

Measuring the Poisson's Ratio of Fibre Reinforced Metal Composites

Summary

The elastic mechanical properties are important parameters in designing with fibre-reinforced metals (FRM), and a unidirectional composite that exhibits transverse isotropy has 5 independent elastic constants describing its mechanical behaviour. Measurements of the modulus and in plane Poisson's ratio have been made within this study, using a range of strain measurement methods on commercially available materials. Some elevated temperature data is also presented.

Results are presented together with comments and advice regarding the suitability of the different techniques and accuracy of the measurement.

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1 INTRODUCTION

Fibre reinforced metal composites (FRM) are an attractive group of materials because they offer significant performance benefits over conventional materials in terms of their strength and stiffness. Many structural applications of FRM use unidirectional reinforcement, with the material in the form of thin sheet, but for complex loading situations engineers are forced to use more sophisticated lay-ups to improve the in-plane and shear properties. The heterogeneous microstructure and highly anisotropic behaviour of these advanced material systems present special problems with respect to measuring the mechanical properties, and there is still a lack of reliable data for modelling. As part of the current MMS12 project, a survey of shear tests for FRM was carried out and can be accessed on the NPL MMC website at www.npl.co.uk/materials/mmc/publications [1]. The most commonly used shear test methods include thin walled tube torsion tests, 10° off axis tensile test, the Iosipescu (V notched beam) shear test, rail shear tests, [± 45°] tensile shear test and the plate twist test. The large number of test methods available reflects both the difficulties associated with measuring the shear properties of composite materials and the wide range of material types and configurations. Details summarising the methods and their respective merits are given in the report.

This Measurement Note summarises the measurements of in-plane Poisson's ratio of two unidirectional fibre reinforced titanium composites by applying some of the strain measurement techniques being examined and developed within the current project - notably the Digital Image Correlation (DIC) method. The Poisson's ratio, ν_{xy} , is the ratio of lateral strain to longitudinal strain for a material subjected to uniform longitudinal stresses within the proportional limit, and is an important parameter for describing the behaviour of these materials. Where possible, measurements have been made using other techniques for comparison.

A summary and overview of the various mathematical models used to predict FRM mechanical performance is given in Refs 2,3. The application and merits of the basic slab (equal strain, or Voigt model) and shear lag (equal stress, or Reuss model) approaches, and more sophisticated Halpin-Tsai and Eshelby models, and derivatives of these, are presented. Unidirectional FRM are transversely isotropic, and the elastic behaviour can be fully described by 5 independent elastic constants. In such systems the basic Voigt and Reuss models work quite well, and the longitudinal Young's modulus, transverse bulk modulus, shear moduli and associated Poisson's ratios, can be described from the following relationships:

$$E_{11} = V_f E_f + V_m E_m \quad (1) \quad \nu_{12} = V_f \nu_f + V_m \nu_m \quad (2)$$

$$\frac{1}{E_{22}} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (3) \quad \frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \quad (4)$$

$$\nu_{23} = \frac{E_m V_f \nu_f + E_f V_m \nu_m}{E_m V_f + E_f V_m} \quad (5)$$

.. where E , G , ν and V represent the Young's modulus, shear modulus, Poisson's ratio, and volume fraction respectively. Subscripts f and m refer to the fibre and matrix, and directions 1 and 2 are the longitudinal and transverse directions in the plane of the specimen, subscript 3 refers to the out of plane direction. The tests carried out as part of this study have focused on measuring the in-plane Poisson's ratio, ν_{12} , of two commercially available unidirectional FRM from a series of tensile tests.

2 MATERIALS EXAMINED

The materials examined in this study were:

- 8-ply UD SiCf/Ti-6-4 produced by Sigma
- 8-ply UD SCS6 SiCf/Ti-15-3 produced by Textron

Both materials were produced in 1999, and were kindly supplied by Dr C Masuda, NRIM, Japan for evaluation as part of a VAMAS intercomparison exercise. Typical micrographs are shown in Fig 1.

