to measure at high strain rates. There is some evidence to suggest that, for some materials, lateral strain properties are not very sensitive to strain rate.

7. ACKNOWLEDGEMENTS

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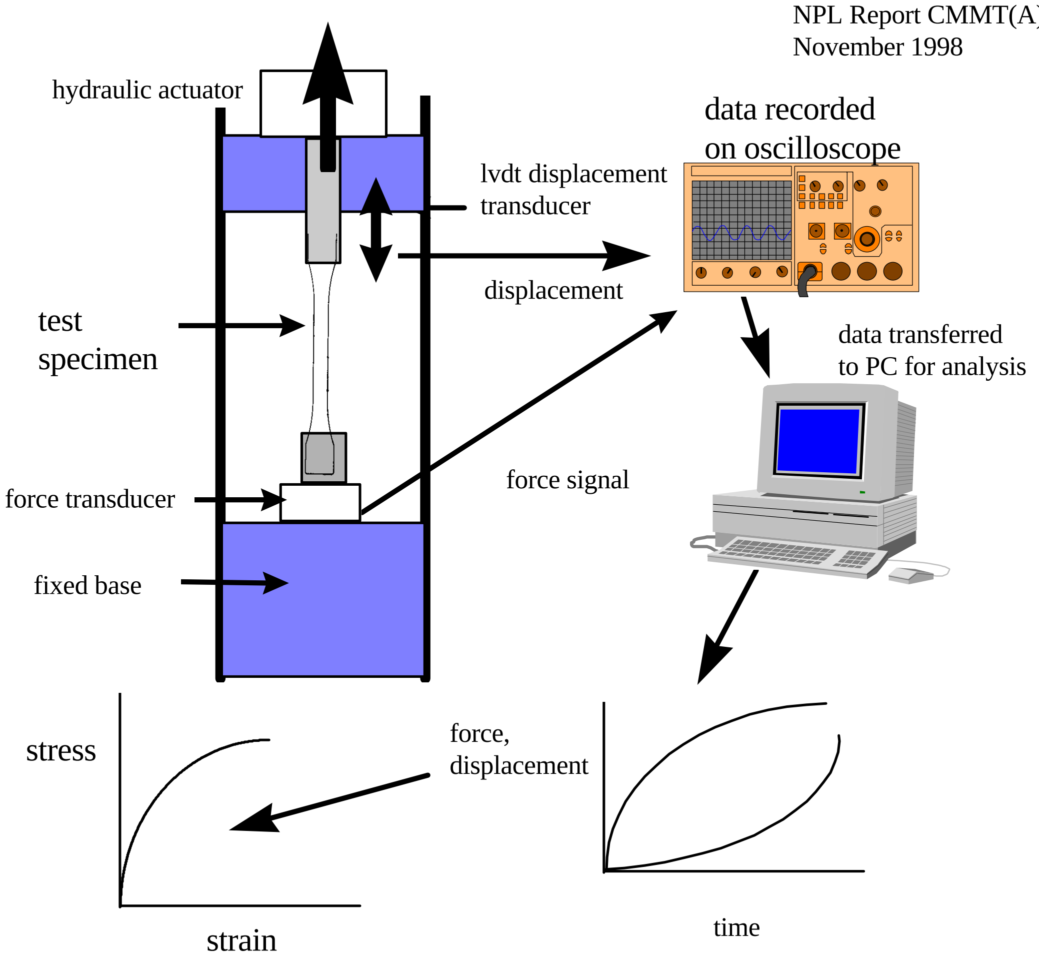
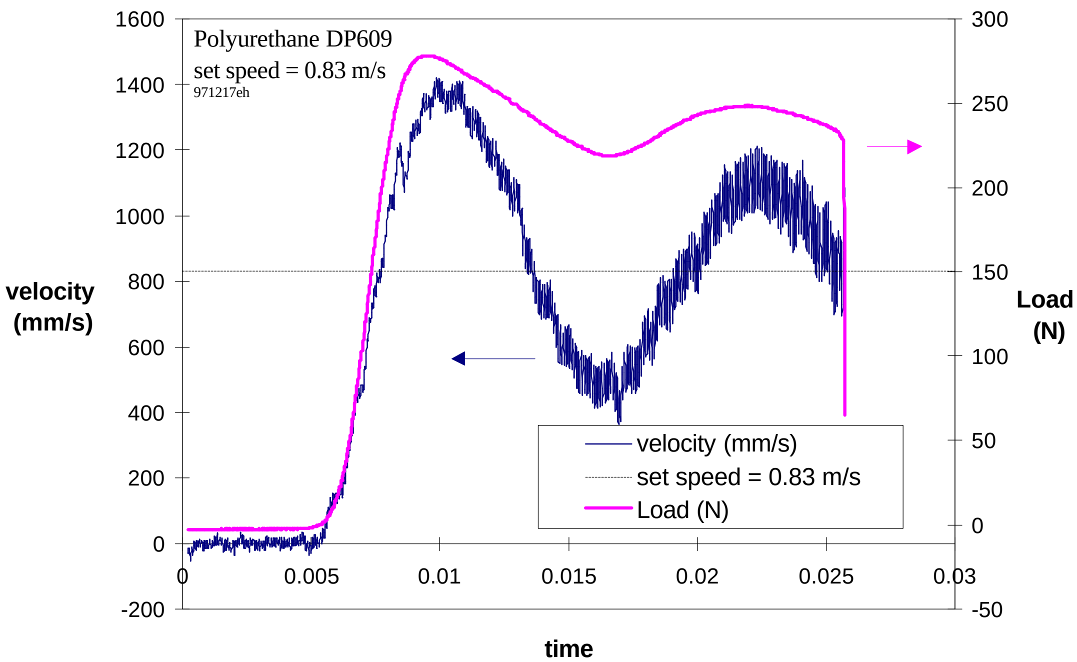


