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"TENSTAND"
WP3 Final Report: Modulus Measurement Methods

J Lord, M Rides, M Loveday

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‘ Computer Controlled Tensile Testing Machines: Validation of European Standard EN 10002-1’

“TENSTAND”

WP3 Final Report: Modulus Measurement Methods

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EXECUTIVE SUMMARY

This is the final report of Work Package 3 concerned with the validation of Tensile Testing software as part of the EU Project ‘TENSTAND’.

Although modulus is an intrinsic material property and a key parameter in engineering design and materials development, the current mechanical test methods for measuring it are not well established. The existing tensile standards EN10002-1 and ASTM E8 focus predominantly on measuring the full stress-strain curve, of which the elastic part is often only a small proportion. An accurate knowledge of the engineering value of Young's modulus is vital for design studies, for finite element and modelling calculations and for giving reliable fits to the constitutive equations for the stress-strain curve. Accurate values of modulus are also necessary for obtaining reliable values for proof stress, because inaccuracies in the slope or modulus fit can give significant errors in proof stress, particularly if the material has a high work hardening rate in the early stages of yield.

A draft revision of EN10002-1, which is currently under formal vote and has been examined and validated within the TENSTAND project, contains more detailed information on computer controlled testing, data sampling and uncertainty evaluation, but still does not cover modulus measurement in any detail.

Specific activities within WP3 included ….

- A review of the current tensile testing standards relevant to modulus measurement
- A survey of modulus measurement practices of the TENSTAND partners
- Comparison of tensile and dynamic methods on the Nimonic 75 certified tensile reference material
- Detailed analysis of the WP2 ASCII dataset
- Development of web-based modulus analysis software
- Review and analysis of some of the WP4 tensile test data

Results from the detailed test programme carried out within TENSTAND WP2, WP3 and WP4 confirm that there are still major difficulties with obtaining reliable modulus measurements from the tensile test. It is possible however to obtain good quality modulus data from the tensile test, but this generally requires a separate and dedicated test set-up using high quality averaging strain measurement focusing only on the early part of the stress-strain curve. It is important to recognise that these are specialised tests, and it might be neither feasible nor realistic to carry them out in a cost effective way on a high throughput computer controlled test machine.

The report highlights and summarises some of the issues necessary for making accurate measurements of Young’s modulus using the tensile test. Recommendations to the Standards committee are presented with particular relevance to specific developments that could be included either as an Annex to future revisions of EN 10002-1, or as a separate Standard.

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FOREWORD

This Report has been compiled primarily by Jerry Lord, Malcolm Loveday & Martin Rides as part of Work Package 3 of the EU Funded Project ‘TENSTAND’, Contract Number G6RD-2000-00412.

The following persons also made significant contributions, either by undertaking tests, supplying information, analysing data or by participation in the Work Package 3 discussions.

NAME	ORGANISATION	COUNTRY
J. Aegerter	Hydro Aluminium	Germany
G. Aldrich-Smith	NPL	UK
S. Brookes	BAM	Germany
H. Bloching	Zwick	Germany
J.-L. Geoffroy	Sollac / USINOR	France
N. Jennett	NPL	UK
H. Klingelhoffer	BAM	Germany
S. Ledworuski	BAM	Germany
R.D. Lohr	Instron	UK
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M. S. Loveday	Beta Technology / NPL	UK
N. McCormick	NPL	UK
M. Nicholson	ASTM / Instron	USA
J. Olschewski	BAM	Germany
M. Rides	NPL	UK
B. Roebuck	NPL	UK

In addition, most of the TENSTAND partners contributed to discussion on the interim WP3 reports presented at the main TENSTAND project meetings.

It is sad to note that Dr J. Olschewski (BAM) sadly died during the course of the project, and it is a fitting tribute to him that he should be associated with this work; he led the group at BAM and provided information relating to thermal compensation of modulus during the TENSTAND project.

1 INTRODUCTION TO THE TENSTAND PROJECT

The current Standard for the Tensile Testing of Metallic Materials, EN 10002-1, now recognises the dominance of computer controlled testing machines but the systematic technological evidence on which such a Standard should be based has not been readily available. The TENSTAND project (2001-2004), which was funded by the EU under their programme "Promoting Competitive & Sustainable Growth", has sought to address this deficiency by detailed examination of various aspects of the test procedure in the current Standard. The project acronym **'TENSTAND'** was chosen to reflect the focus of the work, dealing with the **Ten**sile **Stand**ard.

The uniaxial tensile test is the primary method used for quality control and certification of virtually all metallic materials. This represents over 80 million tons per annum of various ferrous and non-ferrous alloys sold throughout the European Community with a value in excess of 50,000 million euro. Rapid turnaround of testing is essential to prevent production line delays and automatic testing is now becoming commonplace with robots feeding computer controlled testing machines. Reliable tensile data is also crucial in the design of many safety critical components in power plant, nuclear and aerospace applications where inaccurate data can result in catastrophe.

The importance of achieving reliable and reproducible tensile data from different laboratories and test houses throughout the Community is also vital if fair trade on an equitable basis is to be maintained, otherwise inadequacies in the Standard could be exploited to give unfair commercial advantage to companies interpreting the document in a manner that was not intended by the Standards writing body. Activities in the TENSTAND project have sought to examine these issues via a detailed intercomparison exercise evaluating the effect of different test parameters, a study on modulus, and the generation of reference ASCII datafiles for the validation and calibration of tensile testing analysis software.

The project consisted of a series of targeted research activities carried out within a framework of five Workpackages (WPs), namely:

WP 1: Literature Review A review of relevant literature on tensile test machine control characteristics, modulus determination and inter-comparison exercises, compiling data suitable for the assessment of uncertainty.

WP 2: Evaluation of Digital Tensile Software Specification of software including evaluation of mathematical and graphical methods and preparation of ASCII format tensile data sets of typical engineering alloys. The data sets were used to compare results from the determination of designated material properties including proof stress or upper and lower yield stress, tensile strength, and elongation at fracture using commercial software from the testing machine manufacturers, and in-house university and industrial software.

WP 3: Modulus Measurement Methods Evaluation of algorithms used for determining tensile modulus by software validation using ASCII tensile data sets and by mechanical testing. Findings were also compared with modulus determined using alternative techniques.

WP 4: Evaluation of Machine Control Characteristics This part of the project validated options of test machine control criteria, i.e. new speed changes during the test proposed for inclusion in the Standard. This was achieved by a test programme using a selection of materials, including the Nimonic 75 Tensile Certified Reference Material CRM661, and a range of other industrial relevant materials.

WP 5: Dissemination, Exploitation and Project management Included reviewing interpretations of the existing Standards, EN 10002-1 & EN 10002-5, dissemination of the Project's findings and the preparation of recommendations for a Normative Annex for the Tensile Testing Standard. This WP also included the co-ordination and management of the Project.

The work described in this report deals with the activity in WP3 – evaluating the methods and software for measuring modulus from the tensile test, and where appropriate other techniques.

Reports from the other work packages are available separately or can be down-loaded as pdf files from the TENSTAND website, at www.npl.co.uk/products-services/advanced-materials/Tensile-testing

To avoid repetition throughout the document, EN 10002-1 is sometimes referred to as the "Standard". As the focus of the work is to provide validation of EN 10002-1, it is hoped that the reader accepts that this terminology does in fact refer to EN 10002-1.

Also, throughout the document, whenever the uncertainties in the measurement are reported, they have been calculated from twice the standard deviation, representing a 95% confidence limit.

2 OBJECTIVES AND ACTIVITIES OF WORK PACKAGE 3 (WP3)

Although modulus is an intrinsic material property and a key parameter in engineering design and materials development, the current mechanical test methods for measuring it are not well established. The existing tensile standards EN10002-1 [1], ASTM E8 [2] and ISO 6892 [3] focus predominantly on measuring the full stress-strain curve, of which the elastic part is often only a small proportion. A draft revision of EN10002-1, which is currently under formal vote and has been examined and validated within the current TENSTAND project, contains more detailed information on computer controlled testing, data sampling and uncertainty evaluation, but still does not cover modulus measurement in any detail. ASTM E111 [4] is the only standard currently addressing some of the issues relevant to making accurate modulus measurements from a tensile test, although a number of in-house proprietary procedures exist.

An accurate knowledge of the engineering value of Young's modulus is vital for design studies, for finite element and modelling calculations and for giving reliable fits to the constitutive equations for the stress-strain curve. Accurate values of modulus are also necessary for obtaining reliable values for proof stress, because inaccuracies in the slope or modulus fit can give significant errors in proof stress, particularly if the material has a high work hardening rate in the early stages of yield.

To address the industry needs and deficiencies of the current Standard, the activity in WP3 has sought to investigate current practice in measuring modulus from the tensile test, providing recommendations for improving the accuracy and reliability of the data. To achieve this, specific activities within WP3 have included ….

- A review of the current tensile testing standards relevant to modulus measurement
- A survey of modulus measurement practices of the TENSTAND partners
- Comparison of tensile and dynamic methods on the Nimonic 75 certified tensile reference material
- Detailed analysis of the WP2 ASCII dataset
- Development of web-based modulus analysis software
- Review and analysis of some of the WP4 tensile test data

Particular emphasis is given to developments that could be included in future revisions of EN 10002-1.

3 REVIEW OF EXISTING TENSILE TESTING STANDARDS

Young's modulus can be defined as the ratio of stress to strain during elastic loading. Traditionally, the modulus was determined 'by eye' from a straight line drawn on the linear part of the stress-strain curve, but more recently automatic testing machines using computer control and data acquisition use some form of curve fitting to get a best fit to the data. With the general tensile testing standards at present, there is little guidance on how modulus should be measured, and aspects of strain measurement are covered only briefly. Both EN10002-1 [1] and ASTM E8 [2] give no formal definition for modulus, and yet accurate measurement of the slope of the stress-strain or load-displacement curve is necessary for calculating reliable proof stress data. ASTM E111 [4] covers the measurement of Young’s modulus, tangent modulus and chord modulus in more detail, the latter two being recommended for non-linear materials. Table 1 overleaf shows a comparison of the scope and test conditions of the current tensile testing standards and their relevance to modulus measurement [5].

The main differences between ASTM E111 and EN10002-1 and ASTM E8 are the scope of testing and the level of detail related to testing at low strain values. ASTM E111 covers the measurement of modulus in both tension and compression testing and by the use of dead weight loading; EN10002-1 and ASTM E8 cover tensile testing only. In all three standards averaging extensometry is recommended, but only ASTM E111 gives specific guidelines for the uniformity of strain measurements over the range of the test, stating that the strain increments on opposite sides of the testpiece must not differ by more than 3%. ASTM E111 also advocates the use of a higher resolution extensometer compared with the conventional tensile test methods, and also gives detailed advice on data analysis.

Within the tensile test itself, there are many practical difficulties associated with achieving a straight portion at the beginning of the stress-strain curve, and the modulus of some materials is notoriously difficult to measure. However, an accurate value is important for design purposes and for subsequent calculation of proof stress values and non-proportional elongation values in the full tensile test. The stress-strain curve in Fig 1 was generated as part of the ASCII dataset in WP2 and shows the effect different values for the modulus can have on these parameters.

From the analysis of the datafiles generated as part of both TENSTAND WP2 and WP4, the uncertainty in modulus was the highest of all the parameters examined. This further illustrates the difficulty of obtaining good quality modulus data, but perhaps such large uncertainty should not be unexpected as the tests were carried out according to the current procedures in EN 10002-1, which does not specifically cover the measurement or calculation of Young's modulus. More specific guidance on the determination of the slope of the curve in the elastic range is given in Section A.4.9 in Annex A in the draft Standard, but this is still inadequate.

In Fig 1, two lines for the slope or modulus are shown, with values of 205 GPa and 199 GPa. It can be seen that the variation in modulus has an impact on the calculated values for R_p and A, with the agreed range of values for $R_{p0.2}$ being 560.5-563.0 MPa in this case. Although the differences in proof stress values are small (~ 0.5%) they might be expected to be greater for materials with significant work hardening since small variations in the modulus may result in large differences in the values of R_p. The corresponding values for $R_{p0.1}$ were 519.3-526.1 MPa, showing larger uncertainty as expected. All the uncertainties reported in this example are associated with the analysis procedures used to calculate the modulus of the file, although significant uncertainties may of course originate from practical aspects associated with carrying out the test. They do not however include any contribution from material variability or variation between laboratories as a result of different testing procedures.

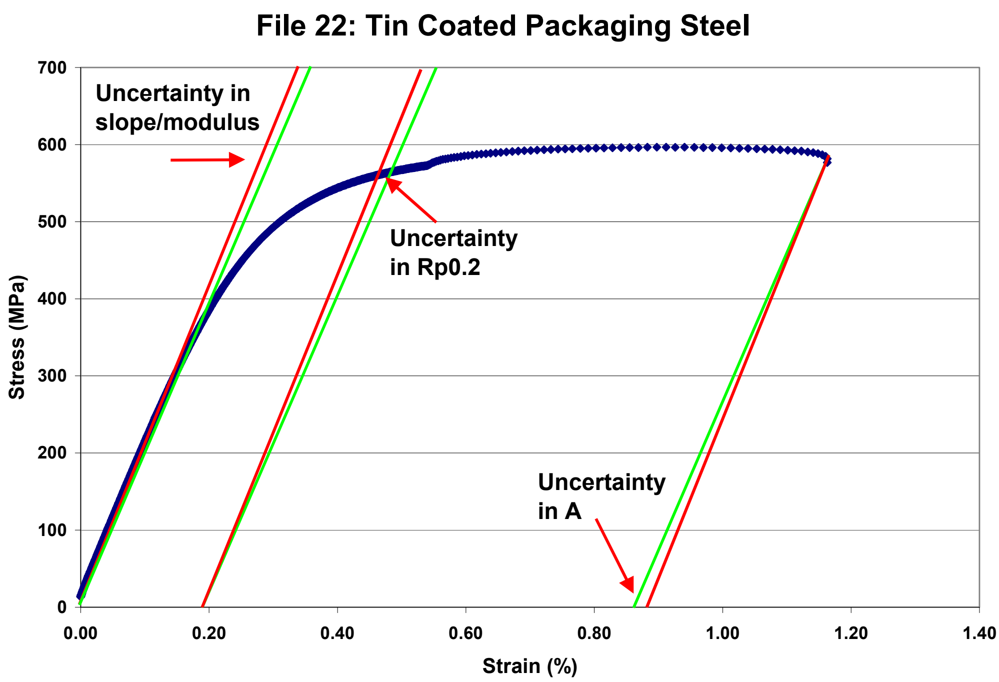


Fig 1: The influence of the variation in modulus on other parameters [6]

Table 1: Comparison of EN10002-1, ASTM E8 and ASTM E111

	EN10002-1	ASTM E8	ASTM E111
Scope	Tensile testing of metals at ambient temperatures **Modulus is not explicitly defined in either standard**		Young's modulus, Tangent modulus and Chord modulus.
Test conditions	Uniaxial tensile testing Elevated temperature testing in EN10002- 5	Tensile testing of metallic materials Room Temperature (RT) only	Tension or compression RT, elevated temp (below creep), sub zero
	Continuous loading		Continuous or incremental loading (via dead weights). Measurements during the loading or unloading cycle
	Hysteresis tests can be used to measure modulus/slope Preloads permitted but the value must be noted		Preload is recommended; Specimen should be free of residual stress. Tests should be carried out below elastic limit, and below 0.25% strain
Speed of testing	Recommendations given for various materials and conditions		Not specified
Extensometry	Class 1 for R_p Class 2 elsewhere	Class B-2 for R_{eL}, R_{eH} and A_t Averaging extensometry recommended for R_{eL}, R_{eH}	Class B-1 Averaging extensometry recommended
Strain uniformity and alignment	No recommendations, other than general guidelines to reduce misalignment and bending		As ASTM E8, E9 Recommend that strain increments on opposite sides should differ by less than 3%
Repeat measurements	Not applicable		Minimum of 3 runs recommended, but single test is permissible
Uncertainty	Example calculations given for a number of parameters (not Modulus) in Annex A of prEN10002-1.	Some advice regarding precision statistics, but no uncertainty calculations	Should be included with the report. No examples or guidelines.
Data fitting	No recommendations – some guidelines on data sampling and measuring the slope included in Annex A of prEN10002-1.	Only basic advise on data analysis.	**Linear elastic:** Least squares fit and/or strain deviation **Non-linear elastic materials:** Polynomial approximation and chord modulus

To some extent the difficulties in measuring the slope at the beginning of the stress–strain curve is recognised in Section 13.1 of EN 10002-1, and the use of hysteresis loops and preloading is recommended. Further advice is also given in the Annex (Section A.4.9) of the latest draft of EN 10002-1 that is being examined within the current TENSTAND project, but more explicit details and recommendations are still required.

Due to the practical difficulties of obtaining reliable modulus values from the tensile test some organisations select pre-determined or handbook values for the initial slope and modulus values, which they then use to calculate the proof stress. In the WP2 exercise, only one laboratory used default values for modulus (200 GPa for steel and 70 GPa for aluminium) in a complete set of analysis returns. Other users turn to dynamic techniques and a large variety of dynamic modulus methods are available including flexural resonance methods, the impulse excitation technique (IET), and various ultrasonic, resonance or acoustic wave propagation methods [7-12]. The most commonly used methods for metals are probably the resonance techniques. Table 2 below summarises the relative merits of the tensile and dynamic modulus approaches.

The dynamic methods have the advantage that they are relatively quick and simple and involve small elastic strains and high strain rates. Some can be readily modified to enable high temperature measurements. They typically use a small and simple specimen geometry, but the methods can be sensitive to machining damage, surface finish and poor dimensional tolerances, all of which affect the accuracy of the result. A variety of commercial equipment is available and the theoretical errors in measurement of modulus by dynamic methods are small, typically of the order of ±1%.