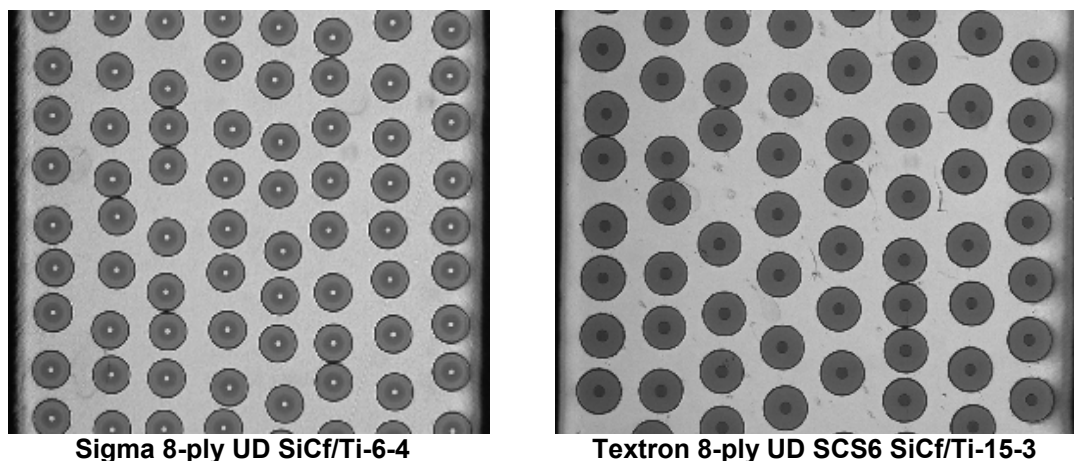


Fig 1: Micrographs of the two Ti-based FRM examined

Both the Textron and Sigma materials were produced by diffusion bonding and were supplied in the form of thin sheets, respectively 1.75mm and 1.4 mm thick. Both materials are 8-ply unidirectional composites, and the reason for the difference in thickness is due to the different diameter fibres used - the Textron SCS-6 fibre is approximately 140 μm in diameter with a tungsten core, whilst the Sigma 1240 is 100 μm in diameter with a carbon core. The nominal volume fractions of reinforcement for the Textron and Sigma materials are respectively 33% and 35%. In both cases, the micrographs show reasonably uniform fibre spacing, but with some touching fibres. This is probably a feature of the 1999 vintage, and more recent materials are significantly better in terms of regular fibre spacing. A few test were also carried out on a UD Nextel Al_2O_3 / Al material with 65% fibre volume produced by 3M. The Nextel 610 fibres are typically 7-10 μm in diameter, and the composite is produced by metal infiltration techniques. Sheets were approximately 150mm x 100mm x 2.3mm thick, which placed some limitation on the maximum size (length) of specimens that could be tested.

Based on the equations 1-5, the predicted values for the elastic constants for the three materials are:

		Textron SiC/Ti-15-3	Sigma SiC/Ti-6-4	3M Nextel Al₂O₃ / Al
Input parameters	Fibre Diameter	140	100	10
	Fibre Modulus, E_f	350	330-360	370
	Fibre fraction, V_f	0.33	0.35	0.65
	Fibre Poisson's ratio, ν_f	0.24	0.25	0.275
	Matrix Modulus, E_m	110	110	70
	Matrix Poisson's ratio, ν_m	0.3	0.3	0.3
Predicted Values	E_{11}	189.2	197.5	265.0
	E_{22}	142.2	145.3	148.0
	G_{12}	48.3	49.3	82.4
	ν_{12}	0.280	0.283	0.294
	ν_{23}	0.292	0.293	0.316

Table 1: Predicted values of elastic properties

Values for the input parameters used in the Table above varied considerably depending on the source. Representative values have been selected but it should be noted that there is some uncertainty in these figures, that will affect the predicted properties. The predictions are compared with the measured values in the following sections.