Figure 1: Schematic of high speed servo-hydraulic test machine



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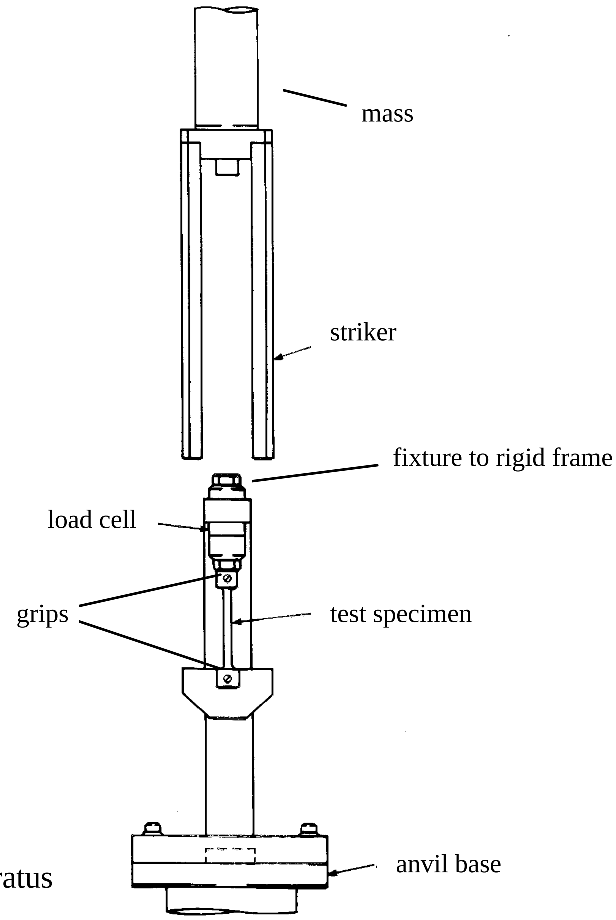
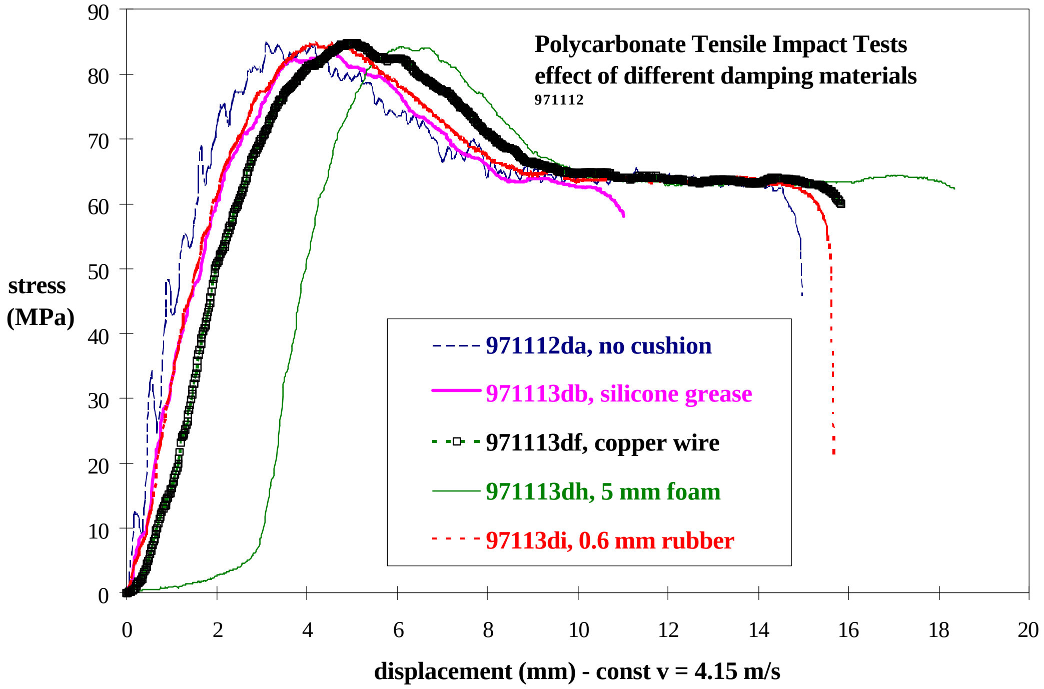


Figure 3: Tensile impact apparatus



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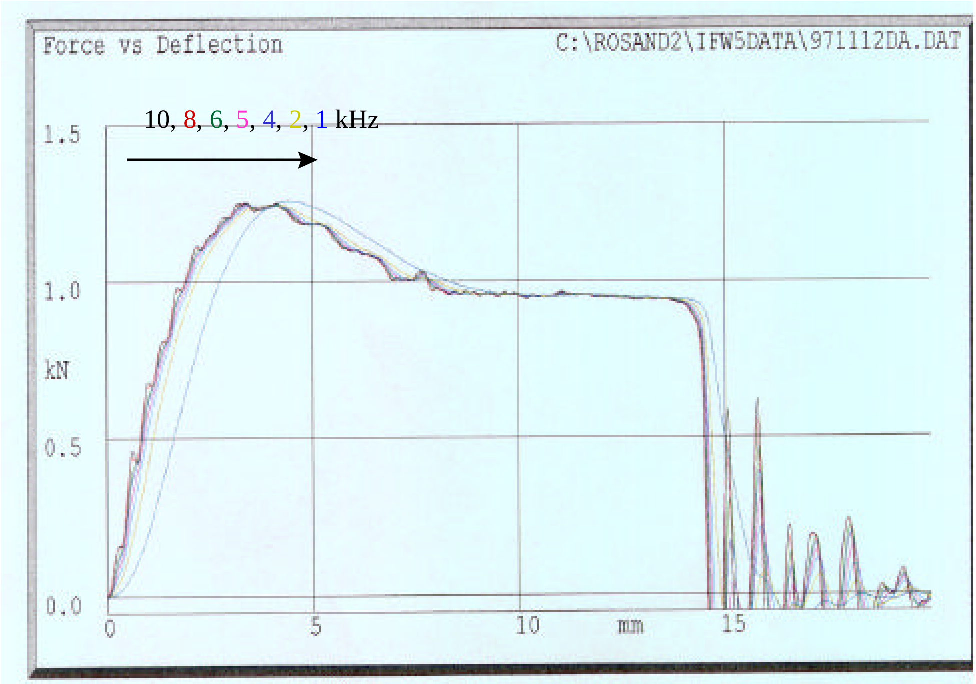