Table 2: Summary of relative merits of the dynamic and tensile approaches for measuring modulus

Tensile Test	Dynamic Methods
Advantages: ▪ "Engineering value" for modulus	**Advantages:** ▪ Quick, simple, non destructive ▪ Good inherent accuracy ▪ Uses small specimens
Disadvantages: ▪ High accuracy strain measurement required ▪ Need averaging extensometry ▪ Specialised test ▪ Larger specimens required ▪ Large interlaboratory scatter	**Disadvantages:** ▪ Relevance of dynamic modulus to engineering applications & design? ▪ Sensitive to dimensional tolerances ▪ Methods don't work well for some materials and composites ▪ Calculations require some knowledge of other material parameters

4 SURVEY OF MODULUS MEASUREMENT PRACTICE AMONGST TENSTAND PARTNERS

A survey of the TENSTAND partners revealed that most did not measure modulus routinely by the tensile test. Of those who did, the modulus measurements were usually made using a different set up and test conditions than would be used for measuring the full stress-strain curve according to EN 10002-1. The implication of this is that it might be neither feasible nor realistic to carry them out in a cost effective way on a high throughput computer controlled test machine. Details of the replies are given in Tables 3 and 4.

Generally the main driver for measuring modulus is for product and material specification, modelling data or customer request. In some cases the need was material specific, for example much of the modulus measurement work at NPL has arisen because of the work on metal matrix composites (MMCs). To realise the potential of these materials for higher strength and stiffness compared with conventional unreinforced alloys, accurate methods for measuring the properties are required. In some cases the identification of the linear part to the curve was difficult, due to presence of high tensile residual stresses that developed in the matrix material during processing and heat treatment, leading to very low proportional limits and a short elastic portion of the curve. In other situations the need for accurate measurement is driven by legislation. For example, NPL has been working closely with the FIA technical department and Formula One industry to define the test procedure for measuring the specific modulus of metallic alloys used in the cars. It was important that reliable methods were developed to reduce the scatter and uncertainty in the measurements, thus allowing the material designers to make small changes in composition to maximise the performance of the material and car.

Table 3 shows that, in the absence of specific guidance in EN 10002-1, a range of test machines, extensometry, software and test conditions has been used by the TENSTAND partners. The typical uncertainties quoted for the modulus data is 2-5%, which is significantly lower than that obtained from the tests in TENSTAND WP4 [13], carried out according to EN 10002-1, and from the analysis of some of the ASCII datafiles generated in WP2 [6].

Some of the other partners involved in the project including those representing the test machine manufacturers did not complete the questionnaire, but Zwick, Instron and DMG provide a range of extensometry and modulus algorithms in their tensile testing software that are at the disposal of the user. The participants representing Corus, TKS and Sollac/Usinor also reported that they had developed their own analysis software. A major concern with the large variety of algorithms available to the user is that, without specific guidance or consideration, the algorithms can give very different values for modulus. In fact the method used to analyse the data has an important effect on the calculated modulus value. In some cases graphical techniques are still used but most systems today use computer-based analyses. Commercial test machine software such as *Zwick testXpert* and *Instron Merlin* offer a wide range of options relating to the calculation of the slope or modulus, some of which are illustrated schematically in Figure 2 [14]. It is not the intention of this report to discuss in detail the aspects of all the individual options, but to highlight some of the issues that the user should consider in their choice of test method and analysis procedures.

Table 3: Details of the modulus measurement practice used in the tensile test amongst the TENSTAND partners [5].

	NPL		BAM	ISQ		
When do you measure modulus?						
Routinely	Yes					
Occasionally		Yes	Yes	Yes		
Use a different set-up		Yes	Yes			
What do you use the modulus values for?	Product or material spec customer request	Product or material spec	Product or material spec customer request modelling	to check proof stress values		
Equipment and Test Details						
Machine type	Instron 5500R	Instron 6027	Instron / MTS	Instron 4208	Instron 4208	Instron 8502
Load capacity	500 kN	200 kN	10 & 100 kN / 250 kN	300 kN	50 kN	250 kN
Load cell	5, 100, 500 kN	200 kN	Autoranging	0-300kN	0-50 kN	0-250kN
Specimen geometry	Flat dogbone	round, threaded ends	round, threaded ends, flat	Flat, round		
Specimen dimensions	100 x 12 x 3	120 x 10 mm dia.	eg 5-15 mm dia.	DIN 50125, ASTM E8, EN 10002-1		
Extensometer type	strain gauges	Instron ceramic rod	HBM DD1	Axial		
Single side or averaging	averaging	averaging	averaging	Single		
Gauge length	6mm s. gauge	25 mm	25 / 50 / 100 mm	12.5 - 50 mm		
Class			1	1	0.5	1
Range (%)	test to ~1-3%	10%	2.5 / 5 / 10	to 50%	to 50%	to 50%
Test control mode	position	position, load, strain	stress or strain	position, load, strain		
Loading rate	1 mm/min	EN 10002-1	EN 10002-1	0.0025 x g.l mm/s		
Type of grips	manual wedge	screw thread	Instron wedge grips MTS hydraulic wedge	hydraulic parallel	hydraulic wedge	manual wedge
Alignment ?	universal joint + special fixture		universal joint alignment fixture, ref testpiece with s.g	centring device	Instron Alignpro	universal joint
Modulus Calculations	software		manually & software	software		
	in -house	Instron Merlin	in-house	Instron Series IX		
Which routine?	Automatic - tangent/secant	Automatic - selected by operator	Automatic - chordal + least sqrs regression	Automatic - selected by operator		
Over how many data points	15	20	20	20		
Stress levels	whole stress-strain curve	selected by operator	varies	20-200 MPa	not predefined	not predefined
Uncertainty	< 2%	5%	< 3%	2.7 GPa		
Reference material	Yes - MMC	Yes	No	No		
RR exercises?	Yes		Yes	Yes, but not modulus		
Which standard?	EN 10002-1 & ISO/TTA2	EN 10002-1	EN 10002-1	EN 10002-1		

Table 4 gives details of the dynamic modulus equipment and procedures used by BAM and NPL – the only two TENSTAND partners with the capability of measuring dynamic properties.

Table 4: Details of dynamic modulus practice amongst TENSTAND partners [5].

	NPL	BAM
What do you use the modulus values for?	Product or material spec customer request	Product or material spec customer request modelling
Equipment and Test Details		
Machine type	Grindosonic + HP frequency analyser & IMCE	Emotron 2000
Dynamic method	Impulse Excitation	Sonic resonance?
Specimen geometry	rect & circular bars discs for Poisson's R	rect & circular bars
Specimen dimensions	30-100mm L/t > 20	>50 mm < 50g
Testpiece supports	various	
Reference material?	No - but periodic checks	No
Comparison with tensile?	Occasionally	
How do you calculate the modulus	ASTM E1876	ASTM E1875
High temperature capability	Yes	Yes
Temperature range	up to 1100 ^{o}C	
Uncertainty	< 1%	< 1%
RR exercises?	Yes	Yes
Which standard?	ASTM E1876	ENV 843-2, ASTM C1198 ASTM E1875

Some of the typical analysis options available to the user include methods of calculating modulus based on the:

- Maximum slope
- Tangent modulus
- Chordal modulus
- Secant modulus
- Segment modulus
- Initial tangent modulus
- Hysteresis loop measurements
- Combined tangent/secant
- Combinations and variations of the above

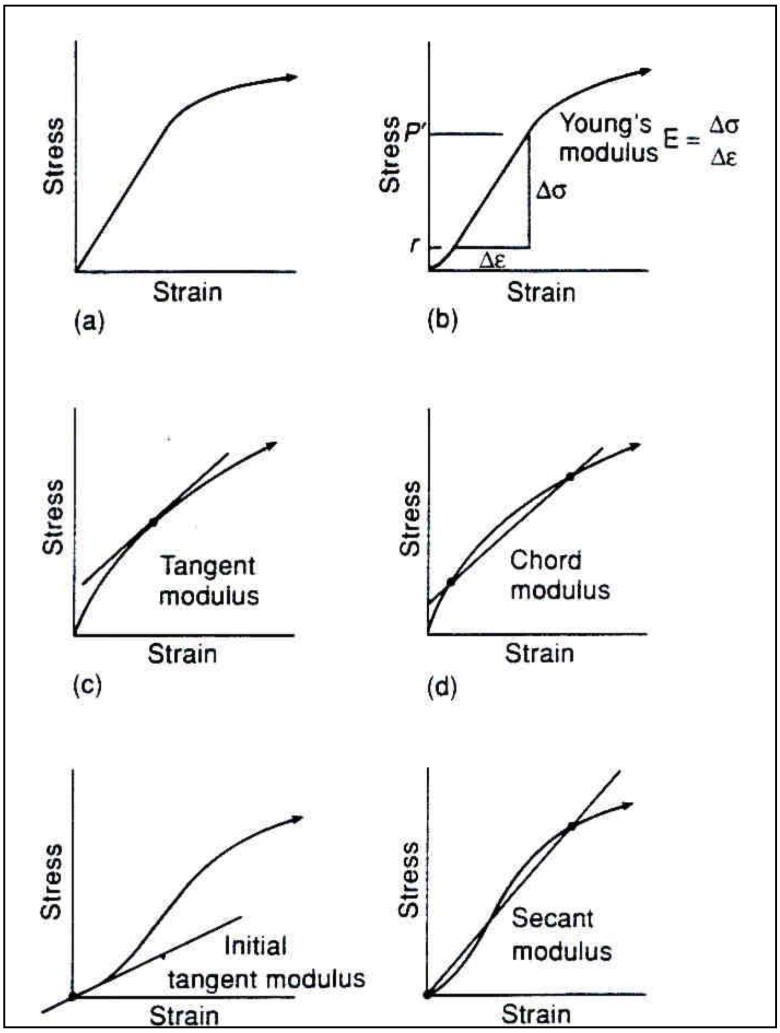


Fig 2: Schematic of modulus definitions and calculations [14]

The preferred procedure is to examine the early part of the stress-strain curve (below the elastic limit) and automatically optimise the fit of the modulus line to the data by consideration of least squares regression analyses or other statistical fitting techniques, with little or no operator intervention. Many of the data analysis procedures are carried out between discrete data points, and others use some sort of fitting or interpolation between automatically or user selected limits, either as a simple straight line or by use of least squares regression. Some algorithms only consider part of the curve, some split the curve into a fixed number of discrete regions (which may or may not overlap) and calculate values of the slopes according to particular criteria, such as the region with maximum slope. Others are designed to take account of anomalies at the start of the test such as non-linearity associated with bedding in, specimen straightening and initial slack in the load train etc.

The accuracy in modulus calculation is also affected by the quality of the data and test set-up. Ideally the data should be linear, free from excessive noise and contain sufficient data points in the elastic range for detailed analysis. This is an important point because, if the test was designed to measure the whole of the stress-strain curve, there may be insufficient datapoints in the early part for accurate calculation of modulus. From analysis of the ASCII dataset developed in TENSTAND WP2, the typical number of datapoints was in the range of 150-500 using a high sampling rate (50Hz) and a strain range of 0.2%, see Table 5 [6].

Table 5: Comparison of datapoints and strain range for typical WP2 ASCII files [6]

File No.	Material	Strain Range (%)	No. of datapoints	
			50Hz data	5Hz data
1,3	Nimonic 75, CRM 661	0.1	171	17
		0.2	253	25
17, 19	316L Stainless Steel	0.1	149	14
		0.2	197	19
22, 24	Tin Coated packaging steel	0.1	275	25
		0.2	507	52
42, 44	Aluminium Sheet	0.1	181	23
		0.2	309	41

Data acquired at significantly lower sampling rates can lead to problems due to the limited number of datapoints in the elastic part of the curve. In some cases the limited amount of data means that the resolution of the stress-strain curve is lost, and there are problems detecting parameters where there is a sharp change, such as R_{eH}. This was the evident in WP2 where the 50Hz data was filtered to give an equivalent 5Hz data (see Table 5) leading to significantly higher scatter and uncertainties.

A recommendation of this study therefore is that the test conditions and sampling rates should be chosen to give sufficient data points for analysis. It is recommended that the stress-strain data is captured using a computer based acquisition system, and that at least 50 data points are sampled for each strain increment of 0.1%.

Furthermore, some knowledge of the function of the particular algorithm used to calculate the modulus from the stress-strain data is desirable (& should be recorded in the test report), and ideally the software should be able to analyse the data automatically with minimal operator intervention.

5 COMPARING DYNAMIC AND TENSILE DATA

To compare the modulus data generated from tensile and dynamic methods, an intercomparison exercise was carried out using the BCR Nimonic 75 tensile reference material (CRM661) [15]. Details of the test matrix are given in Table 6, with measurements carried out at NPL, Bristol University and BAM. As is common practice with such intercomparison exercises, the results have been presented in a form that preserves the anonymity of the organisation, and are subsequently labelled as Labs A, B and C (chosen randomly). Initial measurements were undertaken on 20 un-machined samples cut straight from the extruded bar, approximately 14mm diameter x 84mm long, using the Impulse Excitation Technique (IET). A further set of repeat tests was made when the specimens were returned to Lab A, prior to sending them to Lab C for measurement. Results are presented in Table 7 and plotted in Fig 3. All measurements were made at room temperature, and results between the three laboratories generally showed excellent agreement. The mean modulus values obtained for the batch were 220.4 GPa, 220.8 GPa and 220.8 GPa for measurements carried out respectively at Labs A, B and C. The typical uncertainty (expressed as twice the standard deviation, giving the 95% confidence limit) for the measurements on the extruded bar was less than 1%.

Several of the testpieces were then machined into flat rectangular bars, 82mm long x 3mm thick with a width of either 6mm or 12mm. Room temperature dynamic tests were then carried out on 10 of the machined specimens and several testpieces (GAQ4, 6, 10, 12, 16 and 18) were also tested in tension for direct comparison with the dynamic measurements. To ensure that the measurements were repeatable and not influenced by plastic deformation all the tensile tests were carried out in the elastic part of the stress-strain curve, below the proportional limit. Results from the Lab C tests are included in Table 7 and plotted in Fig 4 together with a subsequent set of tensile and dynamic measurements carried out at Lab A on the same specimens. Both Labs carried out measurements according to their in-house test procedures (See Tables 3, 4) and analysis routines. The Lab C measurements were carried out using a high precision side-to-side averaging extensometer; the Lab A tests were made using strain gauges bonded to both sides of a rectangular testpiece. Additional tests were carried out on a couple of testpieces using a new Surface Acoustic Wave (SAW) technique.

Figs 3 and 4 are plotted on the same scale, and it is clear that the modulus results on the machined rectangular specimens are lower than those measured on the extruded bar. It is not clear why this should be the case. The dynamic measurements are generally more sensitive to variations in dimension than the tensile tests, so it might be expected that the opposite be true. The results generally show good agreement but the tensile data has greater scatter and uncertainties than the dynamic methods, probably due to the difficulties of measuring modulus at low strain values. SAW measurements were in good agreement with the other measurements.

Dynamic measurements clearly offer an accurate means of measuring modulus. Although the preference is to measure modulus from the stress-strain curve, the use of dynamic techniques should be considered if sensible values of modulus cannot be measured, because of problems with the practical set up, or to validate and support the use of using handbook values. It is recommended that wherever possible measurements be made rather than relying on default handbook values, because these might not be available for the specific alloy being tested. Users will often have considerable experience with the behaviour and properties of the materials that are testing, but if realistic values of modulus cannot be achieved through the tensile tests it is an indication that the test set-up is inappropriate. Users are encouraged to examine aspects of the tests such as alignment, gripping, strain measurement and the use of different test conditions and data analysis procedures that might help them achieve better quality results.

Table 6: Matrix of tests carried out on Nimonic 75 (CRM 661) reference material

Previous work - HTMTC							TENSTAND							
Testpiece	Original	Lab A	Lab B	Lab A		Lab C	New	Lab C			Lab A			
ID	Geometry	RT	RT	RT	HT	RT	Geometry	RT dynamic	RT Tensile	HT dynamic	RT dynamic	RT tensile	HT dynamic	SAW*
GAQ1	○	✓	✓	✓	✓	✓	○				✓			
GAQ2	○	✓	✓	✓		✓	▯	✓		✓	✓	✓		
GAQ3	○	✓	✓	✓		✓	○				✓			
GAQ4	○	✓	✓	✓		✓	▯	✓	✓		✓	✓		
GAQ5	○	✓	✓	✓		✓	○				✓			
GAQ6	○	✓	✓	✓		✓	▯	✓	✓		✓	✓		
GAQ7	○	✓	✓	✓	✓	✓	○				✓			
GAQ8	○	✓	✓	✓		✓	▯	✓		✓	✓			✓
GAQ9	○	✓	✓	✓		✓	○				✓			
GAQ10	○	✓	✓	✓		✓	▯	✓	✓		✓	✓		
GAQ11	○	✓	✓	✓		✓	○				✓			
GAQ12	○	✓	✓	✓		✓	▯	✓	✓		✓	✓		
GAQ13	○	✓	✓	✓		✓	○				✓			
GAQ14	○	✓	✓	✓	✓	✓	▯	✓		✓	✓	✓		
GAQ15	○	✓	✓	✓		✓	○				✓			
GAQ16	○	✓	✓	✓		✓	▯	✓	✓		✓	✓		
GAQ17	○	✓	✓	✓		✓	○				✓			
GAQ18	○	✓	✓	✓		✓	▯	✓	✓		✓			✓
GAQ19	○	✓	✓	✓		✓	○				✓			
GAQ20	○	✓	✓	✓	✓	✓	▯	✓		✓	✓	✓		

○	Original geometry - 14 mm dia. X 84 mm
▯	Machined by Lab C into rectangular bars (82mm x 12mm x 3mm or 82mm x 6mm x 3mm)
SAW*	Surface Acoustic Wave technique
	HT measurements up to 750 °C in 100°C steps.