3 POISSON'S RATIO MEASUREMENT

The accuracy of Poisson's ratio measurement measured from the tensile test was examined using the following strain measurement methods:

- Conventional XY strain gauges
- Biaxial extensometer
- Electronic Speckle Pattern Interferometry (ESPI)
- Full field Digital Image Correlation (DIC)
- Split prism system/Linescan camera
- Impulse Excitation Technique (IET)

Most of the results reported are at room temperature, but some measurements have been made using high temperature strain gauges to extend the scope of the measurement methods to elevated temperatures.

The room temperature tensile tests were carried out on conventional parallel-sided tensile testpieces, approximately 200 mm long x 10 mm wide and the thickness of the respective sheet of material. Profiled aluminium tabs, 25mm long were bonded to the ends of each testpiece to protect the specimen from damage in the wedge grips. Alignment of the testpiece was carried out by means of a special fixture and universal joint. All of the specimens were initially tested using conventional XY strain gauges attached to both sides of the specimen, from which the longitudinal modulus, E_{11} and Poisson's ratio, ν_{12} were measured. Some initial tests on each batch of material were tested to failure, but subsequent testpieces were

kept below the elastic limit and the same testpiece retested a number of times using the different techniques.

Further details of the strain measurement methods are given below, and results presented in Table 2. Not every specimen was tested with every technique, but in most cases there are multiple measurements for comparison. No Poisson's ratio measurements were possible with the IET dynamic technique, so only longitudinal modulus data is given. Where appropriate the analysis of the stress-strain curve was carried out using the NPL web-based modulus algorithm <http://materials.npl.co.uk/modulus/>, which has also been developed as part of the MMS12 project.

Conventional XY strain gauges

Tests were carried out using conventional XY strain gauges, bonded to both sides of the specimen. Tests were carried out at room temperature and also at elevated temperatures, up to 400 °C using special high temperature gauges (see results later). The Poisson's ratio was calculated from the respective stress-strain data from the individual longitudinal and transverse gauges, analysed using the NPL modulus software as detailed above. Specimens were prepared for gauging by light abrasion with 320-grade SiC paper, taking care not to remove too much material, particularly with the 3M Nextel FRM where the fibres were relatively close to the surface. The gauges were connected to the datalogger in quarter bridge mode using a 3-wire configuration to give temperature compensation. Individual gauge readings could be accessed to determine the variability between measurements on both sides of the testpiece, but for analysis of the data corresponding pairs of gauges were averaged and the mean readings analysed. The gauges were not corrected for transverse sensitivity effects, as this was expected to have only a small effect on the measured strain values in this case.

Biaxial extensometer

Tests were performed using a single-sided Instron 25 mm gauge length biaxial extensometer, calibrated to ISO 9513 Class 1. Data analysis was carried out on the longitudinal and transverse stress-strain data using the NPL web-based modulus software as detailed above.

Electronic Speckle Pattern Interferometry (ESPI)

The NPL Ettemeyer Q-300 Electronic Speckle Pattern Interferometry (ESPI) system was also used in the test programme. ESPI is a full field non-contact strain measurement technique, which uses laser light to illuminate the surface of the specimen, causing interference between the reflected light waves and the image of the object, producing a variable speckle effect that can be recorded by camera. The pattern is defined by the microscopically rough topography of the sample surface, and when the sample deforms the speckle pattern changes. Correlation fringes, which represent the deformation of the object in the applied direction, are created by comparing the speckle pattern for the object in a reference (unloaded) condition and then in a deformed state. The fringe pattern and correlation fringes are then analysed using software that transforms them into a quantitative set of deformation and strain data using phase unwrapping algorithms.

ESPI has the advantage that high accuracy deformations can be measured remotely on samples with relatively large dimensions, and with minimal surface preparation. Fig 2 shows the longitudinal and transverse stress-strain data obtained from the ESPI test on the Textron TEN3 specimen, compared with the XY strain gauge data previously measured. Data plotted in Fig 3 shows the variation in the measured values over the stress range.