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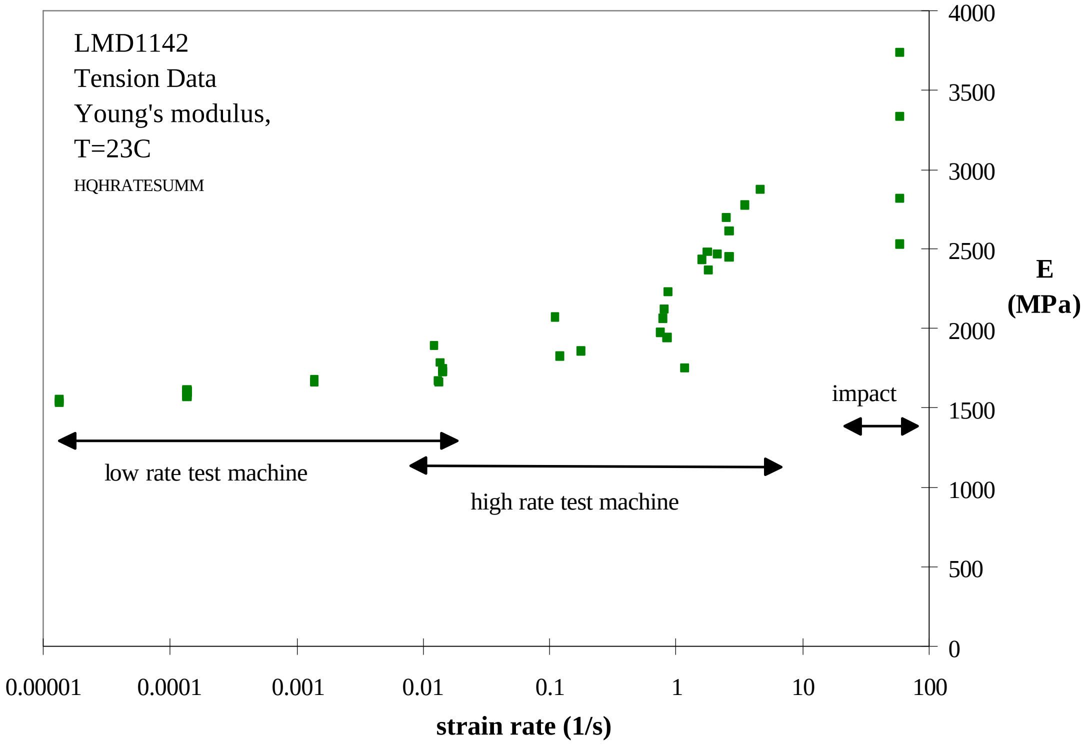

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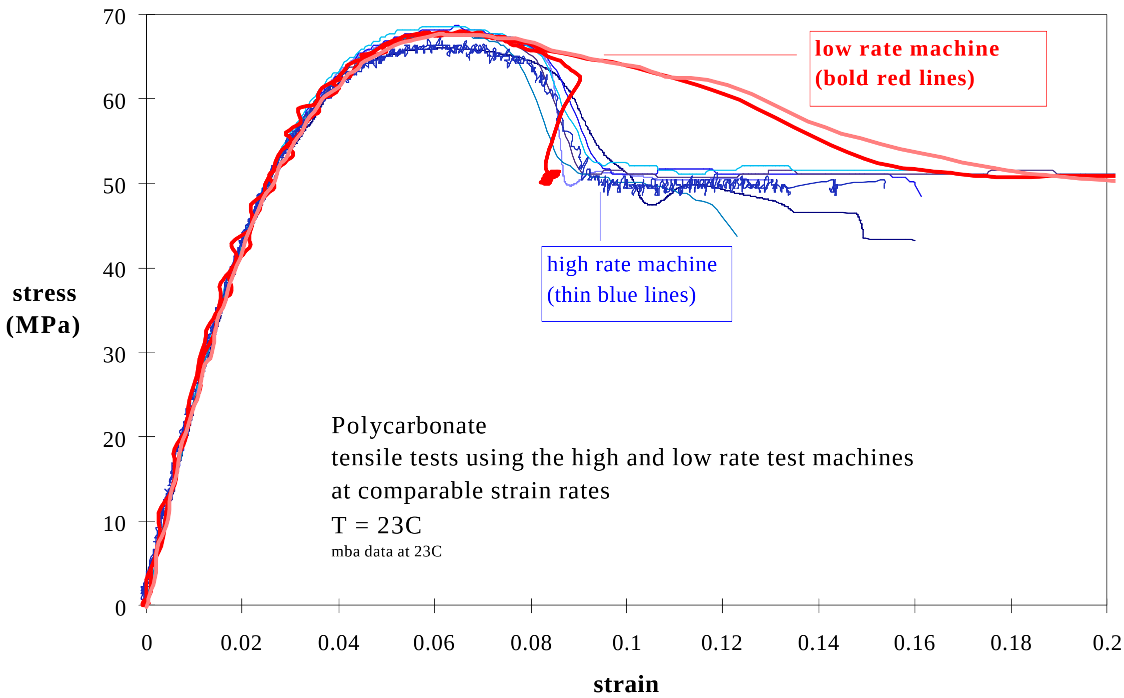