Table 7: Results from modulus intercomparison exercise on the Nimonic 75 (CRM 661) reference material

EXTRUDED BAR				MACHINED SPECIMENS				
				Lab C		Lab A		
	E (GPa)	E (GPa)	E (GPa)	E (GPa)	E (GPa)	E (GPa)	E (GPa)	E (GPa)
ID	Lab A	Lab B	Lab C	Dynamic	Tensile	Dynamic	Tensile	SAW
GAQ1	220.5	221.9	221.1					
GAQ2	220.5	221.4	220.8	215.4		218.2	221.0	
GAQ3	219.3	222.2	220.6					
GAQ4	220.1	221.6	220.5	216.0	213.8	217.9	218.5	
GAQ5	220.0	220.2	220.8					
GAQ6	221.3	222.1	221.5	217.2	211.3	217.0	219.7	
GAQ7	221.5	222.3	221.0					
GAQ8	219.8	220.6	221.0	217.0		215.7		218.7
GAQ9	220.3	220.5	220.9					
GAQ10	219.9	221.4	220.1	217.7	215.0	218.4	220.5	
GAQ11	221.1	220.2	220.6					
GAQ12	220.3	220.9	220.5	217.2	217.1	214.7	220.5	
GAQ13	220.2	221.0	220.2					
GAQ14	220.0	219.8	220.1	216.2		216.5	219.4	
GAQ15	219.8	219.9	220.7					
GAQ16	221.5	219.8	222.1	217.0	218.7	216.7	218.9	
GAQ17	221.1	220.7	222.2					
GAQ18	219.3	220.4	220.3	217.3	216.0	216.9		216.3
GAQ19	220.7	219.8	220.4					
GAQ20	220.2	220.2	220.8	215.6		218.6	221.5	
Mean E (GPa)	**220.4**	**220.8**	**220.8**	**216.7**	**215.3**	**217.1**	**220.0**	
SDev (GPa)	**0.7**	**0.8**	**0.6**	**0.8**	**2.6**	**1.3**	**1.0**	
Uncert (%)	**0.6**	**0.8**	**0.5**	**0.7**	**2.4**	**1.2**	**1.0**	

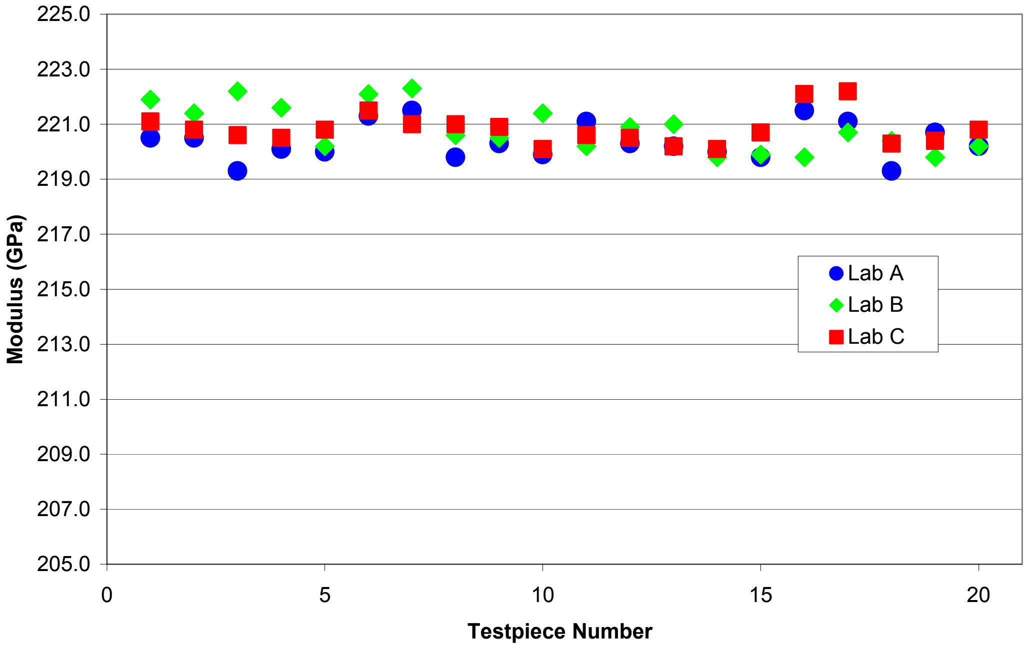


Fig 3: Comparison of BAM, Bristol and NPL dynamic data on extruded bars – BCR Nimonic 75 (CRM 661) tensile reference material

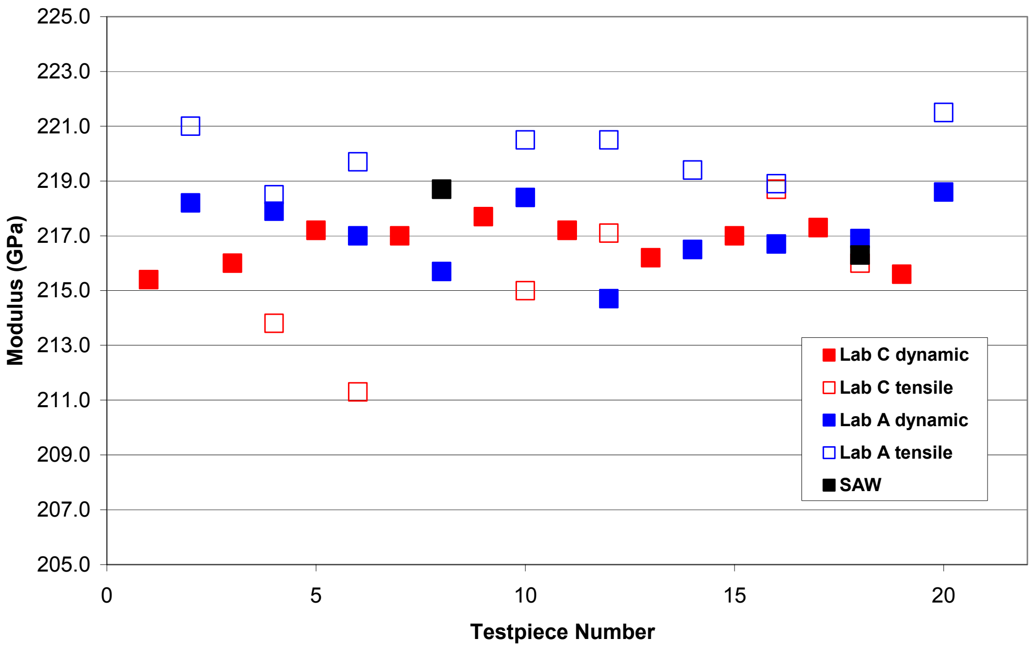


Fig 4: Comparison of dynamic, tensile and SAW measurements on machined testpieces - BCR Nimonic 75 (CRM 661) tensile reference material

6 DEVELOPMENT OF THE NPL WEB-BASED MODULUS ANALYSIS

As part of the TENSTAND project NPL has developed and implemented a web-based version of the modulus analysis software, which is currently available to access at http://materials.npl.co.uk/modulus. Users can import their own stress-strain data in the form of ASCII or Excel datafiles, and analyse the data to calculate modulus. The software is an implementation of a modulus analysis that had been developed previously [16], whereby the tangent and secant moduli are calculated at each data point, and used to define the straight line fit to the early part of the stress-strain curve (see schematic in Fig 5). Example screenshots are given in Fig 6. The analysis works by sequentially fitting a quadratic polynomial to the stress-strain data, point by point along the curve, by a least squares regression analysis. The fitted polynomial is then differentiated at each point to obtain a value for the tangent modulus, which is then plotted against strain. The best fit to the tangent modulus-strain curve is then obtained and this modulus value is used to define a new origin for the stress-strain data. The data is then replotted with a new origin, and the secant modulus-strain curve is calculated. For a good fit to the linear part of the curve, the tangent and secant moduli should coincide and this is taken to represent the true value of Young's modulus from the test. The analysis of the secant and tangent moduli data is a very sensitive method for checking whether the value selected is a good fit to the stress-strain curve.

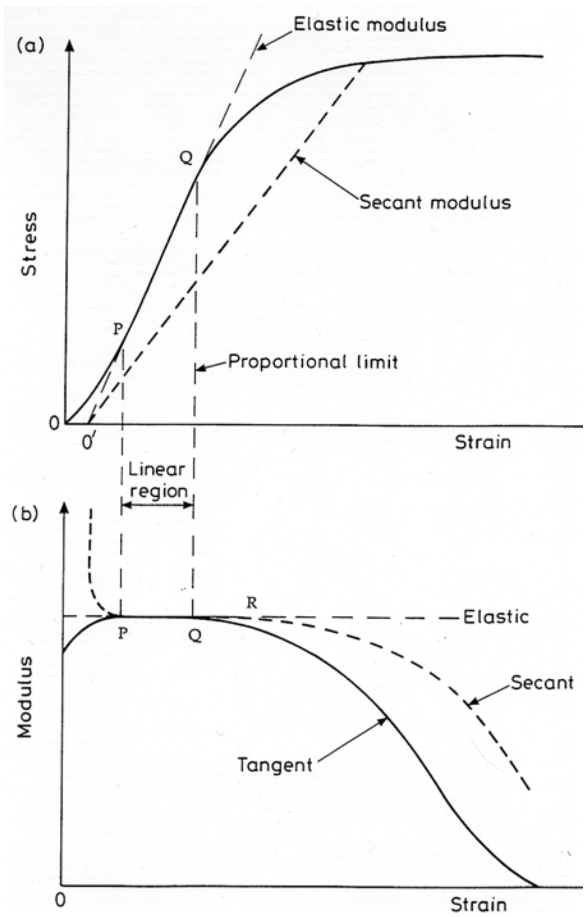
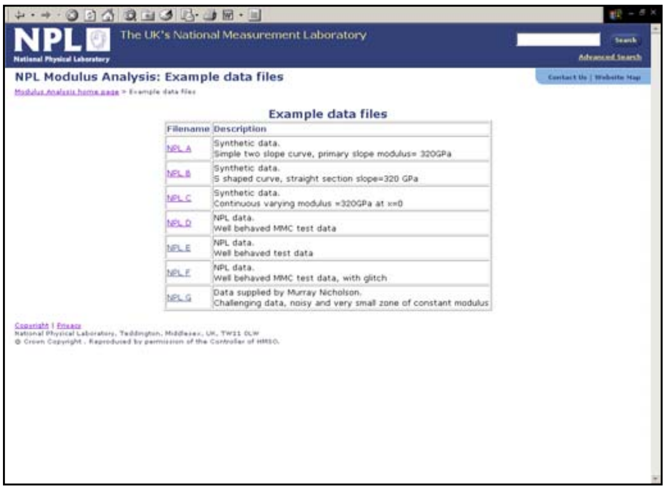
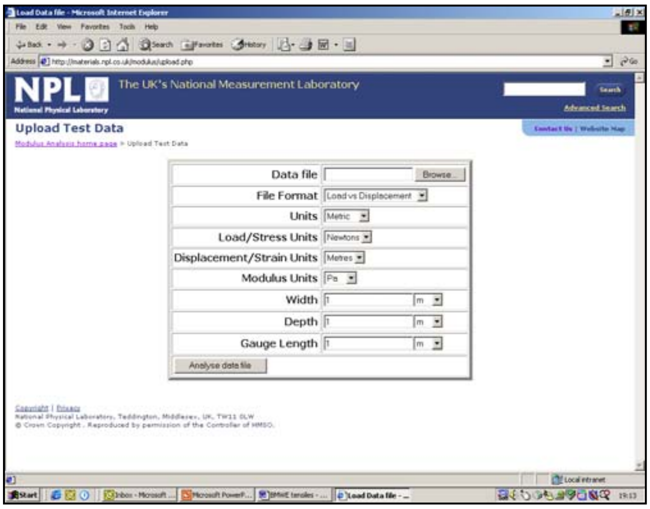


Fig 5: Schematic of NPL modulus software and analysis procedure

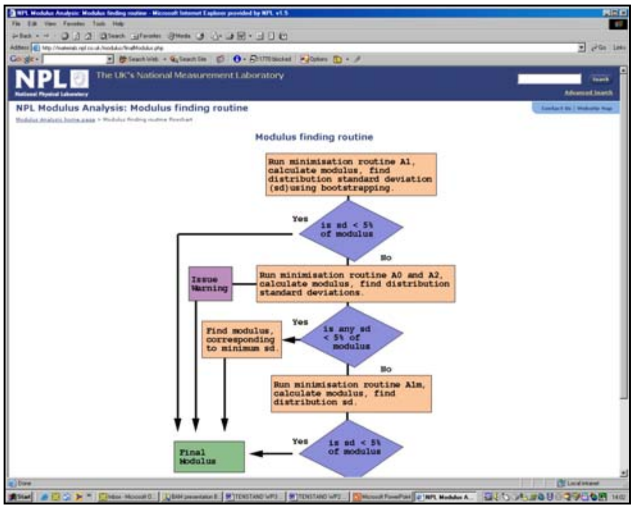
Home page



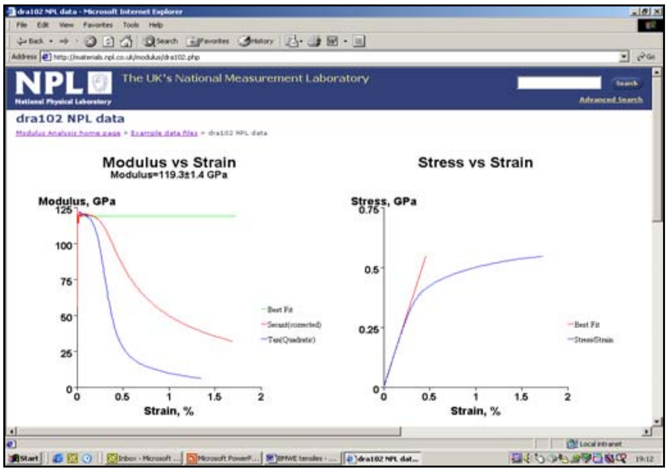
Example Files



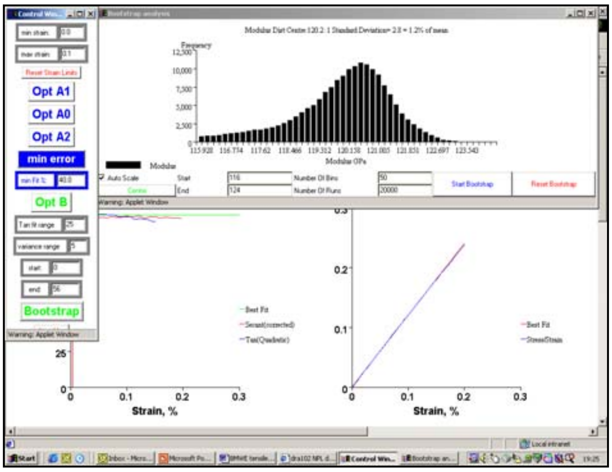
File upload



Details of Modulus algorithm



Modulus fit



“Bootstrapping” page

Fig 6: Example Screenshots of the NPL web-based modulus analysis software

The full procedure for the analysis method is given in Ref. 16 and the algorithms have been used to analyse data in various intercomparison studies and been adopted by a number of users and commercial software packages [17-21].

Fig 7 shows typical stress-strain data obtained from modulus tests at NPL, and analysed using the web-based software. The data has been generated from special tensile tests on flat rectangular specimens, using strain gauges bonded to both sides of the specimen. The tests were carried out to failure but a high data-sampling rate was used to ensure sufficient datapoints in the early part of the curve. In Fig 7, the plot of the tangent and secant moduli vs. strain are shown on the left hand side, and the corresponding stress-strain curve, with the modulus fit overlaid on the curve on the right. Three different materials are shown and in all cases there is excellent agreement between the tangent and secant modulus values in the early part of the curve, and excellent modulus fits.

Fig 8 shows a stress-strain curve from the WP2 ASCII dataset that has been analysed using three different algorithms to show the sensitivity of the tangent-secant moduli approach. The top figure shows the tangent/secant moduli plot and the corresponding stress-strain curve with the modulus fit. The value selected gives 192.0 GPa, with 194.4 GPa and 190.2 GPa for the middle and bottom cases respectively. Although the fit to the stress strain curve looks reasonable in all cases, there is a clear difference in the tangent/secant moduli curves. Only in the top figure do the tangent and secant coincide, and the value from this analysis has been chosen as the "correct" modulus for the test. The differences between the values calculated from the other analyses are only 2.4GPa and 1.8 GPa, but do not give as good a fit to the data and are in error by about 1%.

To obtain a statistical indication of the quality of the data, a procedure that automatically selects the best fit to the modulus using a "bootstrapping" technique has been developed. Bootstrapping is a statistical technique that can be used to examine the variability of data and data fitting procedures without making any assumptions about the shape of the error probability distribution [22,23]. It is ideally suited to computer-based analyses since it uses repeated calculations of parameters, rather than simple analytical solutions that are used in most other statistical calculations. Generally analytical solutions are calculated assuming a normal distribution of errors, but bootstrapping can deal with arbitrary distribution shapes.

Bootstrapping can be used in conjunction with a simple curve fitting algorithm such as a linear least squares fit to determine the likely distribution of errors of both intercept and gradient. This is achieved by generating information about the whole population of data from the sample of data. Since the sample of data contains all the information available about the population it is the best starting point for generating a much larger supply of data. The synthesised population data samples are then processed and the parameters from the curve fit algorithm stored. This process can be repeated many times and a distribution of the curve fit parameters can be constructed. The width of these distributions can be used as measures of the success of the curve fitting procedure and the quality of the data. Bootstrapping has been implemented in the NPL analysis system, developed as part of the TENSTAND project to measure the robustness of particular modulus algorithm fitting parameters. Various functions of tangent modulus, secant modulus, final modulus and a variance parameter in the form of a standard deviation value have been used as minimisation variables. No bootstrapping results are presented in this report, but the reader is recommended to access the web-based software for further details and advice on applying the test to their own data.