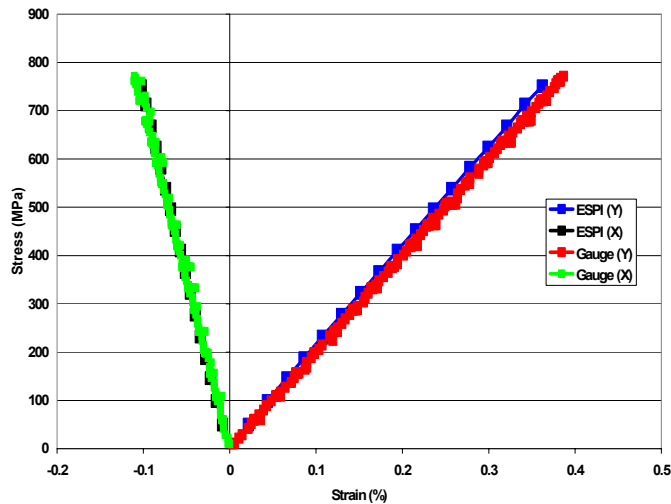


Fig 2: Longitudinal and transverse strain data (Textron TEN3)

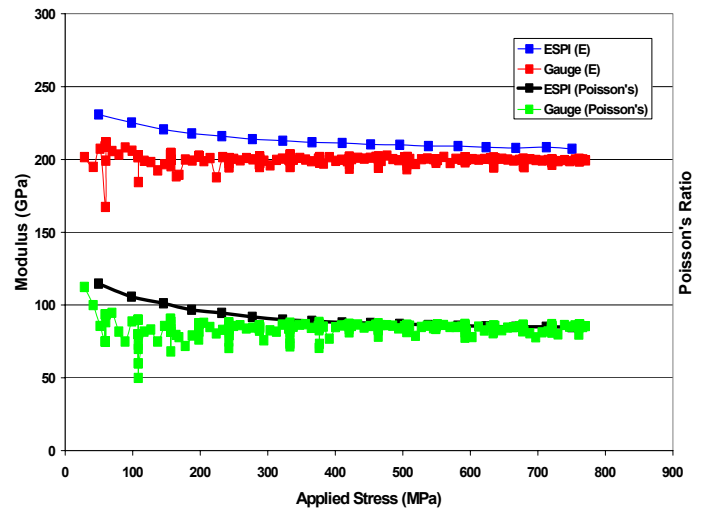


Fig 3: Variation of modulus and Poisson's ratio with the applied stress

At low stress levels, there is considerable variation in the “instantaneous” calculated values for both modulus and Poisson's ratio, and only above 300-400 MPa are the values consistent. Often in the tensile test there is some non-linearity at the beginning of the curve due to bedding in of the grips and load train, and it is recommended that in such cases a small preload be applied to the specimen and the modulus and Poisson's ratio be calculated over a representative range of the stress-strain curve, below the proportional limit, where there are higher strain levels and reduced uncertainties. Consequently, all tests were carried out with a small preload and up to a maximum stress level of 500MPa. This was still below the elastic limit for all the materials, but ensured sufficient levels of strain to obtain reasonable accuracy.

The importance of specimen alignment can be seen in the images presented in Fig 4, which show typical surface displacement maps obtained from the tensile tests. The pair of images on the left were recorded where the strain field was non-uniform, indicating that there was some degree of misalignment. The right hand set, shows the same specimen realigned and retested.

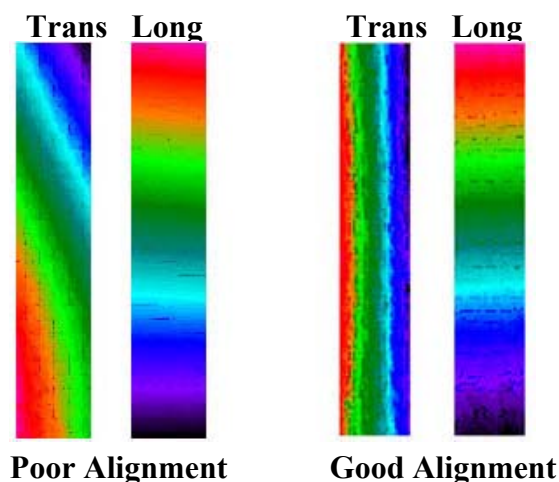


Fig4 : Representative ESPI surface displacement maps showing the effect of misalignment