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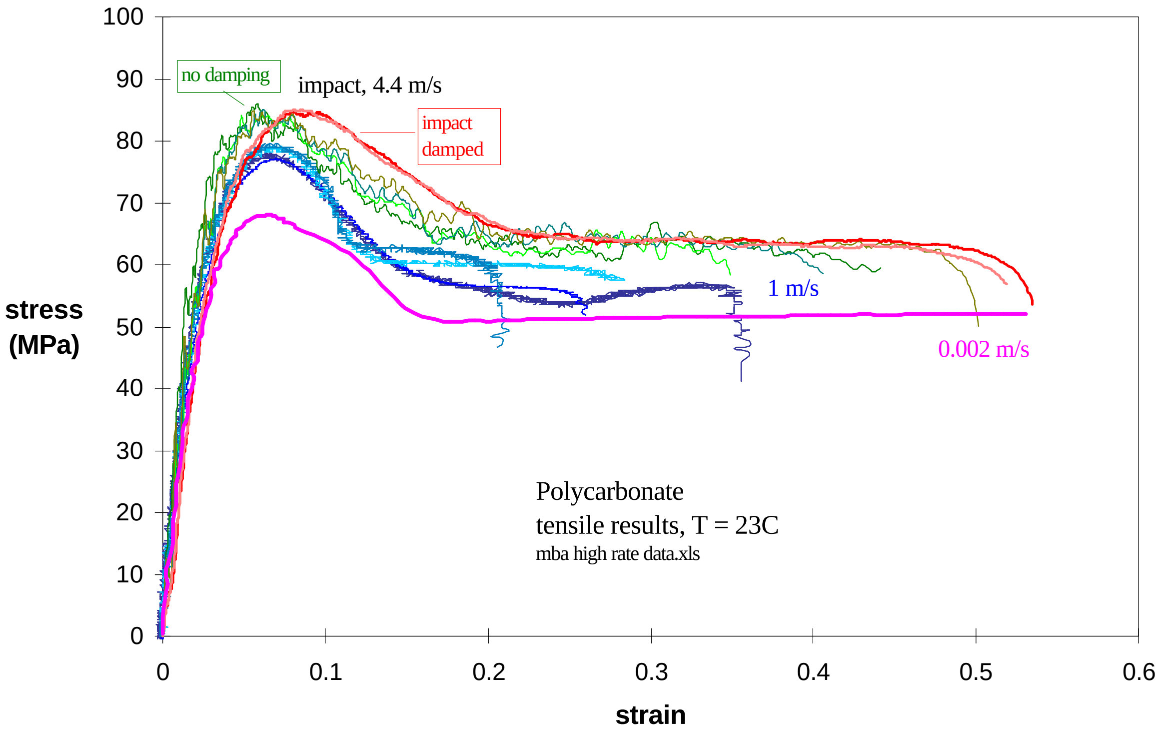

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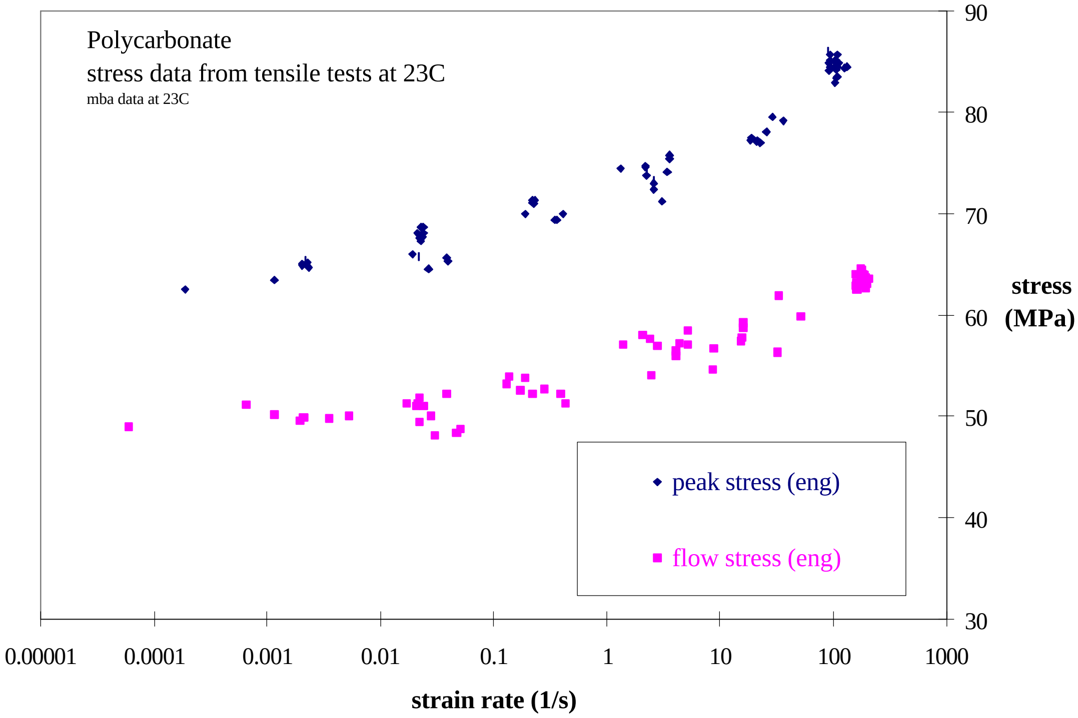