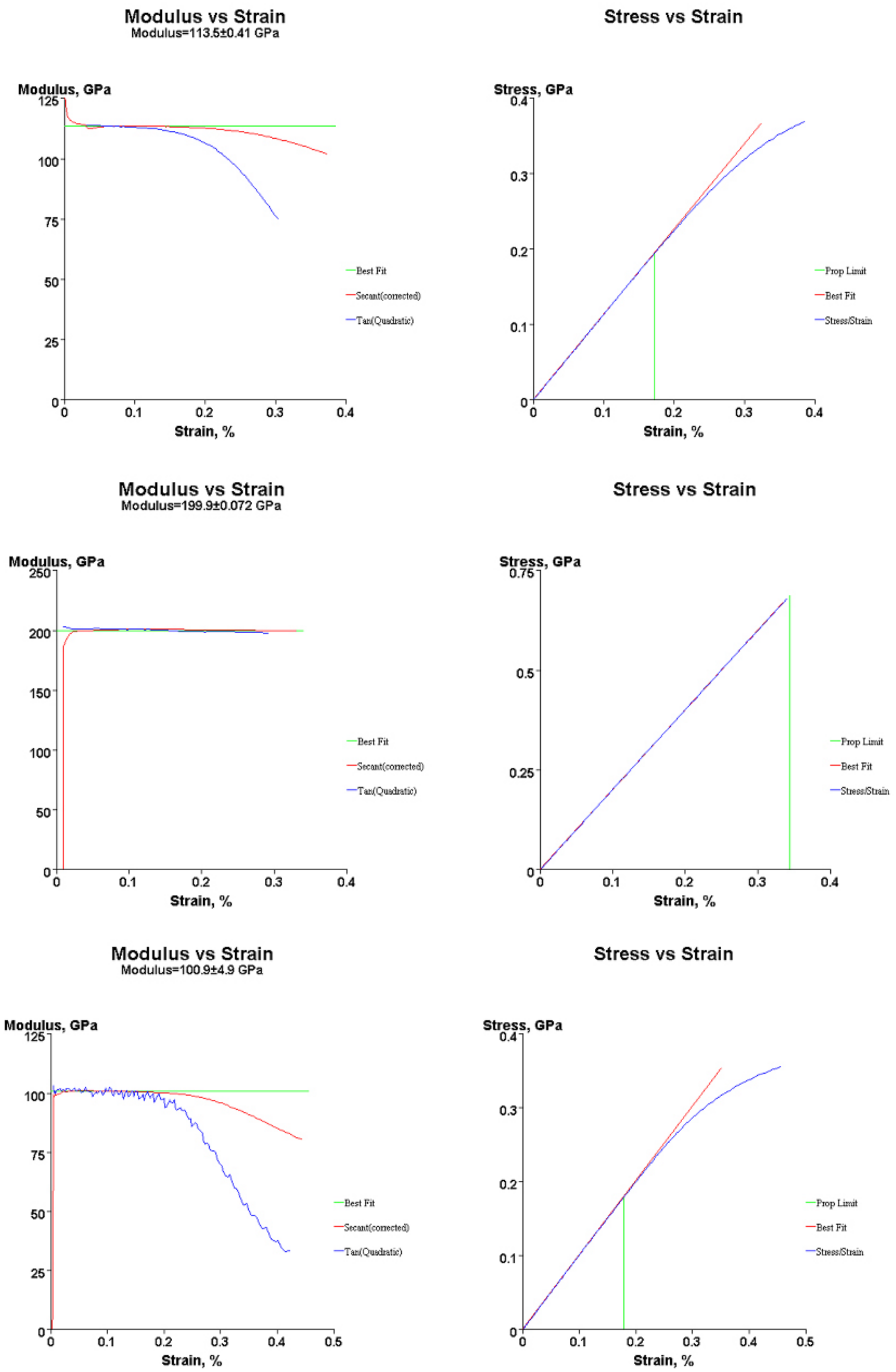


Fig 7: Typical stress-strain data obtained from dedicated modulus tests at NPL

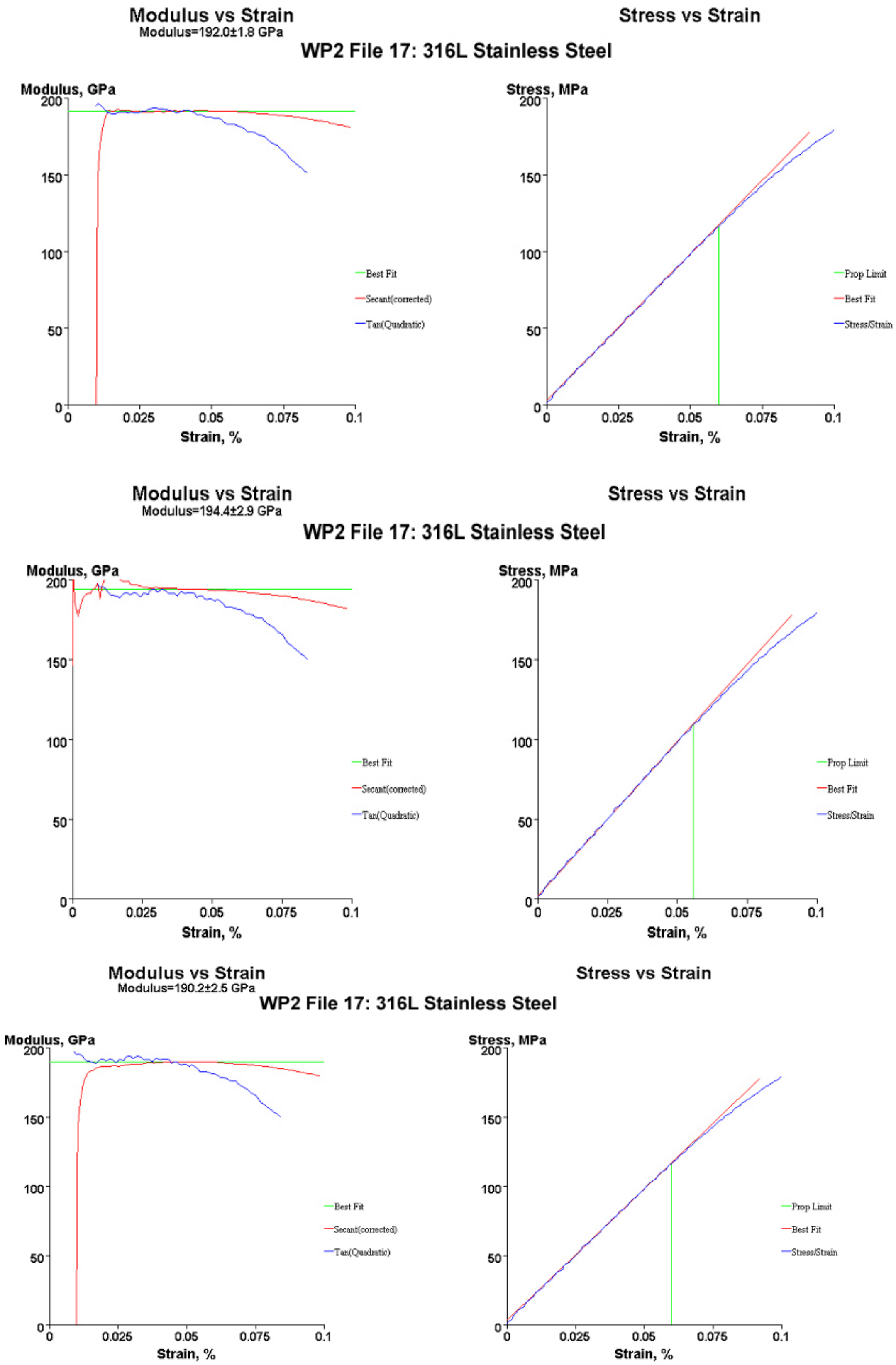


Fig 8: Examples showing the sensitivity of the tangent/secant approach

To further evaluate the effect of using different algorithms for calculating modulus, ten stress-strain curves generated on a variety of materials from other projects were examined. All of the tests were carried out as dedicated modulus tensile tests, using double-sided, averaging strain measurement, and not loaded beyond 0.2% strain.

Five different analysis approaches were used with the NPL software: **Method A** minimises the difference between the secant modulus and the calculated value for Young's modulus; **Method B** minimises the difference between the tangent and secant moduli; **Method C** minimises the difference between the tangent modulus and the calculated value for Young's modulus and **Method D** selects the value obtained from A, B or C based on the minimum standard deviation. Values were also calculated using simple linear regression.

Each individual datafile was analysed using the NPL software over the range 0-0.1%, 0-0.15% and 0-0.2% strain to determine whether the range selected had an influence on the modulus calculation. Table 8 summarises the results. In total over 150 analyses were carried out. The uncertainties from the exercise based on the range of analysis methods and strain range covered were very low, typically below 0.5% and illustrate the quality of modulus data that can be obtained from a dedicated tensile test.

Table 8: Modulus analysis tests carried out on a variety of materials at NPL, analysed using different algorithms with the NPL modulus software.

File No.	Material	Strain range	A	B	C	D	Mean	SDev	U%	LinReg	From mean
1	F15	0.10%	113.5	113.5	113.5	113.5	113.5	0.0	0.0	113.6	0.1
		0.15%	113.7	113.7	113.7	113.7	113.7	0.0	0.0	113.4	-0.3
		0.20%	113.6	113.6	113.1	113.6	113.5	0.3	0.4	113.6	0.1
2	F44	0.10%	142.9	143.1	143.3	143.1	143.1	0.2	0.2	142.1	-1.0
		0.15%	142.9	142.7	142.7	142.7	142.8	0.1	0.1	140.9	-1.8
		0.20%	142.9	142.7	142.5	142.7	142.7	0.2	0.2	139.9	-2.8
3	R1	0.10%	100.4	100.4	100.2	100.4	100.4	0.1	0.2	100.0	-0.3
		0.15%	99.9	100.4	99.6	100.0	100.0	0.3	0.7	99.6	-0.4
		0.20%	99.9	99.7	99.3	99.7	99.7	0.3	0.5	99.2	-0.5
4	R6	0.10%	101.5	101.4	101.4	101.4	101.4	0.0	0.1	101.1	-0.3
		0.15%	101.5	101.5	101.1	101.1	101.3	0.2	0.5	100.9	-0.4
		0.20%	101.0	101.5	101.1	101.1	101.2	0.2	0.4	100.5	-0.7
5	T1	0.10%	173.1	173.1	172.6	173.1	173.0	0.3	0.3	173.6	0.6
		0.15%	174.1	173.8	173.3	174.1	173.8	0.4	0.4	173.9	0.1
		0.20%	174.1	173.8	173.3	174.1	173.8	0.4	0.4	173.6	-0.2
6	T5	0.10%	172.8	172.8	172.8	172.8	172.8	0.0	0.0	173.3	0.5
		0.15%	173.2	173.2	173.7	173.2	173.3	0.2	0.3	173.8	0.5
		0.20%	173.2	173.2	173.7	173.2	173.3	0.2	0.3	173.8	0.5
7	N43	0.10%	201.1	201.7	201.8	201.7	201.6	0.3	0.3	201.4	-0.2
		0.15%	201.5	201.6	201.6	201.6	201.6	0.0	0.0	201.3	-0.3
		0.20%	201.2	201.2	201.2	201.2	201.2	0.0	0.0	201.0	-0.2
8	NPL D	0.10%	121.4	121.4	121.4	122.2	121.6	0.4	0.7	121.6	0.0
		0.15%	121.6	121.6	121.6	121.6	121.6	0.0	0.0	120.8	-0.8
		0.20%	121.0	121.0	120.3	121.0	120.8	0.3	0.6	119.7	-1.1
9	NPL E	0.10%	105.0	105.0	105.1	105.1	105.1	0.1	0.1	104.9	-0.2
		0.15%	105.0	105.1	104.8	104.9	105.0	0.1	0.2	103.8	-1.1
		0.20%	104.9	105.0	104.9	104.9	104.9	0.0	0.1	102.2	-2.7
10	NPL F	0.10%	114.6	114.6	114.6	114.6	114.6	0.0	0.0	115.3	0.7
		0.15%	115.8	115.8	115.8	115.8	115.8	0.0	0.0	112.6	-3.2
		0.20%	114.5	114.5	114.5	114.5	114.5	0.0	0.0	106.1	-8.4

Generally the values for modulus calculated using simple linear regression were in good agreement with those using other algorithms (and this probably reflects the fact that the dedicated modulus tests had resulted in good quality data), but in some cases (eg. Files 2, 9, 10) the value of modulus calculated using simple linear regression varied considerably depending on the strain range over which it was calculated, even though there was no evidence of yielding and deviation from the elastic behaviour.

Further analysis of the TENSTAND WP2 and WP4 data is covered in the following sections.

7 ANALYSIS OF THE TENSTAND WP2 ASCII DATAFILES

The generation of the ASCII data files for the intercomparison exercise is described in detail in the TENSTAND WP2 report [6]. The tensile testing was carried out according to the conditions in the current standard, EN10002-1, and all the files presented in a single agreed format. Tests were carried out in crosshead control, at the fastest rates permitted, which gave the most demanding situation for the machine control and analysis software, and resulted in a smaller file size. All tests used data sampling at 50Hz, but an aspect of the exercise was to examine data that had been captured at lower sampling rates. Instead of carrying out an expensive set of repeat tests with a lower data sampling rate (outside that specified in the Standard), a pragmatic approach was taken whereby the original datafiles were filtered to reduce the 50Hz data to an equivalent 5Hz test.

Analysis of the WP2 modulus data returned from the exercise showed larger variations than expected, especially considering that all the participants were analysing the same data and the scatter was due to the software and analysis alone. A summary of the mean modulus values, 2 standard deviations and percentage uncertainty is given in Table 9 for all the WP2 files examined, and the uncertainties are plotted in Fig 9. Ten datasets (highlighted in yellow) had uncertainties in the modulus in excess of 10%. Closer examination of the stress-strain curves indicated that, although few test showed significant non-linearity, the quality of the data itself (noise, number of datapoints, offsets) was probably the likely cause of the large scatter and this was probably a consequence of the test method and type and class of extensometry used to generate the stress-strain curve. In many cases long travel extensometers were used and these remained on the specimen up to the point of failure. It is unrealistic for such devices to be suitable for measuring modulus in the first 0.2% of the stress-strain curve, when they are designed for elongations of 40% or more.

The identification of outliers and agreed values for the WP2 ASCII dataset was a long and difficult process. Initially the results were inspected for obvious errors and mistakes, and these values were removed or corrected. A rigorous assessment for outliers, such as that proposed by the Cochran test, was not carried out, but the agreed values and outliers for each datafile were chosen by careful examination of the data and inspection of the individual stress-strain curves. For some parameters - such as the maximum force and tensile strength - an absolute value (in most cases) could be agreed, but for others such as the modulus a range of values were agreed. These modulus values were selected by analyzing each curve using the NPL modulus software and selecting a range of representative values that gave a reasonable visual fit to the early part of the curve. Typically the variation in modulus expressed by the range is 4-5%, and based on these modulus values, a corresponding range of values for $R_{p0.1}$ and $R_{p0.2}$ was calculated. The database of all the values returned from the analysis is included as an Appendix to the WP2 report [6].

Table 9: Summary of the modulus values returned from the WP2 analysis (All participants – all data, no outliers removed)

File No.	Material	Mean	2SDev	U%
1	Nimonic 75, CRM 661-GBX 178-1, 50Hz	208.7	7.0	3.4
3	Nimonic 75, CRM 661-GBX 178-1, 5Hz	208.4	8.6	4.1
6	Nimonic 75, NPL CRM 66 N0 8-2, 50Hz	186.7	9.9	5.3
8	Nimonic 75, NPL CRM 66 N0 8-2, 5Hz	186.3	9.6	5.2
10	13%Mn Steel, P1M 23-2, 50 Hz	182.3	2.4	1.3
12	13%Mn Steel, P1M 23-2, 5 Hz	182.1	3.4	1.9
13	S355 Structural steel, P1M 24-1, 50 Hz	227.9	17.6	7.7
15	S355 Structural steel, P1M 24-1, 5 Hz	225.2	8.0	3.6
17	316L Stainless Steel, S1C 20-1, 50 Hz	183.6	24.3	13.2
19	316L Stainless Steel, S1C 20-1, 5 Hz	182.4	24.7	13.5
22	Tin Coated packaging steel, SOLLAC F72-No7-2, 50 Hz	197.6	20.3	10.3
24	Tin Coated packaging steel, SOLLAC F72-No7-2, 5 Hz	196.8	21.4	10.9
26	Sheet steel, SOLLAC T462 No6-2, 50 Hz	203.3	2.6	1.3
28	Sheet steel, SOLLAC T462 No6-2, 5 Hz	203.2	2.5	1.2
30	Sheet steel, TKS-DX56 No 2-2, 50 Hz	197.5	28.6	14.5
32	Sheet steel, TKS-DX56 No 2-2, 5 Hz	195.1	26.3	13.5
34	Sheet steel, TKS-ZStE-180-No1-2, 50 Hz	206.9	2.7	1.3
36	Sheet steel, TKS-ZStE-180-No1-2, 5 Hz	206.8	2.0	1.0
38	Aluminium Sheet, VAW-hard AA5182-No3-2, 50 Hz	68.9	0.7	1.0
40	Aluminium Sheet, VAW-hard AA5182-No3-2, 5 Hz	68.9	0.7	1.0
42	Aluminium Sheet, VAW-soft AA1050 No5-2, 50 Hz	67.1	7.5	11.2
44	Aluminium Sheet, VAW-soft AA1050 No5-2, 5 Hz	67.1	9.4	14.0
46	Aluminium Sheet, VAW soft AA5182 No 4-2, 50 Hz	69.0	0.8	1.2
48	Aluminium Sheet, VAW soft AA5182 No 4-2, 5 Hz	69.0	0.8	1.2
50	Sheet steel, TKS-DX56-L050-B12-5-2, 50 Hz	161.9	21.5	13.3
52	Sheet steel, TKS-DX56-L050-B12-5-2, 5 Hz	163.8	25.6	15.6
53	Sheet steel, TKS-ZStE-180-L050-B12-5-1, 50 Hz	203.3	4.4	2.2
55	Sheet steel, TKS-ZStE-180-L050-B12-5-1, 5 Hz	204.1	2.9	1.4
57	Synthetic Digital Curve, NPL zero noise, 50 Hz	207.4	0.6	0.3
58	Synthetic Digital Curve, NPL zero noise, 5 Hz	207.7	0.9	0.4
61	Synthetic Digital Curve, NPL 0.5% load noise, 50 Hz	207.9	5.8	2.8
62	Synthetic Digital Curve, NPL 0.5% load noise, 5 Hz	203.5	18.1	8.9
63	Synthetic Digital Curve, NPL 1% load noise, 50 Hz	204.5	14.4	7.0
64	Synthetic Digital Curve, NPL 1% load noise, 5 Hz	209.6	17.3	8.3

Figs 9 and 10 show the uncertainty in the modulus values before and after the outliers were removed (note the different scales). As mentioned previously the uncertainty in modulus was the highest of all the calculated parameters in the WP2 exercise, and the mean value for the uncertainty of all the modulus values was 8.2% and 3.1% respectively, before and after the outliers were removed.