Digital Image Correlation (DIC)

Tests were also carried out using the NPL LaVision Digital Image Correlation (DIC) system, which is another full field non-contact strain measurement technique. DIC works by comparing the movement of unique, but well-defined blocks of pixels on an image, before and after deformation, and calculating the resultant vector plots and strain maps. The testpieces were prepared by applying a fine, random paint spray pattern and imaging an area of the testpiece gauge length, over which the deformation of the specimen could be tracked. Results applying DIC to other aspects of testing within the current project are given in Ref 4.

For all the tests, a small preload was applied to the specimen to take up any slack in the load train, as early trials had shown evidence of a small, lateral displacement in the specimen on initial loading. Values for the longitudinal and transverse deformations, modulus and Poisson's ratio data were calculated simply from the respective stress and strain values at the preload and maximum load condition.

A close up of the pattern applied to the testpiece is shown in Fig 5, together with typical vector and strain maps in Fig 6, obtained from the test at the maximum load condition. The resolution and accuracy of DIC is less than that obtained using strain gauges, extensometry and ESPI, but offers the advantage of being relatively quick to set up and provides full field measurement. During processing of the images and vector maps in this study, a area of the specimen was selected away from the edges, and a default interrogation window size of 16 x 16 pixels chosen over which the calculations were made. The vector and strain measurements are calculated from the relative displacements of adjoining 16 x 16 pixel blocks, and averaged. For the Textron TEN4 specimen the average longitudinal strain values were calculated over an area of interest of 500 x 150 pixels and the average transverse strain from an area of 150 x 100 pixels. In both cases it was assumed that the strain was constant within the selected region, and a single strain value calculated. Although the DIC technique offers sub-pixel resolution the strain values obtained from the test showed considerable variability, particularly in the calculation of transverse strain due to the limited effective gauge length and pixels across the width of the specimen, for the test conditions and set-up used.

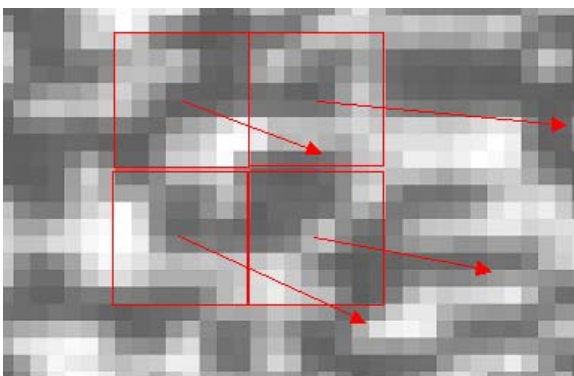
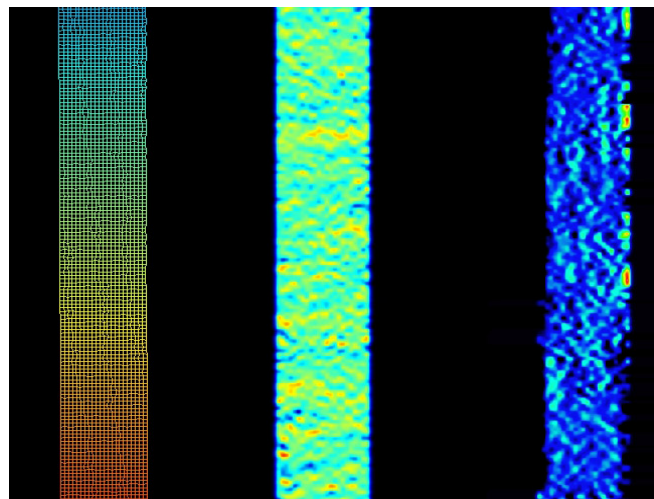


Fig 5: DIC concept – tracking blocks of pixels



Vector map ϵ_{yy} ϵ_{xx}
Fig 6: Vector maps and strain plots from DIC experiment on Textron FRM

This is reflected in the accuracy of the results in Table 2 for this technique. Some compromise must be made between the spatial resolution and the strain resolution, but increased resolution and accuracy could be achieved by using higher magnification images and higher resolution cameras to increase the number of pixels.