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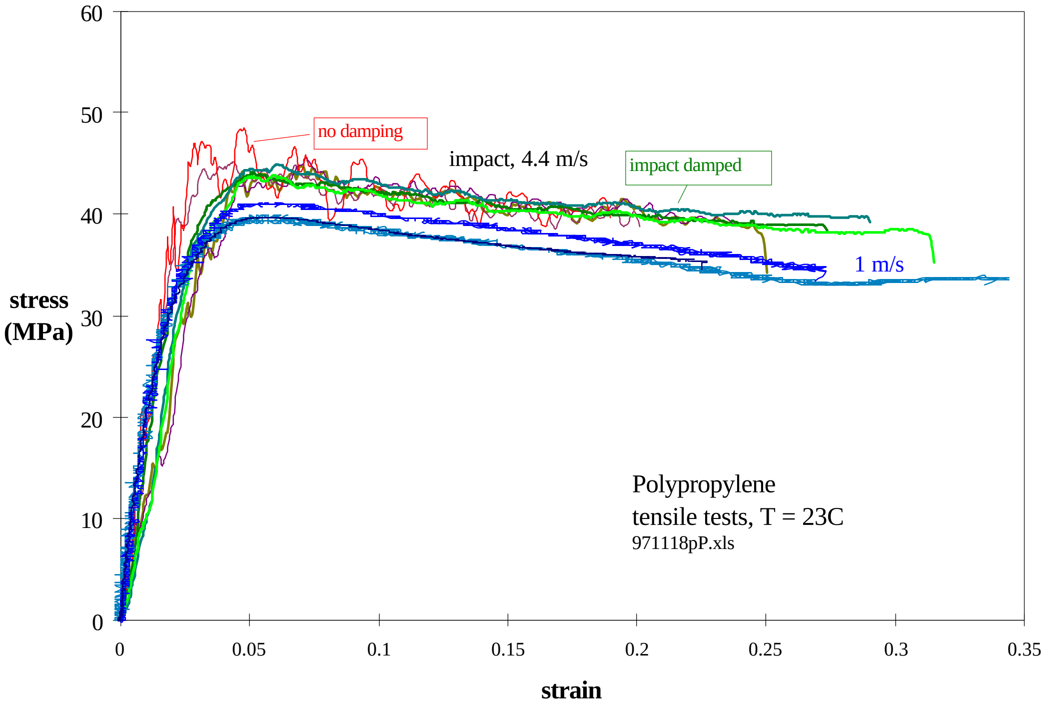

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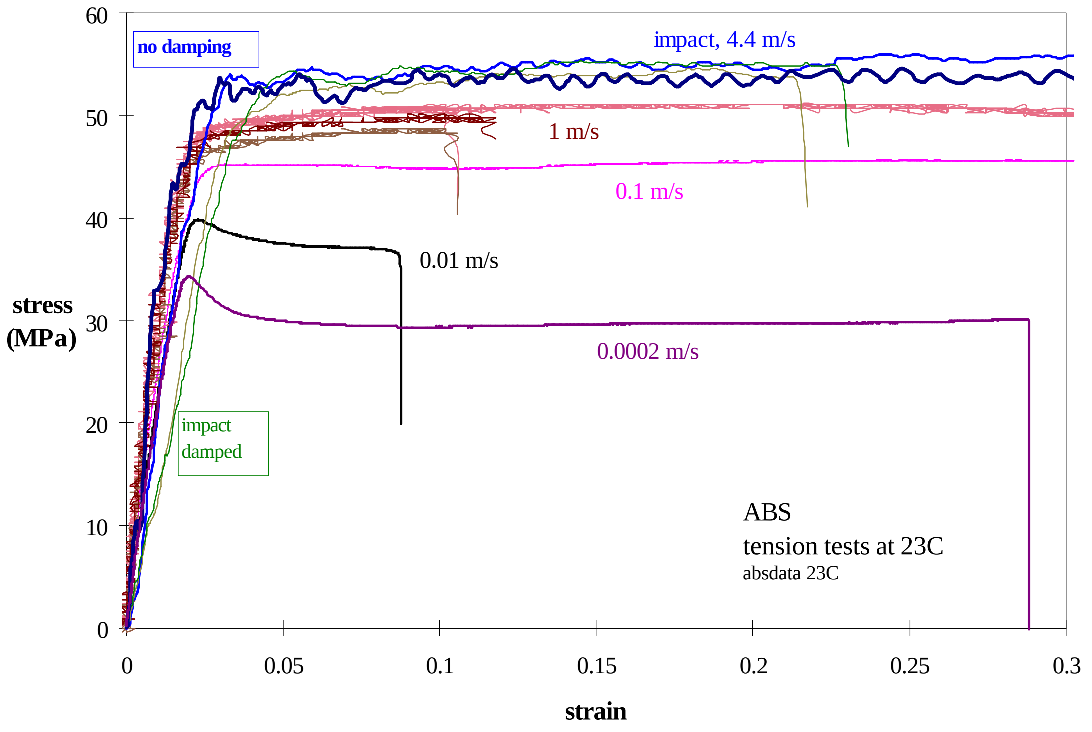

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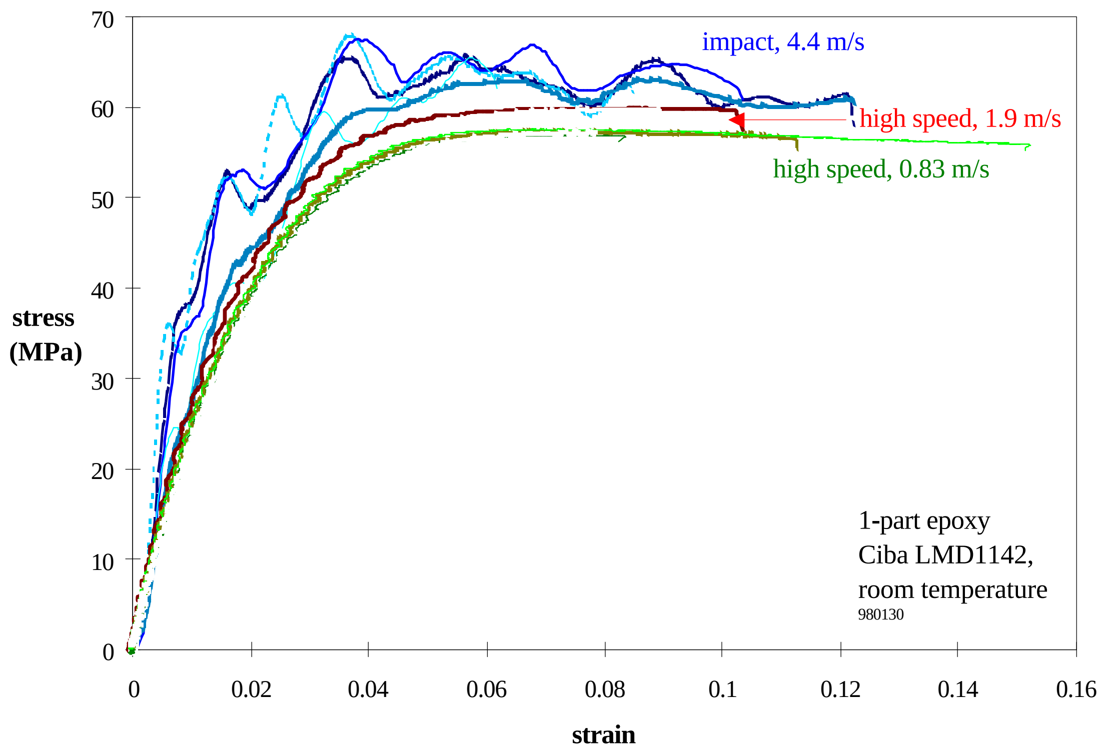