Fig 11 shows representative stress-strain curves for selected WP2 datafiles. Clearly the quality of the data varies considerably. Some of the stress-strain curves (such as File 22, 30, 42 and 63) show some of the problems encountered. Files 22 and 63 are somewhat noisy and this is reflected in the tangent/secant plots, and participants probably had difficulty in identifying the best fit to the data in such cases. Files 30 and 42 caused difficulties because the stress-strain curves do not appear to have significant linear sections over which the modulus could be calculated. Many of the curves were generated with offsets and preloading. This in itself should not be detrimental to the quality of the data, but files with this behaviour did tend to have problems and increased scatter in the calculated modulus values.

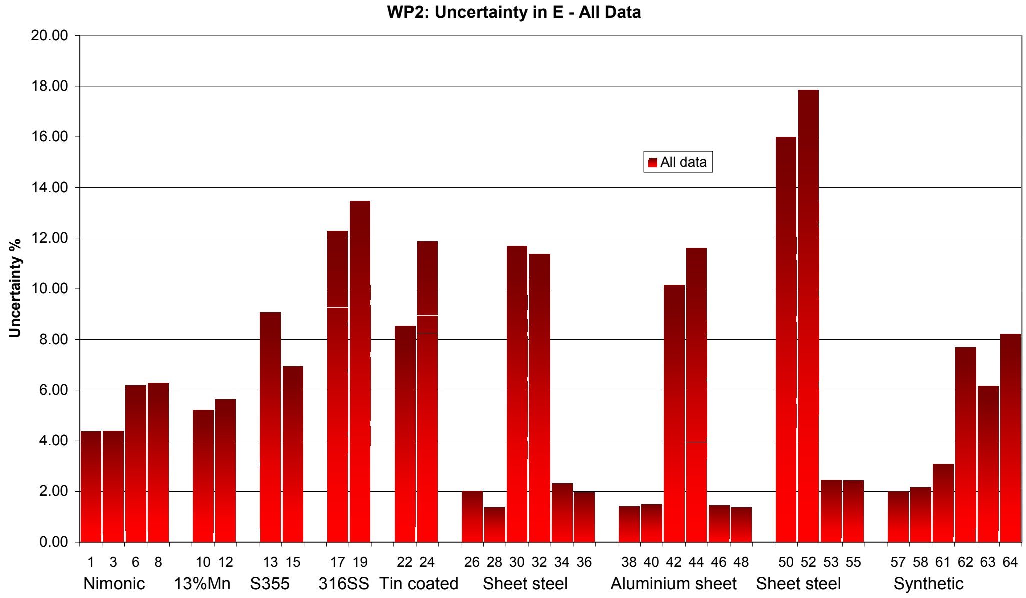


Fig 9: Uncertainty in Modulus (expressed as 95% confidence limit) – All data (including outliers

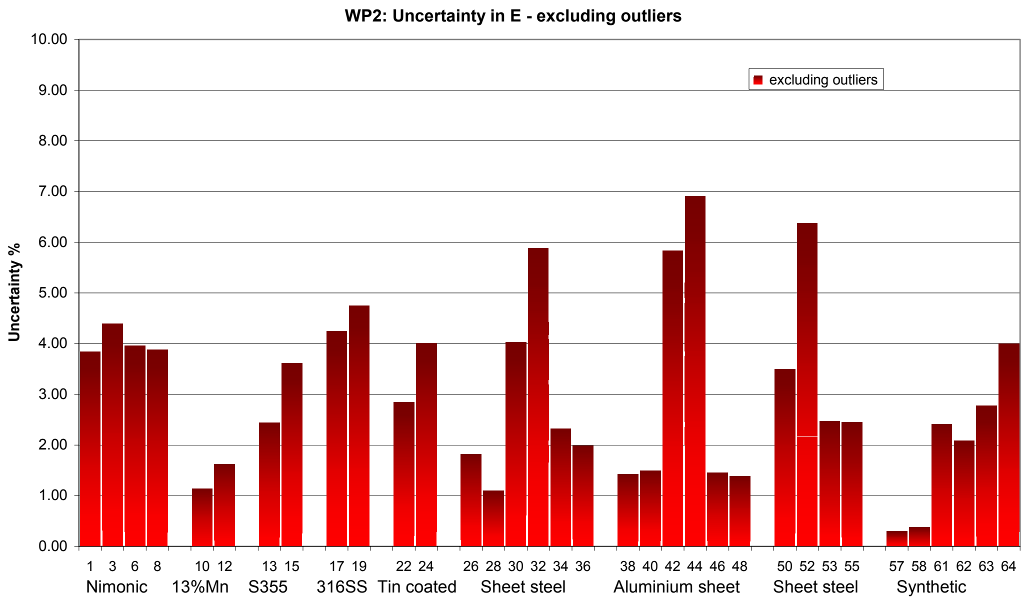


Fig 10: Uncertainty in Modulus (expressed as 95% confidence limit) – excluding outliers

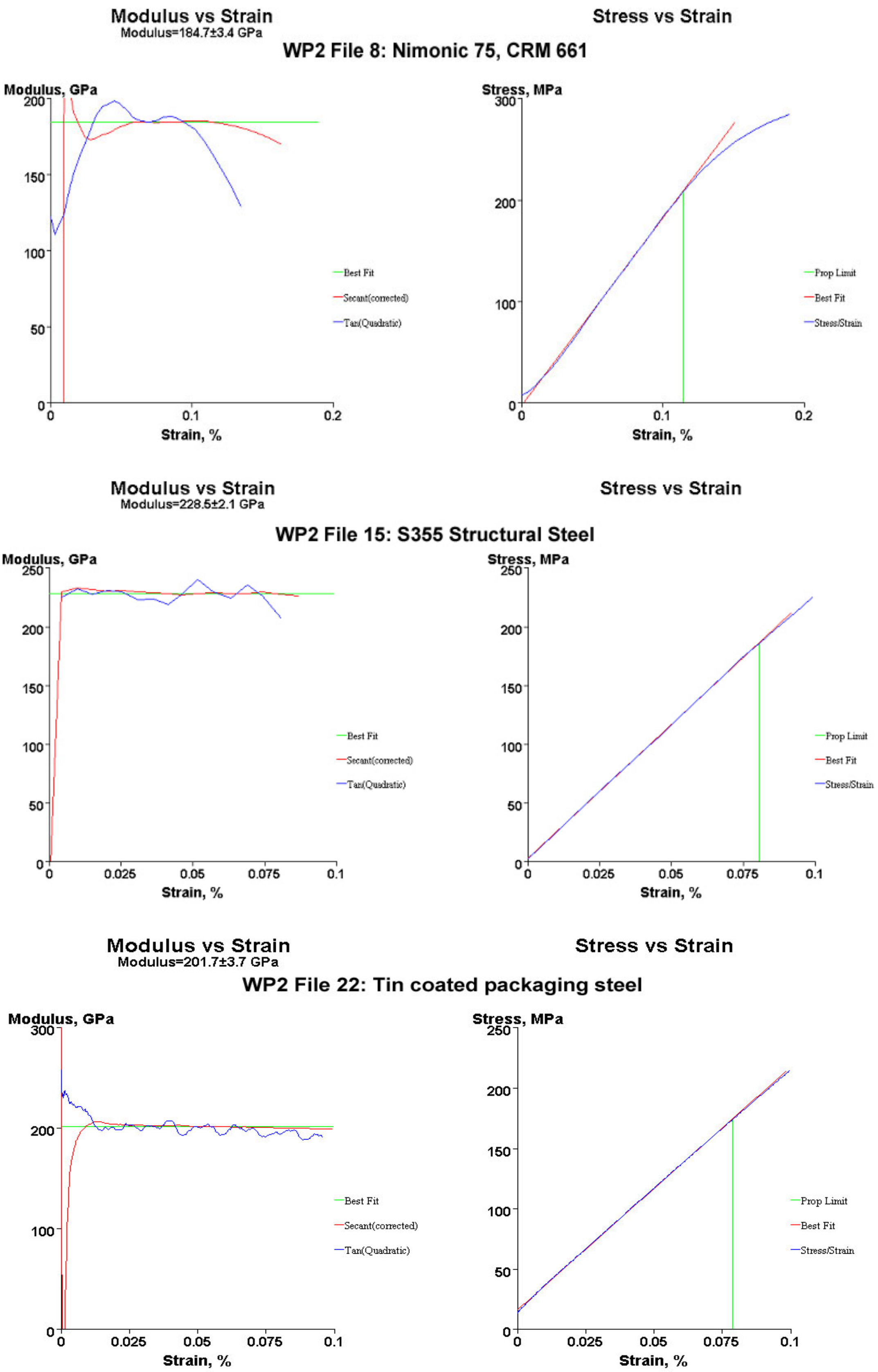
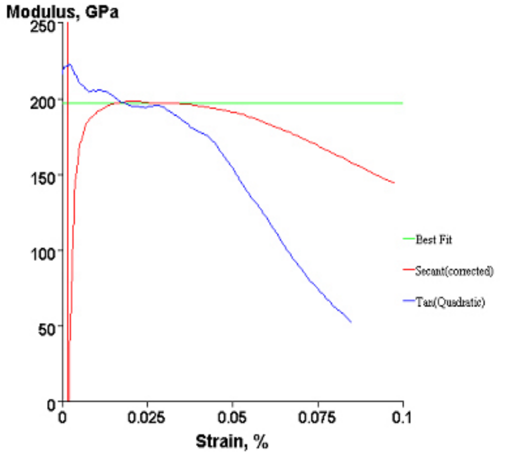


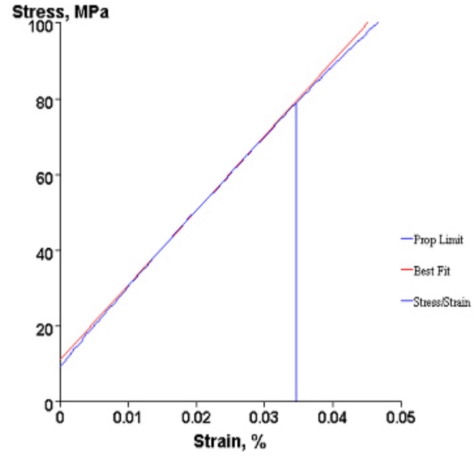
Fig 11 : Representative WP2 ASCII datafiles

Modulus vs Strain
Modulus=197.2±6.9 GPa

Stress vs Strain

WP2 File 30: DX56 Sheet Steel

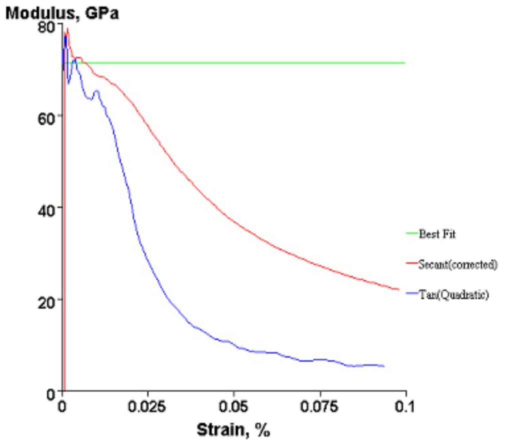


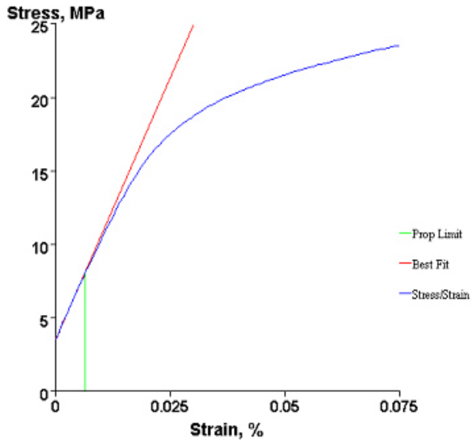


Modulus vs Strain
Modulus=71.62±6.2 GPa

Stress vs Strain

WP2 File 42: Soft Aluminium sheet

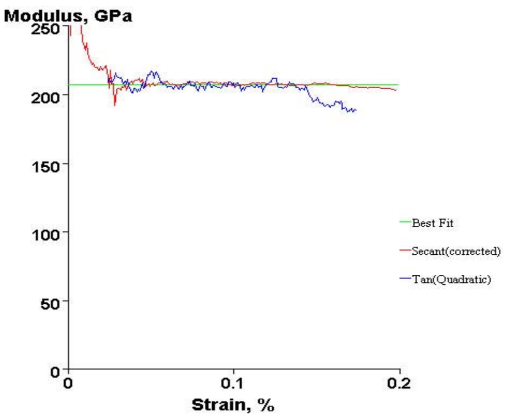




Modulus vs Strain
Modulus=207.2±19 GPa

Stress vs Strain

WP2 File 63: Synthetic data with 1% noise



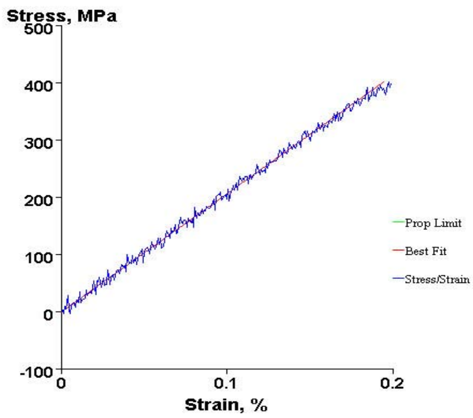


Fig 11 (contd): Representative WP2 ASCII datafiles

To evaluate the robustness of the different NPL algorithms on the calculated modulus values, all the WP2 datafiles were examined using the NPL web-based software, as detailed in the previous section. Over 500 files were analysed, and results are shown in Table 10. The cells and values highlighted in yellow are the values for modulus accepted by NPL as representing the best fit to the linear part of the stress-strain curve. One goal of this approach was to determine whether it was possible to recommend a specific analysis algorithm for a particular stress-strain response, or material class.

It is important to stress that the NPL algorithms are not the only approach for calculating modulus. The major test machine manufacturers such as Instron and Zwick offer comprehensive analysis software that offer a wide range of options, and many organisations have developed their own analysis procedures. Results from the study do show that the modulus value measured depends on a number of factors including aspects of the test set-up, the accuracy of strain measurement, the strain range examined, number of datapoints and method of evaluation. Care and consideration should be made by the test machine operator to ensure the best quality data is achieved.