Split field/Linescan cameras

Another approach for improving the resolution of the DIC system was to use a split-prism device to separate the areas of the specimen that could be imaged, thus providing a larger effective gauge length. Due to limitations in the experimental set-up and software, automatic processing of the images was unsuccessful, but point measurements could be made on the two areas imaged, which could be tracked during deformation to get a value of the shift (in pixels) from which the strain values were calculated. This is similar in practice to commercial line scan camera systems, where lines or marks on the specimen are imaged and tracked.

Results presented in Table 2 are the mean values obtained by tracking the relative displacements (both x and y locations) of pairs of pixels, obtained from 2 high magnification images of the testpieces, some 100 mm apart, for the longitudinal displacement and as close to the full width for the transverse displacement. As with the full field DIC the same specimen preparation was used. Strain measurements were calculated manually from inspection of the images at the preload and maximum load conditions.

Dynamic modulus techniques

Dynamic techniques are attractive as they offer rapid measurement of properties and can readily be applied to high temperatures. The Impulse Excitation Technique (IET) has already been used successfully to measure the elastic properties of a range of materials [5], but there are many practical problems and issues with applying the techniques to anisotropic materials such as the FRM examined in the study, mainly associated with isolating and identifying the resonant frequencies associated with the relevant modes of vibration.

Because of these problems only longitudinal and flexural modulus values could be successfully measured using the IET in this study. Results are included in Table 2, and generally there is good agreement with the data from the other methods. Sensible values for Poisson's ratio could not be measured, despite trying a range of different specimen geometries because it was impossible to isolate and identify, with any confidence, the frequencies relevant to the various modes of vibration. Work is in hand to refine the technique and NPL is providing input into a new draft EN standard that is currently being developed for ceramic composites [6]. Other dynamic methods such as resonant ultrasound spectroscopy have been used successfully for measuring the elastic constants of unidirectional alumina reinforced aluminium composites [7-9].

4 RESULTS

A summary of the results obtained for all the room temperature tests is presented in Table 2. Although small differences between specimens will contribute to some variability in the measurements, the results obtained on the same specimen tested with the different techniques show larger variation than expected, both in the calculation of modulus and in the Poisson's ratio measurement. Only the strain gauges were used to measure the strain on both sides of the specimen thus taking into account any misalignment and bending; the other techniques therefore could be expected to show greater variability and uncertainty, and this is an

important factor. The XY strain gauges and ESPI measurements seem to offer the most consistent data, the image correlation method the largest scatter and uncertainty. This is almost certainly due to the small strains involved (particularly in the transverse direction) and the difficulties associated with getting good quality images. The split prism/linescan system appears to show some improvement over the full field techniques in this case, and the IET measurements are generally in good agreement with the strain gauge modulus data.