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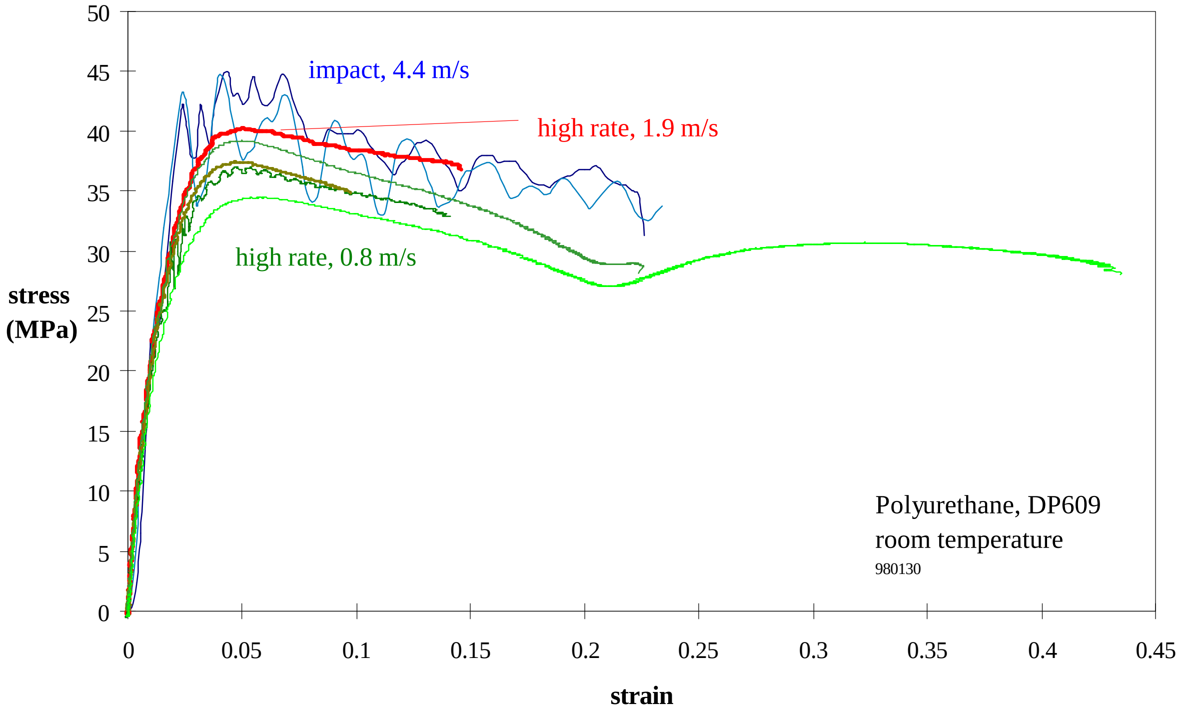

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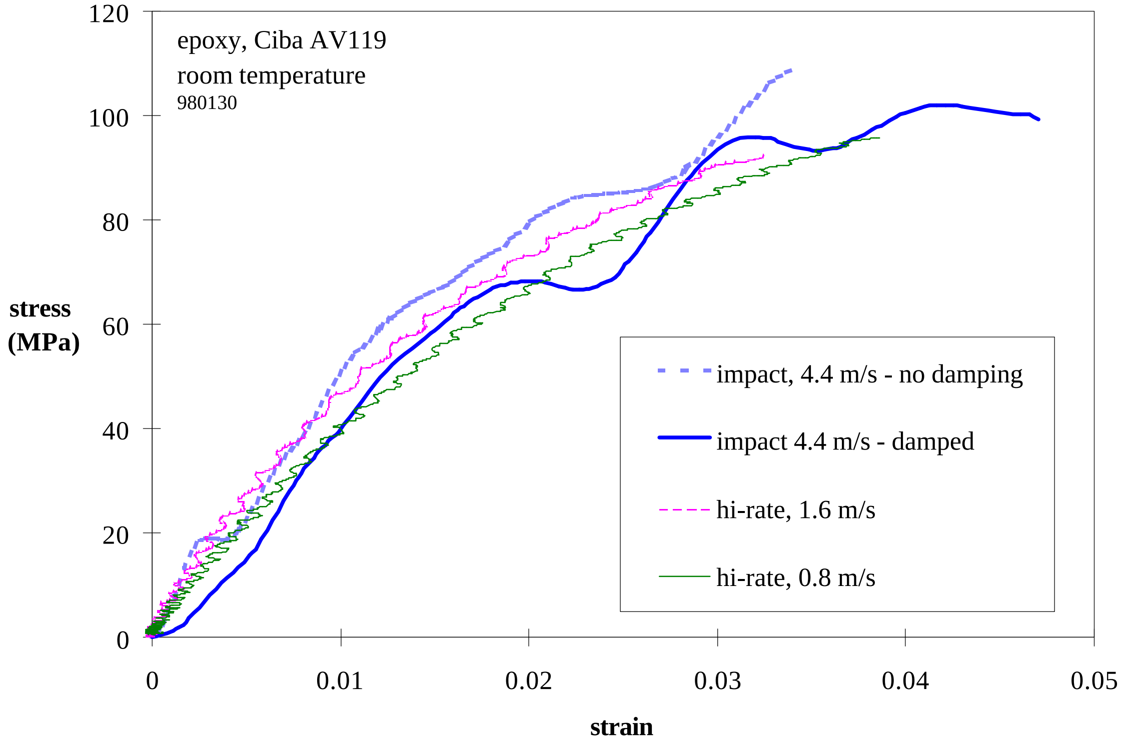