Table 10: Modulus values generated from reanalysis of the WP2 ASCII datafiles using different NPL modulus algorithms

File No.	Material	Strain range	A	B	C	D	Mean	SDev	U%	LinReg
1	Nimonic 75, CRM 661	0.10%	209.2	210.0	210.7	212.0	210.5	1.2	1.1	209.1
	CRM 661-GBX 178-1	0.15%	210.1	209.1	208.3	208.3	209.0	0.9	0.8	197.0
	50 Hz	0.20%	210.0	208.1	207.5	207.5	208.3	1.2	1.1	
3	Nimonic 75, CRM 661	0.10%	225.3	225.3	225.3	225.3	225.3	0.0	0.0	208.7
	CRM 661-GBX 178-1	0.15%	208.5	208.5	208.5	208.5	208.5	0.0	0.0	201.6
	5 Hz	0.20%	212.8	212.8	212.8	208.5	211.7	2.1	2.0	
6	Nimonic 75, CRM 661	0.10%								
	NPL-CRM661 No 8-2	0.15%	184.9	184.9	185.5	187.2	185.6	1.1	1.2	177.8
	50 Hz	0.20%	186.7	186.1	186.1	186.1	186.3	0.3	0.3	
8	Nimonic 75, CRM 661	0.10%	180.8	171.1	171.1	184.5	176.9	6.8	7.7	177.4
	NPL-CRM661 No 8-2	0.15%	184.7	184.7	184.7	184.7	184.7	0.0	0.0	179.2
	5 Hz	0.20%	184.7	184.7	184.7	184.7	184.7	0.0	0.0	
10	13%Mn Steel	0.10%	184.4	183.1	183.0	182.5	183.3	0.8	0.9	182.1
	P1M 23-2	0.15%	180.4	180.4	180.0	182.3	180.8	1.0	1.1	181.5
	50 Hz	0.20%	180.5	180.7	180.2	180.5	180.5	0.2	0.2	
12	13%Mn Steel	0.10%								
	P1M 23-2	0.15%	186.4	186.4	186.4	186.4	186.4	0.0	0.0	181.3
	5 Hz	0.20%	181.0	181.0	181.0	181.0	181.0	0.0	0.0	
13	S355 Structural steel	0.10%	227.9	227.9	226.8	227.9	227.6	0.6	0.5	225.6
	P1M 24-1	0.15%	228.2	224.9	224.2	224.9	225.6	1.8	1.6	
	50 Hz	0.20%	226.1	226.1	222.4	222.4	224.3	2.1	1.9	222.7
15	S355 Structural steel	0.10%	228.5	228.5	228.5	228.5	228.5	0.0	0.0	226.5
	P1M 24-1	0.15%	228.2	228.2	228.2	228.2	228.2	0.0	0.0	222.4
	5 Hz	0.20%	222.4	222.4	222.4	222.4	222.4	0.0	0.0	222.9
17	316L Stainless Steel	0.10%	194.4	192.0	190.2	192.1	192.2	1.7	1.8	183.0
	S1C 20-1	0.15%	194.1	192.8	192.2	190.8	192.5	1.4	1.4	
	50 Hz	0.20%	192.9	189.3	178.5	191.2	188.0	6.5	6.9	
19	316L Stainless Steel	0.10%								187.4
	S1C 20-1	0.15%	179.3	179.3	179.3	179.3	179.3	0.0	0.0	
	5 Hz	0.20%	179.3	179.3	179.3	179.3	179.3	0.0	0.0	
22	Tin Coated packaging steel	0.10%	203.0	201.7	202.1	203.5	202.6	0.8	0.8	201.3
	SOLLAC F72-No7-2	0.15%	200.6	201.7	200.5	202.9	201.4	1.1	1.1	196.5
	50 Hz	0.20%	201.7	201.7	199.6		201.0	1.2	1.2	
24	Tin Coated packaging steel	0.10%	201.2	201.2	201.3	201.3	201.3	0.1	0.1	201.8
	SOLLAC F72-No7-2	0.15%	201.2	200.8	200.7	200.8	200.9	0.2	0.2	197.1
	5 Hz	0.20%	201.2	200.9	200.2	199.8	200.5	0.6	0.6	
26	Sheet steel	0.10%	203.1	204.5	203.0	203.1	203.4	0.7	0.7	203.3
	SOLLAC T462 No6-2	0.15%	203.1	203.2	203.1	203.2	203.2	0.1	0.1	203.2
	50 Hz	0.20%	203.2	203.2	203.0	203.0	203.1	0.1	0.1	203.2
28	Sheet steel	0.10%	201.2	201.2	201.4	201.2	201.3	0.1	0.1	203.3
	SOLLAC T462 No6-2	0.15%	203.3	203.3	202.6	203.3	203.1	0.4	0.3	203.3
	5 Hz	0.20%	203.4	202.5	203.7	203.3	203.2	0.5	0.5	203.3
30	Sheet steel	0.10%	203.3	203.2	197.2	203.2	201.7	3.0	3.0	
	TKS-DX56 No 2-2	0.15%	202.9	203.2	197.2	202.9	201.6	2.9	2.9	
	50 Hz	0.20%								
32	Sheet steel	0.10%	193.9	193.9	193.9	193.9	193.9	0.0	0.0	
	TKS-DX56 No 2-2	0.15%	193.9	193.9	193.9	193.9	193.9	0.0	0.0	
	5 Hz	0.20%								
34	Sheet steel	0.10%	205.8	205.6	205.8	205.7	205.7	0.1	0.1	206.7
	TKS-ZStE-180-No1-2	0.15%	206.0	206.1	205.9	205.7	205.9	0.2	0.2	
	50 Hz	0.20%	205.7	206.1	205.7	205.7	205.8	0.2	0.2	
36	Sheet steel	0.10%	207.4	207.4	207.4	207.4	207.4	0.0	0.0	206.5
	TKS-ZStE-180-No1-2	0.15%	205.7	205.2	205.1	205.2	205.3	0.3	0.3	
	5 Hz	0.20%	205.7	205.2	205.1	205.2	205.3	0.3	0.3	

File No.	Material	Strain range	A	B	C	D	Mean	SDev	U%	LinReg
38	Aluminium Sheet	0.10%	68.9	69.1	69.2	68.5	68.9	0.3	0.9	68.9
	VAW-hard AA5182-No3-2	0.15%	69.2	69.0	69.2	68.3	68.9	0.4	1.2	69.1
	50 Hz	0.20%	69.0	69.0	69.0	69.0	69.0	0.0	0.0	69.1
40	Aluminium Sheet	0.10%	68.9	69.1	69.1	68.9	69.0	0.1	0.3	68.9
	VAW-hard AA5182-No3-2	0.15%	68.7	68.7	69.3	68.7	68.9	0.3	0.9	69.1
	5 Hz	0.20%	69.1	69.1	69.1	69.1	69.1	0.0	0.0	69.1
42	Aluminium Sheet	0.10%			69.3	71.6	70.5	1.6	4.6	
	VAW-soft AA1050 No 5-2	0.15%			70.2	72.0	71.1	1.3	3.6	
	50 Hz	0.20%			70.5	70.0	70.3	0.4	1.0	
44	Aluminium Sheet	0.10%	67.1	67.1			67.1	0.0	0.0	
	VAW-soft AA1050 No 5-2	0.15%			66.2		66.2		0.0	
	5 Hz	0.20%								
46	Aluminium Sheet	0.10%	69.8	69.9	69.4	69.4	69.6	0.3	0.8	69.1
	VAW-soft AA5182 No 4-2	0.15%	69.0	69.1	69.4	69.0	69.1	0.2	0.5	69.1
	50 Hz	0.20%	69.5	69.5	68.1	69.5	69.2	0.7	2.0	
48	Aluminium Sheet	0.10%	69.6	69.6	69.6	69.6	69.6	0.0	0.0	69.4
	VAW-soft AA5182 No 4-2	0.15%	69.5	69.6	69.6	69.6	69.6	0.1	0.1	69.1
	5 Hz	0.20%	69.2	69.2	69.6	69.5	69.4	0.2	0.6	69.5
50	Sheet steel	0.10%	165.6	163.6	163.2	164.1	164.1	1.0	1.3	
	TKS-DX56-L050-B12-5-Probe 2	0.15%	162.4	170.0	162.1	163.9	164.6	3.7	4.5	
	50 Hz	0.20%	160.8	163.4	159.8	165.5	162.4	2.6	3.2	
52	Sheet steel	0.10%	165.1	165.1	165.1	165.1	165.1	0.0	0.0	
	TKS-DX56-L050-B12-5-Probe 2	0.15%								
	5 Hz	0.20%	161.4	164.2	163.1	161.4	162.5	1.4	1.7	
53	Sheet steel	0.10%	205.0	204.2	205.6	204.2	204.8	0.7	0.7	
	TKS-ZStE-180-L050-B12-5-Probe	0.15%	204.2	205.9	205.9	205.9	205.5	0.9	0.8	
	50 Hz	0.20%	204.2	205.9	205.9	205.9	205.5	0.9	0.8	
55	Sheet steel	0.10%	202.8	202.8	202.8	202.8	202.8	0.0	0.0	204.0
	TKS-ZStE-180-L050-B12-5-Probe	0.15%	204.3	205.0	205.0	205.0	204.8	0.4	0.3	
	5 Hz	0.20%	204.3	205.0	205.0	205.0	204.8	0.4	0.3	
57	Synthetic Digital Curve	0.10%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
	NPL Zero Noise	0.15%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
	50 Hz	0.20%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
58	Synthetic Digital Curve	0.10%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
	NPL Zero Noise	0.15%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
	5 Hz	0.20%	207.5	207.5	207.5	207.5	207.5	0.0	0.0	
61	Synthetic Digital Curve	0.10%	211.8	211.8	208.7	211.8	211.0	1.6	1.5	208.7
	NPL 0.5% Load Noise	0.15%	208.7	209.5	208.7	208.7	208.9	0.4	0.4	208.2
	50 Hz	0.20%	208.3	209.2	206.7	207.9	208.0	1.0	1.0	205.6
62	Synthetic Digital Curve	0.10%								
	NPL 0.5% Load Noise	0.15%	235.8	235.8	235.8	235.8	235.8	0.0	0.0	206.7
	5 Hz	0.20%	207.8	207.8	207.8	207.8	207.8	0.0	0.0	205.2
63	Synthetic Digital Curve	0.10%	207.7	208.1	207.4	208.1	207.8	0.3	0.3	208.2
	NPL 1% Load Noise	0.15%	208.4	208.4	207.0	208.4	208.1	0.7	0.7	208.1
	50 Hz	0.20%	207.2	207.2	203.3	207.2	206.2	1.9	1.9	204.2
64	Synthetic Digital Curve	0.10%								
	NPL 1% Load Noise	0.15%	235.5	235.5	235.5	235.5	235.5	0.0	0.0	209.0
	5 Hz	0.20%	202.4	202.4	202.4	202.4	202.4	0.0	0.0	

8 ANALYSIS OF THE TENSTAND WP4 MODULUS DATA

Modulus results were not analysed in detail in the TENSTAND WP4 report, because the Standard does not currently include the requirement to report the parameter, and the main emphasis of the WP4 exercise was to examine the effect of different machine control conditions and test speeds on the proof stress, upper and lower yield and tensile strength values. However the modulus data from the WP4 exercise is summarised in Table 11 and shown in Figs 12 and 13.

Table 11: Summary of the WP4 modulus data

Material		1.1 / 2.1				1.2 / 2.2				1.3 / 2.3			
		mean	Uncert	scatter range		mean	Uncert	scatter range		mean	Uncert	scatter range	
				min	max			min	max			min	max
		[MPa]	%	[MPa]	[MPa]	[MPa]	%	[MPa]	[MPa]	[MPa]	%	[MPa]	[MPa]
AA5754	ISO 12,5 x 50	**70.6**	**7.4**	62.8	76.5	**71.3**	**5.5**	68.3	75.0	**72.4**	**13.5**	67.0	85.8
AA5754	ISO 20 x 80	**71.4**	**3.2**	70.0	75.0	**71.1**	**4.3**	67.8	75.0	**71.5**	**3.9**	69.0	74.0
ZStE180	ISO 12,5 x 50	**215.3**	**21.8**	144.3	258.9	**213.1**	**7.0**	206.0	232.3	**215.8**	**9.9**	206.6	249.2
ZStE180	ISO 20 x 80	**213.6**	**13.2**	191.1	252.1	**212.9**	**10.0**	200.0	241.4	**212.1**	**9.2**	200.0	231.7
DX56	ISO 12,5 x 50	**212.2**	**22.0**	172.9	282.0	**211.1**	**16.1**	179.5	246.0	**207.2**	**12.3**	188.5	244.0
DX56	ISO 20 x 80	**206.2**	**6.6**	190.0	216.7	**204.2**	**10.4**	184.1	219.3	**206.1**	**8.5**	193.8	225.0
NiCr20Ti	M14, 10 x 50	**214.4**	**26.3**	142.7	292.4	**219.8**	**14.0**	179.5	239.0	**210.3**	**12.0**	179.1	233.4
S355	M16, 10 x 50	**210.8**	**8.9**	190.7	234.2	**207.8**	**12.5**	190.3	249.4	**209.8**	**11.3**	193.7	252.5
S355	ISO 12,5 x 50	**208.5**	**13.2**	184.7	259.4	**216.1**	**21.3**	193.7	279.6	**216.4**	**28.2**	185.1	359.4
stainl.st. 316L	M16, 10 x 50	**192.8**	**22.3**	150.6	229.3	**192.7**	**19.6**	133.1	227.5	**195.2**	**27.9**	146.6	296.3
Mean			**14.5**				**12.1**				**13.7**		

Over 900 tests were carried out as part of WP4 involving 10 TENSTAND partners, 4 testpiece geometries, 3 sets of test conditions and 6 materials. Both flat and round specimens were tested, and different test conditions were used to examine the effect of control mode and test speed on the measured tensile parameters. Further details of the test programme are given in the WP4 report [13].

The uncertainties in the measured modulus values from this exercise were alarmingly large, but the mean modulus values for a particular material batch were generally very good, and in agreement with what might be expected for the particular material. The lowest uncertainties were obtained with the aluminium specimens, and some of the highest from tests on stainless steel. The data that gave the highest uncertainties (over 20%) are highlighted in Table 11 in yellow. There does not appear to be a trend in the uncertainty values consistent with the test conditions. In the data presented above, the only comparison of the flat and round testpiece geometry can be made with the S355 results. For the same conditions, tests on the round specimens showed less scatter and variability, and lower uncertainties probably as a result of better alignment of the testpieces with the threaded ends.

Detailed examination of all the individual WP4 stress-strain datafiles was not feasible within the timescale of the project, but some of the data generated at NPL is considered below. Table 12 shows the detailed analysis of data generated on the AA5754 aluminium alloy, Nimonic 75 reference material and S355 steel. Figs 12-19 show data for all tests carried out under one specific test condition (5 repeats) for each material, over the strain range relative to the modulus measurement, together with representative tangent/secant modulus plots and stress-strain curves from one of the corresponding datafiles. All tests were carried out using a single-sided extensometer with a gauge length of 50mm.

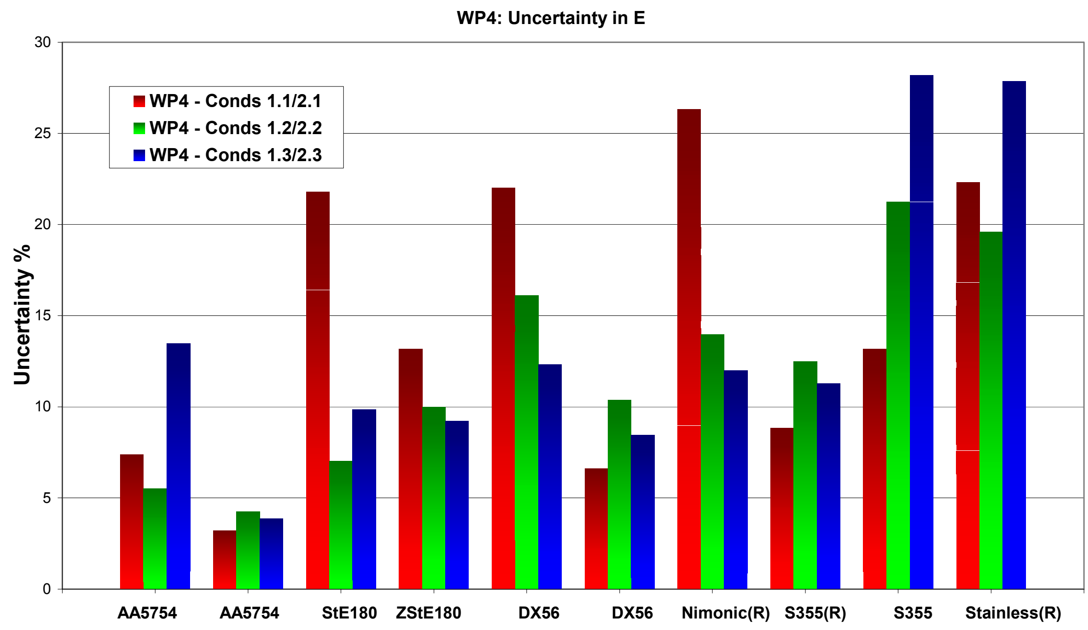


Fig 12: Uncertainty in modulus for each material type and test condition - from the WP4 exercise

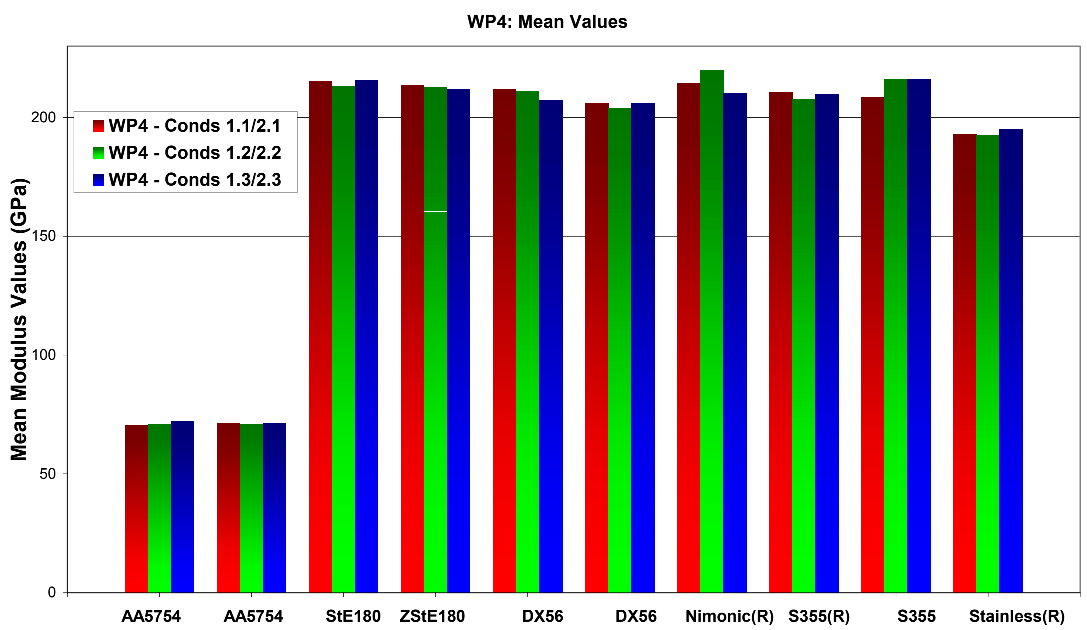


Fig 13: Mean modulus values for each material type and test condition - from the WP4 exercise