Longitudinal Modulus, GPa							
	Spec ID	XY Gauges	Biaxial Ext.	ESPI	DIC	Linescan	IET
Textron	TEN2	197.5	180.1	202.8	191.0	192.0	193.4
	TEN3	199.5	185.4	200.1	181.3	193.8	193.7
	TEN4	199.0	189.7	199.5	184.6	194.2	192.5
Sigma	TEN3	183.4	181.6		164.7	182.5	185.0
	TEN4	184.6	179.2		181.3	188.9	184.3
	TEN5	186.8	185.7	185.4	167.3	175.6	184.5
3M	TEN1	260.2					258.4
	TEN2	262.4				260.4	260.4
	TEN3	259.3				260.9	261.0
	TEN4	260.0			276.0	257.6	260.7
	TEN5	260.5			242.0	261.4	259.5
Poisson's Ratio, ν_{12}							
Textron	TEN2	0.27	0.27	0.29	0.25	0.28	
	TEN3	0.28	0.30	0.28	0.35	0.28	
	TEN4	0.27	0.26	0.29	0.32	0.31	
Sigma	TEN3	0.28	0.29		0.24	0.27	
	TEN4	0.28	0.27		0.22	0.27	
	TEN5	0.27	0.26	0.26	0.26	0.26	
3M	TEN1	0.20					
	TEN2	0.30				0.30	
	TEN3	0.30				0.31	
	TEN4	0.29			0.35	0.30	
	TEN5	0.30			0.19	0.31	

Table 2: Summary of Modulus and Poisson's ratio values measured for each specimen

Poisson's ratio measurements measured using the different techniques were generally comparable, again with the greatest scatter and uncertainty from the DIC approach. It is important to note that many studies report Poisson's ratio measurements to 3 decimal places, but such perceived accuracy is misplaced because of the large potential uncertainties associated with the small transverse strain measurements.

5 VARIATION OF POISSON'S RATIO WITH TEMPERATURE

Generally there is a lack of elevated temperature Poisson's ratio data for FRM and only a limited amount for particulate reinforced MMCs, most of which has been generated using dynamic methods. High temperature Poisson's ratio measurements were carried out in this study using tensile tests up to 400 °C and special high temperature fully encapsulated strain gauges (Vishay WK-series), bonded to the specimen using M-bond 610 adhesive. Tests were carried out in an environmental chamber installed on the Instron test machine. Special clevis grips were used and the testpieces were pin loaded using a 8mm diameter loading pin. Larger 25mm wide specimens were used to ensure effective load transfer without initiating damage around the pin. Although there was no direct gripping of the specimen surface, steel tabs

were applied to the ends of the specimen to protect the specimen and supply a larger bearing area for applying the load. In all cases the specimen was tested below the elastic limit.

Thermocouples attached to the centre of the specimen showed reasonable temperature uniformity within the specimen, varying by less than 5 °C along the length of the specimen. A single specimen was used in all cases, loaded within the elastic region, with tests being carried out at approximately 50 °C intervals. Although the temperature cabinet was rated to 600 °C, because of the considerable thermal mass of the pull rods and grips, tests were only possible up to 400 °C, and this was also the short term temperature limit of the strain gauges. In practice however, some of the data obtained at 350 °C, began to show problems. The results are presented in Table 3 and plotted in Fig 7. Generally the modulus data is good, but the Poisson's ratio results are a little inconclusive due to the scatter in the data, but the general trend is for a small increase in Poisson's ratio with temperature. It had been hoped to investigate the high temperature behaviour using the DIC and ESPI systems, but it was not a practical solution because of modifications necessary to the temperature cabinet to install a suitable viewing window, the disappointing accuracy achieved at room temperature, and issues related to maintaining the pattern on the specimen surface at temperature and the distorting effect of thermal currents on the images. Further work is in hand to develop and evaluate the high temperature applications of the two non-contact strain measurement systems.

Temp (°C)	TEN5		TEN6		TEN7	
	E (GPa)	Poisson's Ratio	E (GPa)	Poisson's Ratio	E (GPa)	Poisson's Ratio
25	198.0	0.27	200.3	0.25	199.6	0.28
100	197.0	0.29	199.6	0.27	199.6	0.28
150	194.0	0.30	198.0	0.27	198.2	0.27
200	192.0	0.27	194.0	0.28	197.6	0.28
250	190.4	0.30	196.2	0.28	196.3	0.29
300	190.0	0.29	191.3	0.28	192.0	0.29
350 *	185.3	0.28	190.0	0.30	192.0	0.27
400 *	172.0	0.28	188.6	0.31	190.0	0.25