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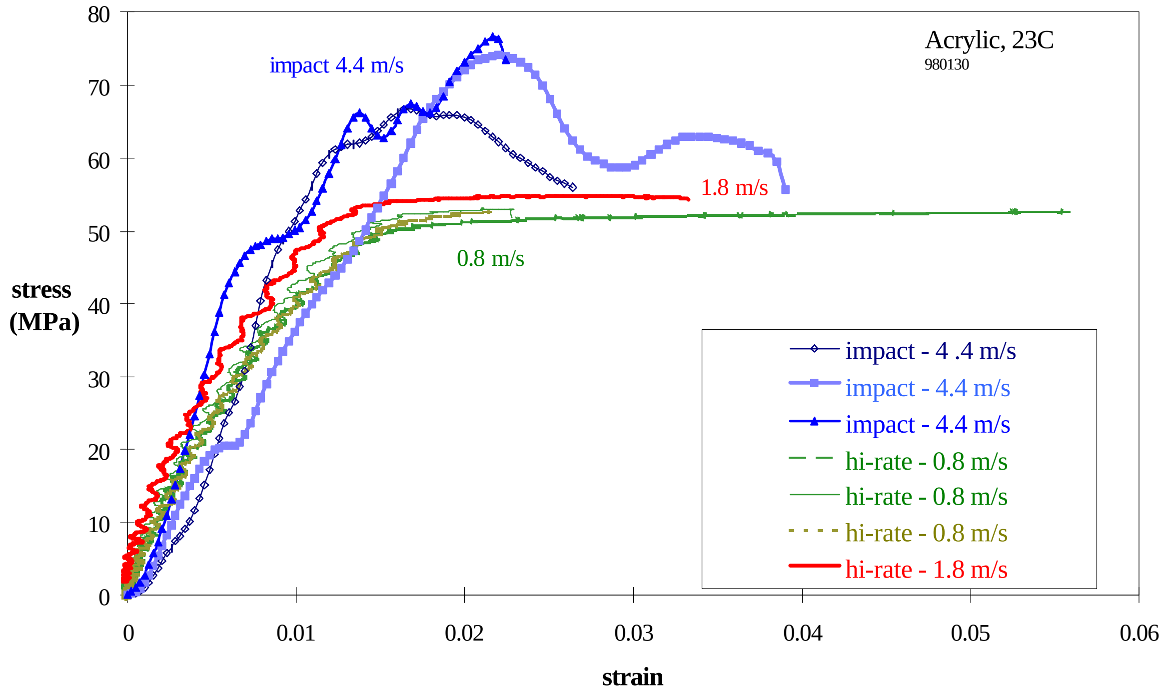

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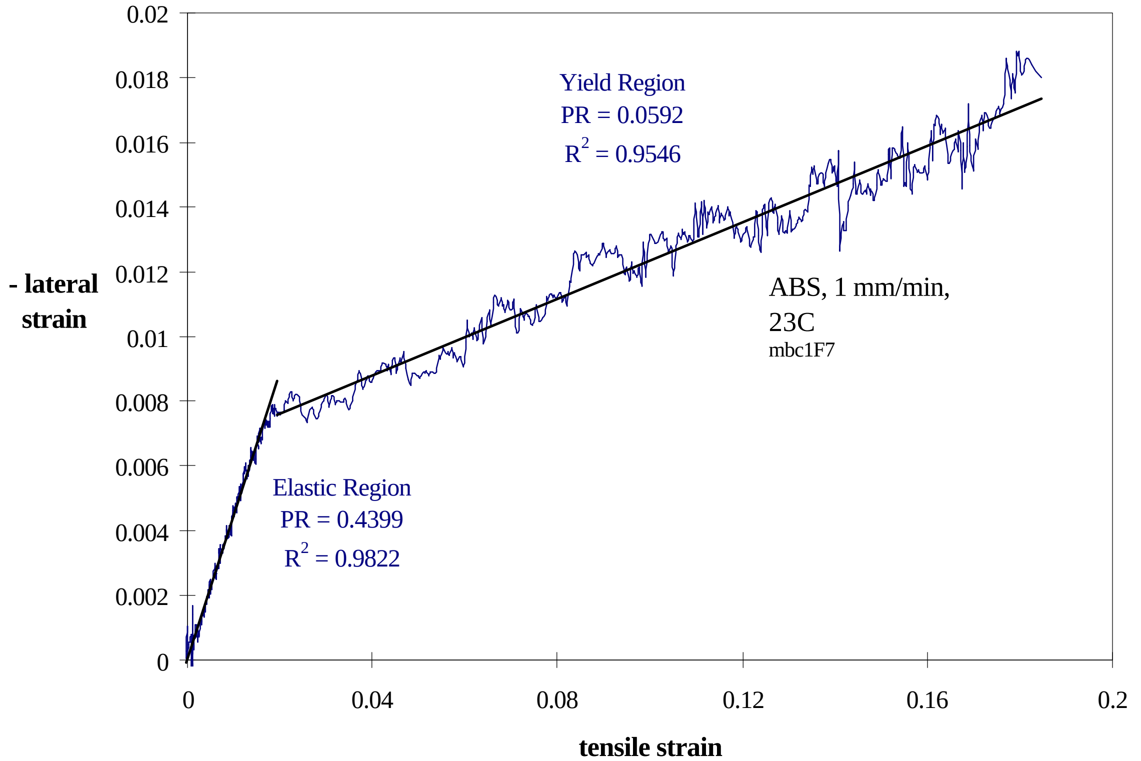