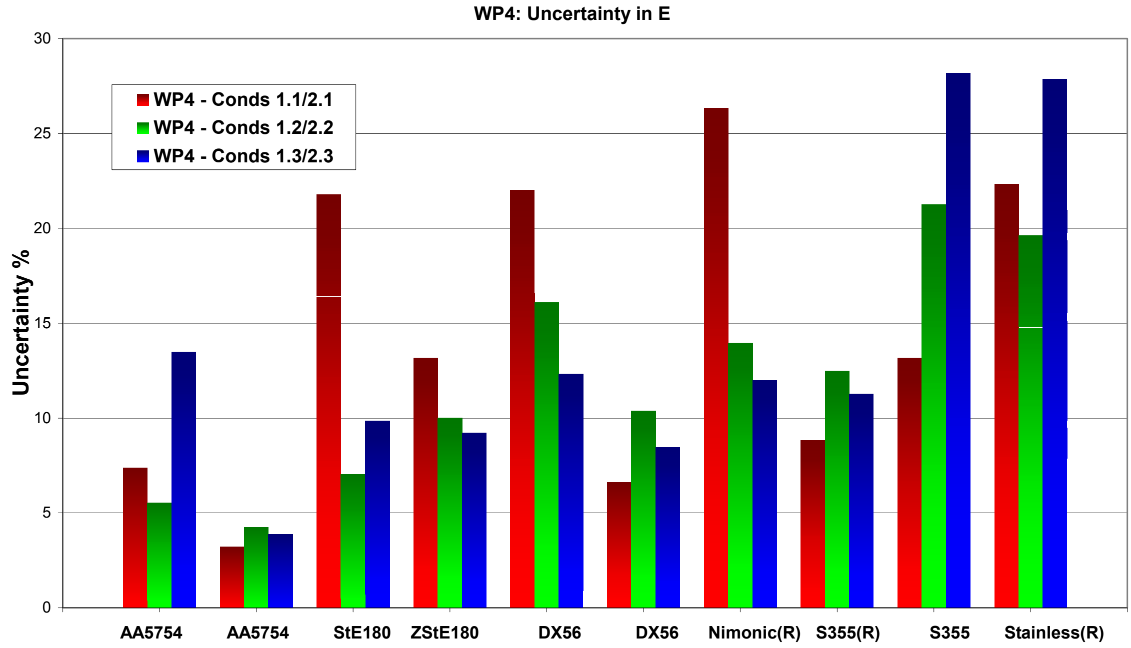


Fig 12: Uncertainty in modulus for each material type and test condition - from the WP4 exercise

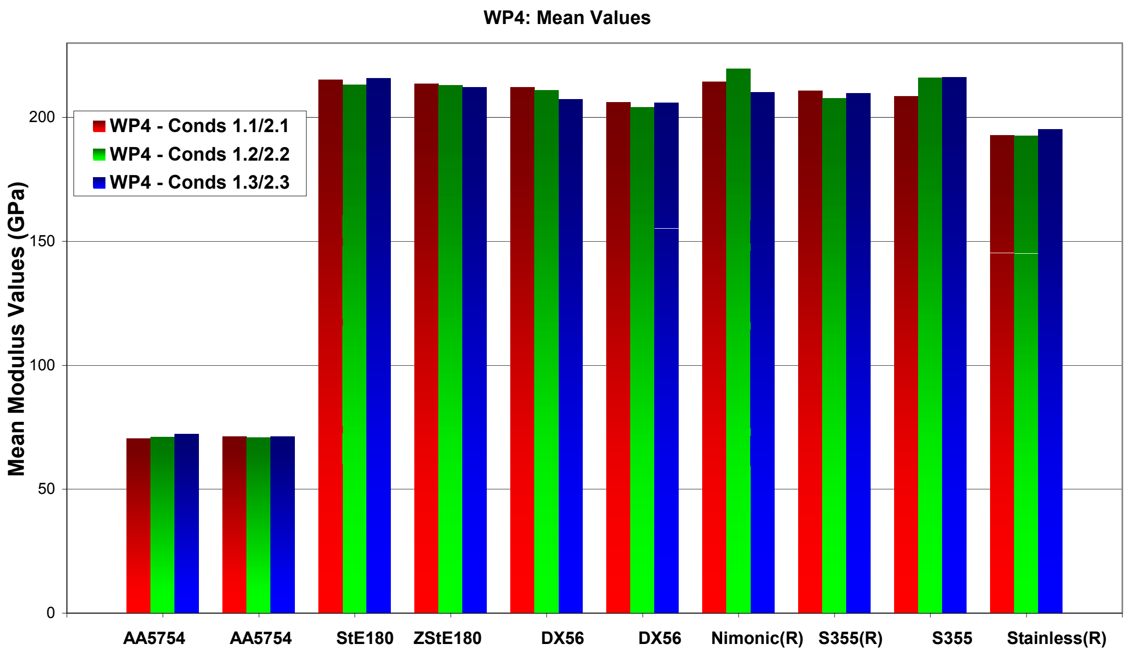


Fig 13: Mean modulus values for each material type and test condition - from the WP4 exercise

Table 12: Comparison of analysis methods on NPL-generatedWP4 stress-strain curves

	File	ANALYSIS METHOD				Mean	SD	Uncertainty
		A	B	C	D	GPa	GPa	%
AA5754	3A22	71.1	71.1	70.8	71.1	71.0	0.1	0.4
	3A28	72.1	72.6	72.6	72.7	72.5	0.3	0.7
	3A7	71.8	71.5	71.6	71.7	71.7	0.1	0.4
	3C12	71.2	71.2	71.0	71.1	71.1	0.1	0.3
	3C8	71.0	71.0	71.0	71.1	71.0	0.0	0.1
	3E1	71.0	69.9	69.9	69.9	70.2	0.6	1.6
	3E12	72.0	72.0	69.8	69.8	70.9	1.3	3.6
	3e8	72.3	72.5	71.6	71.6	72.0	0.5	1.3
	4a11	72.9	70.0	70.0	72.7	71.4	1.6	4.5
	4a24	71.2	71.1	71.0	71.1	71.1	0.1	0.2
	4a4	72.8	72.5	69.4	72.5	71.8	1.6	4.5
	4c12	71.9	72.4	71.5	72.4	72.1	0.4	1.2
	4c8	72.0	71.1	71.1	70.6	71.2	0.6	1.6
	4e15	72.2	72.2	72.6	72.4	72.4	0.2	0.5
	4e2	69.6		70.4	69.6	69.9	0.5	1.3
	4e20	70.3	70.5	70.0	70.8	70.4	0.3	1.0

	File	ANALYSIS METHOD				Mean	SD	Uncertainty
		A	B	C	D	GPa	GPa	%
NIMONIC	nim114	229.7	226.0	229.5	227.7	228.2	1.7	1.5
	nim117	236.4	237.1	237.0	233.6	236.0	1.6	1.4
	nim12	219.4	222.5	221.9	222.5	221.6	1.5	1.3
	nim123	230.6	233.6	229.1	227.4	230.2	2.6	2.3
	nim139	215.4	216.9	216.0	215.8	216.0	0.6	0.6
	nim152	220.3	222.4	220.3	222.4	221.4	1.2	1.1
	nim158	212.3	211.4	211.4	211.4	211.6	0.4	0.4
	nim165	216.8	221.5	221.2	221.5	220.3	2.3	2.1
	nim28	215.1	216.5	215.1	217.3	216.0	1.1	1.0
	nim42	244.0	242.8	246.8	242.8	244.1	1.9	1.5
	nim51	213.6	214.1	211.6	214.3	213.4	1.2	1.2
	nim60	222.6	220.1	220.2	224.0	221.7	1.9	1.7
	nim80	212.7	213.3	210.7	213.4	212.5	1.3	1.2
	nim92	261.8	261.8	236.4	261.8	255.5	12.7	9.9
	nim97	271.9	280.3	225.5	283.3	265.3	26.9	20.3

	File	ANALYSIS METHOD				Mean	SD	Uncertainty
		A	B	C	D	GPa	GPa	%
S355 Round	A9	202.8	202.8	205.8	202.8	203.6	1.5	1.5
	A11	224.9	224.1	224.9	223.7	224.4	0.6	0.5
	A20	207.3	208.7	208.1	208.2	208.1	0.6	0.6
	A31	197.2	196.9	197.2	197.8	197.3	0.4	0.4
	A32	213.1	213.1	212.1	212.1	212.6	0.6	0.5
	A34	183.0	182.9	182.9	183.0	183.0	0.1	0.1
	A61	215.8	215.8	217.1	215.8	216.1	0.7	0.6
	A62	192.7	192.0	192.7	192.0	192.4	0.4	0.4
	A63	216.4	215.7	218.8	215.6	216.6	1.5	1.4
	A75	224.5	224.5	221.2	224.5	223.7	1.6	1.5
	A78	223.8	223.6	223.0	224.1	223.6	0.5	0.4
	A79	194.4	194.5	194.5	194.5	194.5	0.1	0.1
	A95	212.2	211.1	211.0	211.1	211.4	0.6	0.5
	A103	219.3	219.7	219.5	219.7	219.6	0.2	0.2
	A122	200.7	201.1	200.2	200.2	200.6	0.4	0.4
	A99	202.6	201.7	202.6	201.7	202.2	0.5	0.5
	A130	poor						
S355 Rect	3	206.1	206.8	205.8	206.0	206.2	0.4	0.4
	20	196.8	196.8	194.2	197.1	196.2	1.4	1.4
	28	205.3	204.1	204.9	204.9	204.8	0.5	0.5
	47	188.4	188.2	192.4	188.2	189.3	2.1	2.2
	49	193.7	197.5	197.8	197.8	196.7	2.0	2.0
	70	200.8	200.1	200.1	200.1	200.3	0.3	0.3
	78	198.4	198.4	198.3	198.4	198.4	0.1	0.1
	117	201.8	202.1	202.1	202.1	202.0	0.2	0.1
	131	202.3	201.9	201.4	201.9	201.9	0.4	0.4
	145	204.1	204.0	204.1	204.1	204.1	0.0	0.0
	177	202.8	203.3	202.7	202.9	202.9	0.3	0.3
	199	204.4	204.4	204.3	203.9	204.3	0.2	0.2
	212	198.2	198.8	199.6	198.8	198.9	0.6	0.6
	217	203.9	203.3	203.7	203.0	203.5	0.4	0.4
	225	200.2	200.3	200.6	200.2			

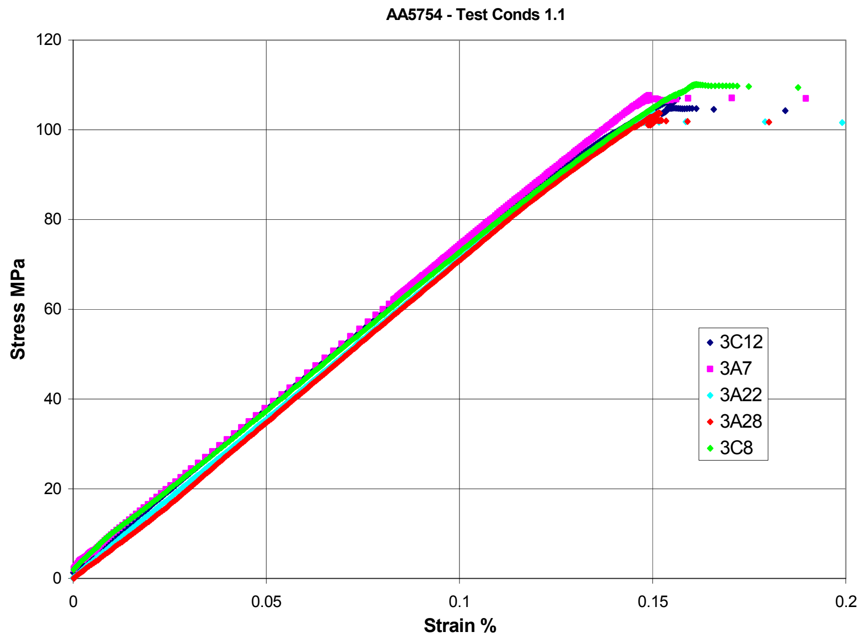


Fig 14: NPL WP4 stress-strain curves for the AA5754 material - Test Conditions 1.1, 5 repeat tests

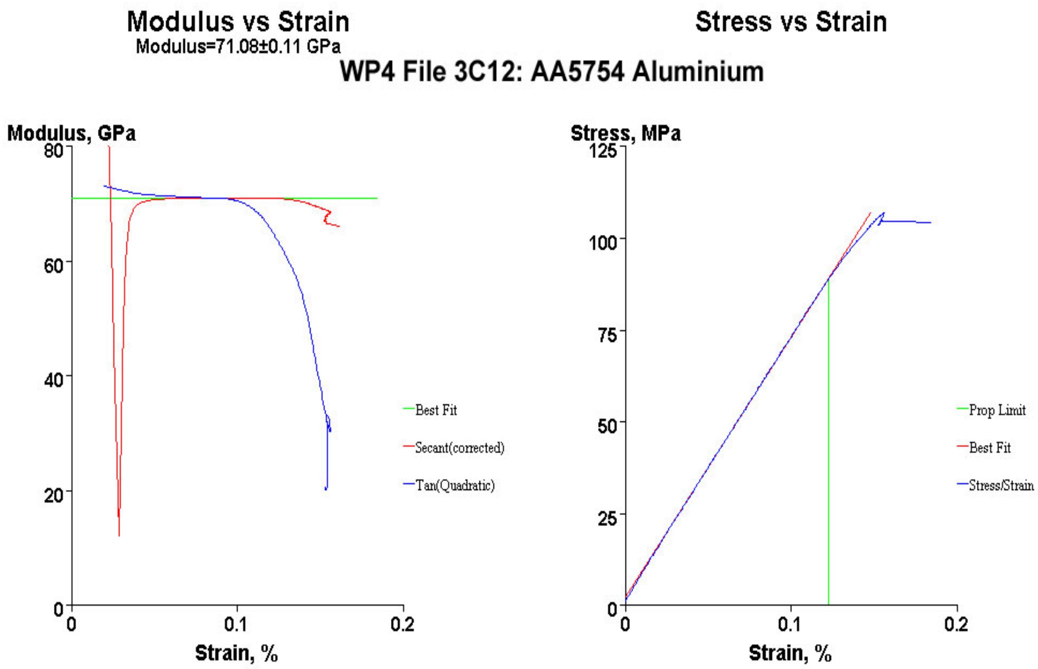


Fig 15: Analysis of NPL WP4 stress-strain curve for the AA5754 material (File 3C12) Test Conditions 1.1

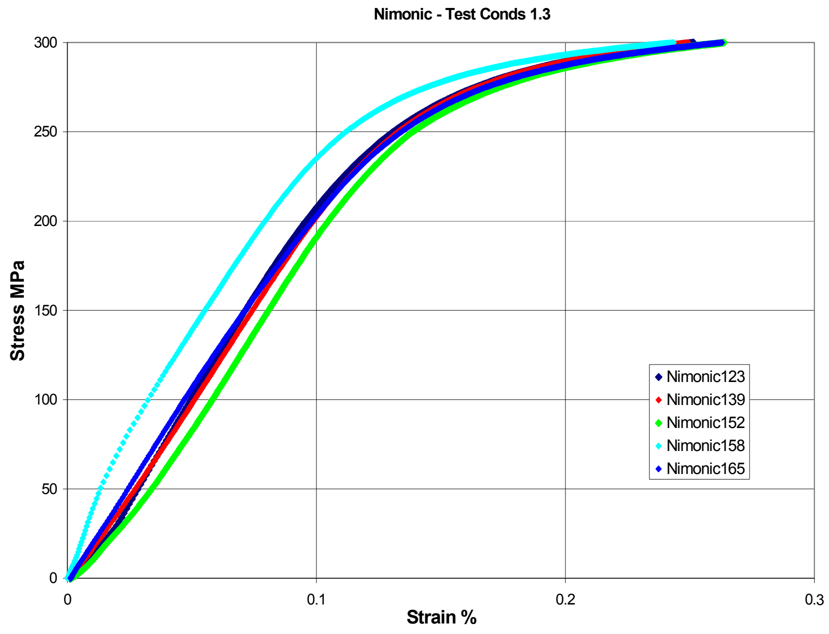


Fig 16: NPL WP4 stress-strain curves on the Nimonic 75 tensile reference material (CRM 661) - Test Conditions 1.3, 5 repeat tests