* Increased uncertainty in the values measured at these temperatures

Table 3: Variation of Modulus and Poisson's ratio with temperature (Textron FRM)

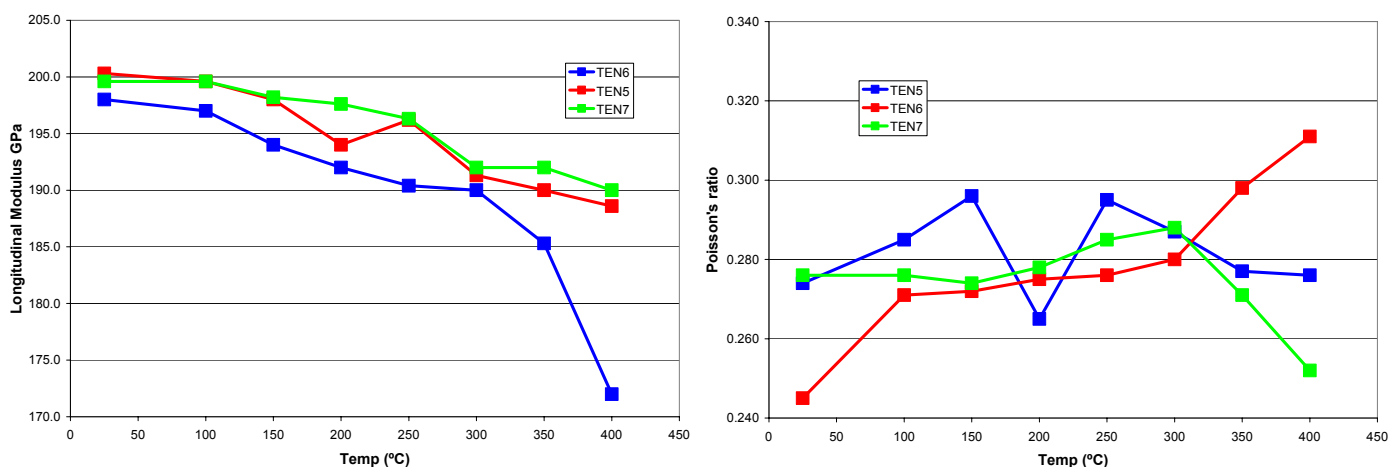


Fig 7: Variation of modulus and Poisson's ratio with temperature (Textron FRM)

SUMMARY

Generally there was reasonable agreement between the different techniques for both the longitudinal modulus and Poisson's ratio measurements. The measurements were also in good agreement with the predicted values. Probably the most reliable, best quality data was obtained from the conventional biaxial strain gauges and this was the only technique examined that measured strain from both sides of the specimen, which was then averaged to take into account misalignment and bending. All the other methods used single sided measurements, and this is an important factor and has been seen to have an important effect on the accurate measurement of modulus. For all modulus measurement, averaging strain measurement is recommended.

It is of some concern that the measured values for Poisson's ratio measured from the image correlation technique varied so widely. This is probably due to a combination of the small transverse strains measured and the limited number of pixels across the width of the specimen. There is scope for improvement by increasing the resolution of the experimental set-up by using higher magnification images and higher resolution cameras to increase the number of pixels.

Dynamic methods offer considerable potential and a means for quickly evaluating the full range of elastic properties. However only limited success was obtained with the IET method and the experimental set-up used in the current study. Recent publications indicate that resonant ultrasound spectroscopy offers a potential solution, but there are still some reservations regarding the applicability of the data to real engineering designs and the complicated nature of testing.

Results at elevated temperatures showed considerable variability and it was difficult to establish with any certainty the effect of temperature on Poisson's ratio. Generally there appeared to be a small increase in Poisson's ratio with temperature. Once again strain measurement is an issue at these temperatures and is not trivial, even for the simple uniaxial case. Further work is required to refine the experimental set up to improve the quality of the data based on some of the shortcomings detailed above but further work is required to reduce the scatter in the data and compare measurements using other techniques.

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