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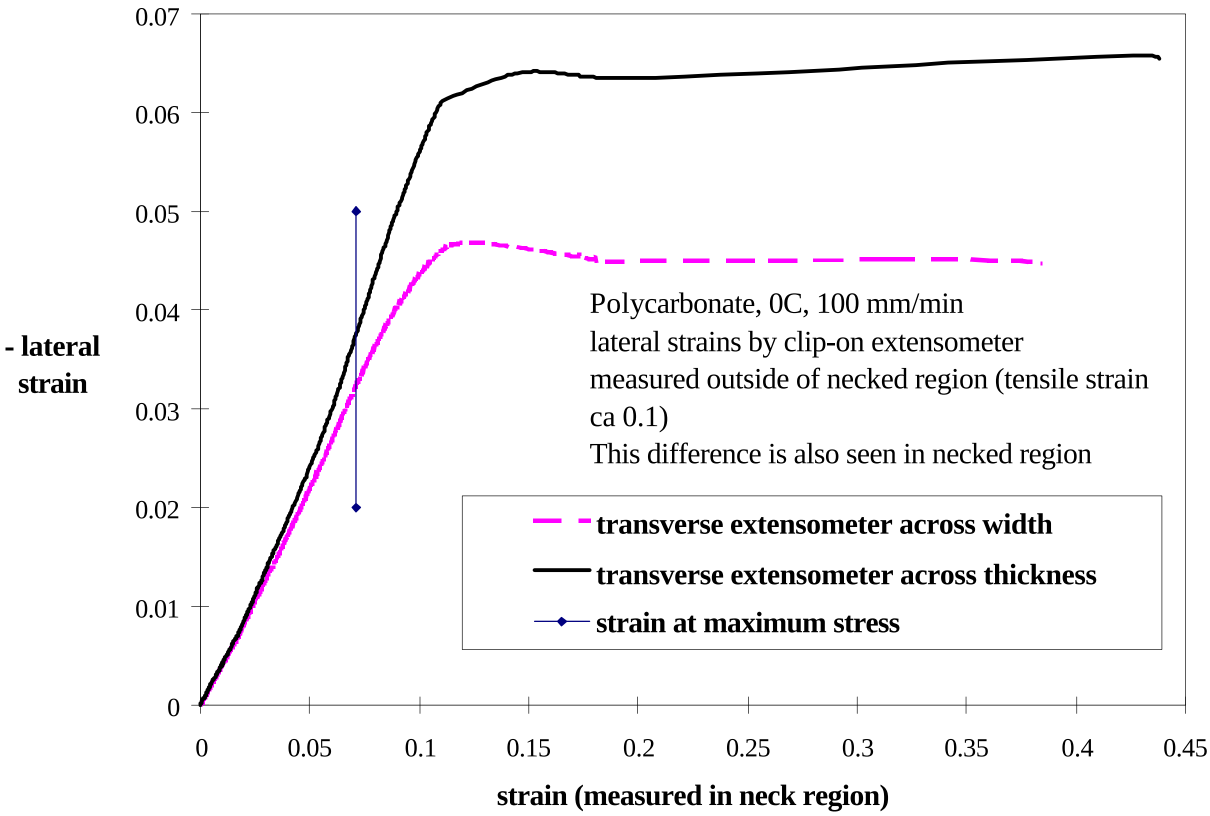

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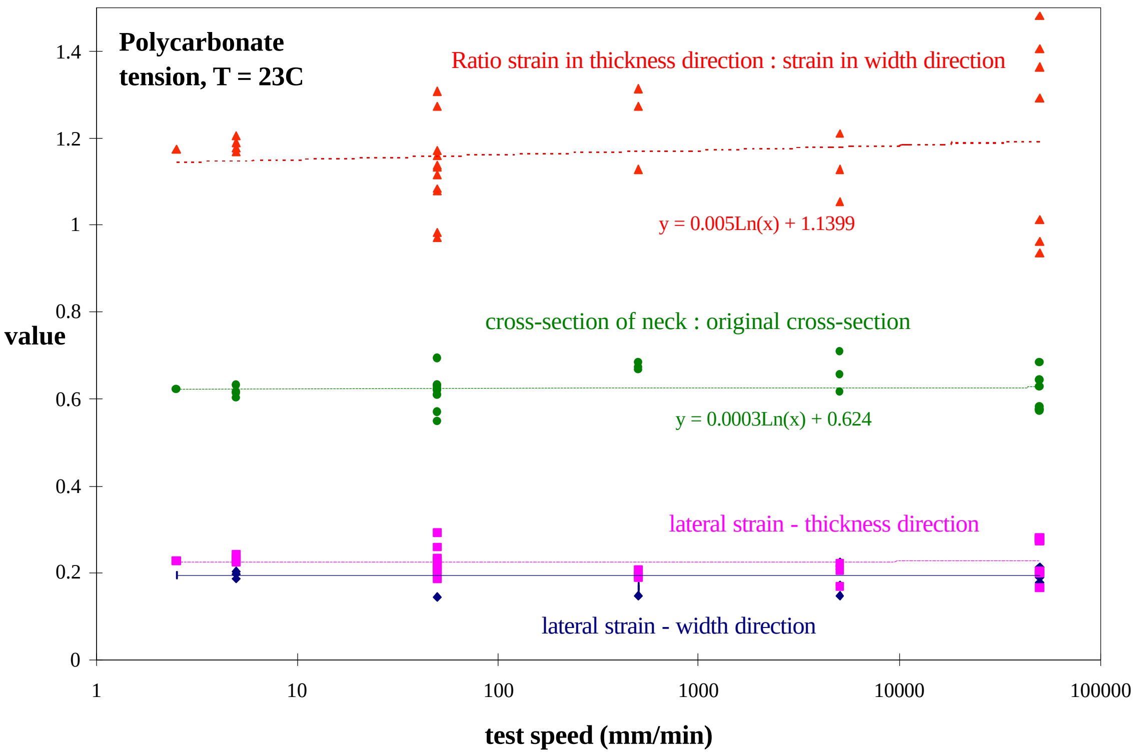

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