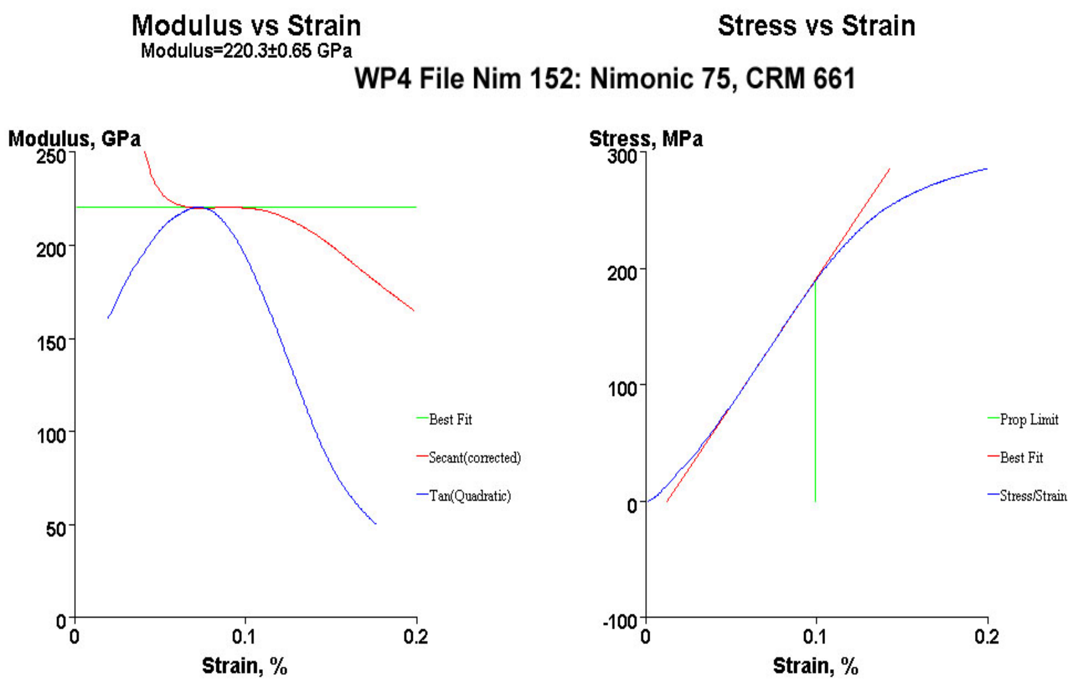


Fig 17: Analysis of NPL WP4 stress-strain curve for the Nimonic 75 tensile reference material (File Nim152) - Test Conditions 1.3

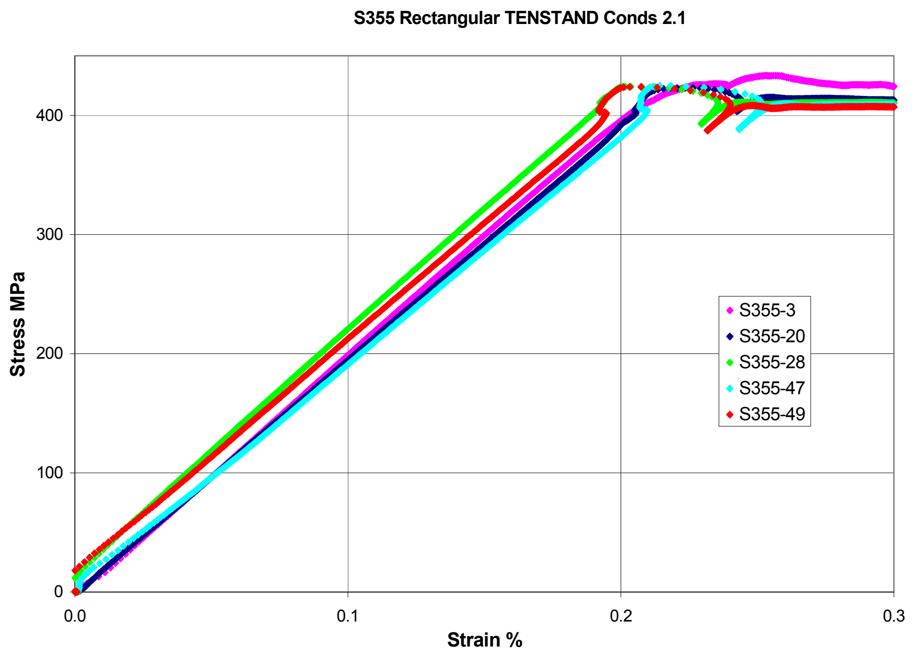


Fig 18: NPL WP4 stress-strain curves for the S355 material - Test Conditions 2.1, 5 repeat tests

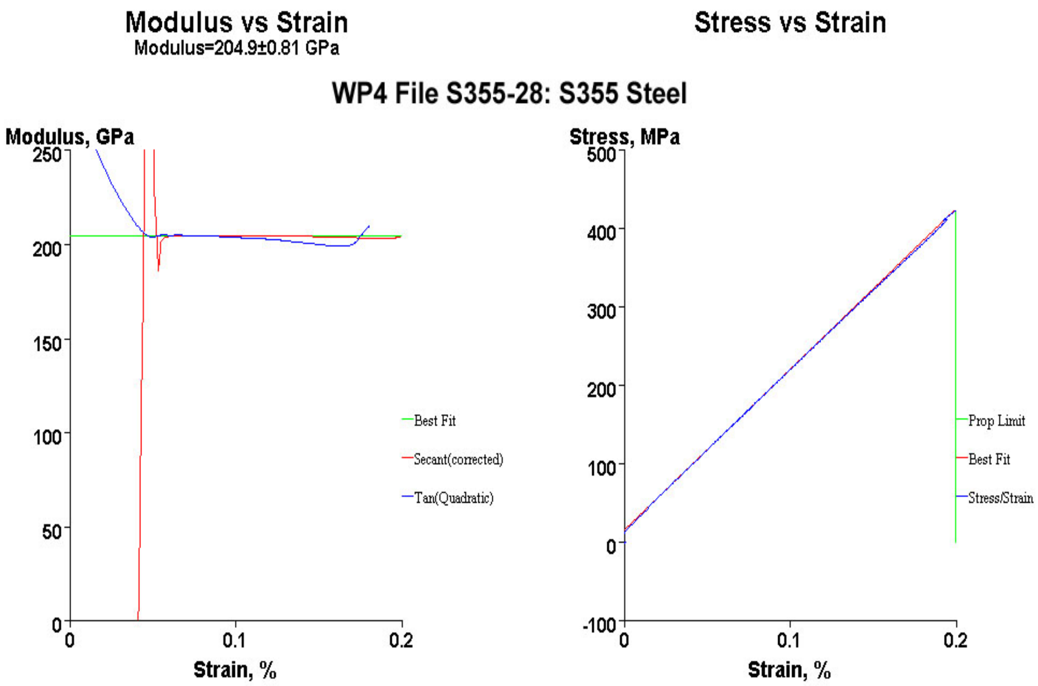


Fig 19: Analysis of NPL WP4 stress-strain curve for the S355 material (File S355-28) - Test Conditions 2.1

It is clear from Table 12 that the scatter in modulus and uncertainties calculated from the different analysis algorithms is significantly greater than that seen previously from the dedicated modulus tests, reported in Tables 8 and Table 10.

9 IMPROVING THE QUALITY OF MODULUS MEASUREMENTS FROM THE TENSILE TEST

From detailed examination of the results from TENSTAND WP2 and WP4 exercises and previous studies [18-21] it is clear that the current test procedure outlined in EN10002-1 is generally unsuitable for obtaining accurate and reliable modulus data.

There are a number of areas that need to be addressed to improve the quality of the modulus data from the tensile test, including…

- **A more closely defined test definition and scope, particularly relating to the strain range examined, test speed, alignment, data analysis procedures and test conditions.**
- **The use of more accurate strain measurement – averaging measurements are essential and higher Class extensometry is preferred.**
- **The use of specimen geometries with longer gauge lengths and improved alignment, to reduce bending.**
- **More careful consideration of data sampling issues and data analysis methods.**
- **Validation of software using the Premium quality WP2 ASCII datafiles.**
- **Checks and validation using certified reference materials.**

Aspects of the test method relevant to data analysis have been examined in the previous sections, but some consideration relative to strain measurement is given below. In most cases a single sided extensometer will be used to measure strain during the tensile test.

For the highest possible accuracy, a Class 0.2 averaging high-resolution extensometer, calibrated according to EN ISO 9513 over the restricted strain range appropriate to the test, is recommended for modulus measurement. Unfortunately Class 0.2 and 0.5 extensometers are not widely available, nor do many users have the appropriate equipment to calibrate these devices over the low strain range encountered in modulus testing so in many cases Class 1 extensometers are used. For such devices the total bias error is ± 1% or 3 μm, whichever is the greater, and this can lead to significant errors at low strains. According to EN ISO9513 [24], the bias error associated with the various class of extensometer is summarised in Table 13 below.

Table 13: Bias error associated with various class of extensometer [24]

Class of Extensometer	Bias Error	
	Relative, %	Absolute, µm
0.2	± 0.2	± 0.6
0.5	± 0.5	± 1.5
1	± 1.0	± 3.0
2	± 2.0	± 6.0

Consideration of Fig 19 [14] illustrates the problem. Because of the 3µm lower limit, the absolute error in strain measurement increases as the strains become smaller. For a 25 mm gauge length and 0.1% strain, the error in modulus can be as high as ± 12%. These are the typical uncertainties that can be attributed to the measurement of strain for a Class 1 extensometer. Other factors – such as the uncertainty in cross-sectional area, load measurements, and data fitting routines - also contribute to the overall uncertainty in the modulus measurement. These individual uncertainties are usually summed using the root mean square method, and then multiplied by a coverage factor to give an expanded uncertainty for the measurement to a known confidence level (typically 95% or 2 standard deviations). It is good practice for users to develop their own uncertainty budget for the modulus measurement, as it is a useful mechanism for identifying which parameters contribute most to the uncertainty in their own particular test set up. Some guidelines are included as an annex in the proposed revision to EN10002-1, but more general advice on uncertainty calculations can be found in Refs 25-28 and in the TENSTAND WP2 report [6].

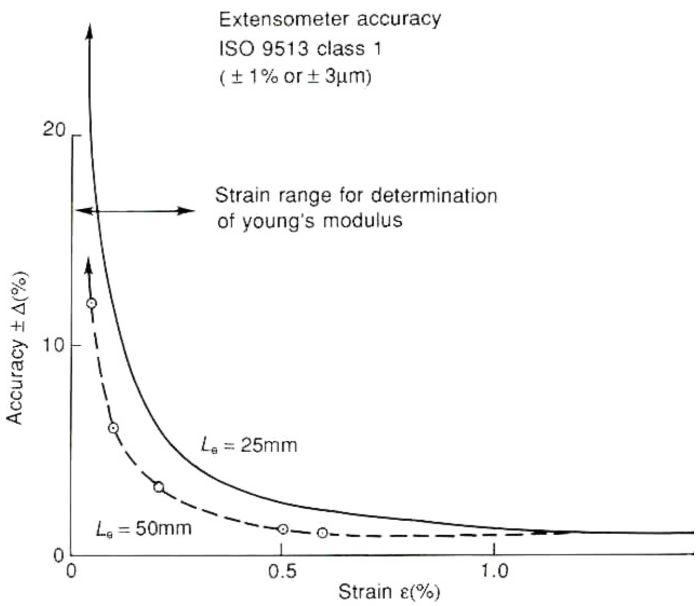


Fig 19: Typical errors likely in determining Young's Modulus with a Class 1 extensometer [14]

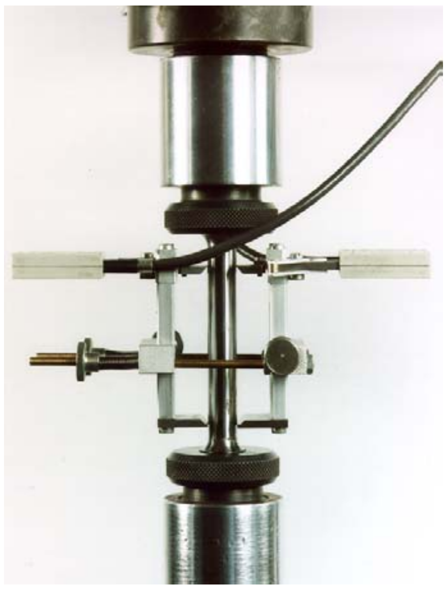


Fig 20: Typical high resolution averaging extensometer (courtesy of BAM)

Due to the difficulties associated with calibrating and setting up a high precision averaging extensometer, consideration should be given to using strain gauges bonded to each side of the testpiece to measure the strain during the test. At present none of the tensile testing standards directly advocate or support the use of strain gauges, however they are an attractive and cost effective alternative to the high-resolution extensometer. A number of practical issues must be considered however to ensure accurate and reliable results:

- **The strain gauge is a precision instrument and installation should only be carried out by suitably qualified staff.**

- **A high instrument gain should be chosen to give the greatest strain resolution and full-scale output over the limited strain range during the modulus test.**

- **An accurate gauge factor must be used.**

- **Calibration of the strain gauge instrumentation should be carried out over a similar strain range to that used in the test.**

Strain gauges are only suitable for measuring the full tensile properties if the failure strains are less than about 3% and the resolution of the strain gauge reading depends on the gauge factor and instrumentation gain. Modern strain gauge instrumentation typically has a resolution of ± 1 $\mu\varepsilon$, (although higher resolution instrumentation is available) but the maximum strain that can be measured may be limited to only 0.5% (5000 $\mu\varepsilon$). If gauges are used to measure a larger part of the stress-strain curve then a compromise must be reached between the maximum strain that can be measured and the measurement resolution required, and **they should not be readily used for machine control.**

Strain gauge installations may also be susceptible to other uncertainties that are difficult to quantify. The instrumentation itself can be calibrated by using a shunt resistor, but the individual gauge installation on the testpiece itself cannot be calibrated easily. Errors can arise due to misalignment of the gauge, poor gauge installation and bonding, temperature effects, Wheatstone bridge non-linearities and transverse sensitivity. All are important factors but are difficult to quantify. However, for modulus measurements at low strain levels, uncertainties of better than ~ ± 1% should be readily achievable. As with extensometry, it is vital that the gauges should be applied to both sides of the testpiece and averaged to take account of out-of-plane bending.

With due consideration of the factors that contribute to the uncertainty in the measurement, and a dedicated test set-up, it is clear that accurate modulus data is achievable in the tensile test. It is equally clear that it is not straightforward and requires a careful approach and an understanding of the factors affecting the quality of the measurement.

10 SUMMARY AND RECOMMENDATIONS TO STANDARDS COMMITTEE

Results from the detailed test programme carried out within TENSTAND WP2, WP3 and WP4 confirm that there are still major difficulties with obtaining reliable modulus measurements from the tensile test. The uncertainties obtained from the WP4 intercomparison were alarmingly large, although the mean modulus values for a particular material batch were generally very good. Results in the present study have shown that it is possible to obtain good quality modulus data from the tensile test, but this generally requires a separate and dedicated test set-up using high quality averaging strain measurement, focusing only on the early part of the stress-strain curve. In such cases the uncertainties associated with the modulus from such dedicated tests were significantly lower than those obtained from the standard approach covered by EN 10002-1. **It is important to recognise that these are specialised tests, and it might be neither feasible nor realistic to carry them out in a cost effective way in a high throughput computer controlled test machine.**

There are two main contributions to the uncertainty in the measurement - from the test procedure itself and from the analysis methods used. The exercise carried out in WP2 to develop a reference set of ASCII data has highlighted the problems in choosing and applying appropriate software algorithms to get reliable modulus data. The uncertainties from the exercise carried out within WP3, examining the different analysis methods and the effect of strain range were very low, typically below 0.5% and illustrate the quality of modulus data that can be obtained from dedicated tensile modulus tests and appropriate data analysis. A major concern however is with the large variety of algorithms available to the user as, without specific guidance or consideration, the algorithms can give very different results. One of the aims of the exercise, and a goal for the development and implementation of the modulus algorithms within the TENSTAND project, was to examine whether it is possible to recommend a particular analysis method based on a material class or particular stress-strain behaviour. At this stage it is not possible to make final recommendations and further work is still required.

The accuracy in modulus determination is strongly affected by the quality of the data and test set-up. Ideally the data should be linear, free from excessive noise and contain sufficient data points in the elastic range for detailed analysis. This is an important point, because if a test was designed to measure the whole of the stress-strain curve, there may be insufficient datapoints in the early part for accurate calculation of modulus. To obtain better quality measurements from the tensile test, there are a number of practical issues and specific recommendations for the user to consider, including….

- The mandatory use of averaging strain measurement methods, with extensometry (Class 0.5 or better) or strain gauges calibrated specifically over the limited strain range relevant to the modulus measurement

- Calibration and validation of software algorithms using the TENSTAND WP2 Premium ASCII datafiles

- The use of reference specimens, either the BCR Nimonic 75 tensile reference material (CRM661) or an in-house reference testpiece.

- Development of uncertainty budgets for the modulus measurement, which will help to identify particular areas of the test set-up that contribute most to the scatter and variability.

- Appropriate choice of test conditions and sampling rates to give sufficient data points for analysis. It is recommended that the stress-strain data is captured using a computer based acquisition system, and that at least 50 data points are sampled for each strain increment of 0.1%.

- Careful consideration of the data analysis techniques used. Some knowledge of the function of the particular algorithm used to calculate the modulus from the stress-strain data is desirable, and should be recorded in the test report. Ideally the software should be able to analyse the data automatically with minimal operator intervention.

Although the preference is to measure modulus from the stress-strain curve, the use of dynamic techniques should be considered if sensible values of modulus cannot be measured because of problems with the practical set up or to validate and support the use of using handbook values. It is recommended that wherever possible, measurements be made rather than relying on default handbook values because these might not be available for the specific alloy being tested. If realistic values of modulus cannot be achieved through the tensile tests it is an indication that the test set-up is inappropriate. In such cases, users are encouraged to examine aspects of the tests such as machine and testpiece alignment, gripping, strain measurement and the use of different test conditions and data analysis procedures that might help them achieve better quality results.

The main conclusion therefore from this study is that the tensile test procedure currently described in EN 10002-1 is inadequate for the accurate measurement of modulus. There is a real need for a dedicated test procedure to provide better guidance on the practical aspects of modulus measurement and the techniques and algorithms used for calculating the slope of the curve. The recommendation to the Standards committee is that this should be progressed immediately and could be developed either as a separate Standard or as a new Annex to the current EN 10002-1.

It is encouraging to note that work is already underway to further examine the modulus measurement procedures and there are two current initiatives addressing some of the issues identified within this study - the German DIN working group NMP 142 is exploring the development of a new standard for the modulus measurement of metallic materials, and a new VAMAS Technical Working Area (TWA) has recently been proposed to investigate aspects of modulus measurement, including the evaluation and development of dedicated tensile tests.

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