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Assessment of strain measurement techniques to characterise mechanical properties of structural steel

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ABSTRACT

Strain measurement is important in mechanical testing. A wide variety of techniques exists for measuring strain in the tensile test; namely the strain gauge, extensometer, stress and strain determined by machine crosshead motion, Geometric Moire technique, optical strain measurement techniques and others. Each technique has its own advantages and disadvantages. The purpose of this study is to quantitatively compare the strain measurement techniques. To carry out the tensile test experiments for S 235, sixty samples were cut from the web of the I-profile in longitudinal and transverse directions in four different dimensions. The geometry of samples are analysed by 3D scanner and vernier caliper. In addition, the strain values were determined by using strain gauge, extensometer and machine crosshead motion. Three techniques of strain measurement are compared in quantitative manner based on the calculation of mechanical properties (modulus of elasticity, yield strength, tensile strength, percentage elongation at maximum force) of structural steel. A statistical information was used for evaluating the results. It is seen that the extensometer and strain gauge provided reliable data, however the extensometer offers several advantages over the strain gauge and crosshead motion for testing structural steel in tension. Furthermore, estimation of measurement uncertainty is presented for the basic material parameters extracted through strain measurement.

1. Introduction

For the design of steel structures as well as simulation based design, mechanical material properties of the materials are usually obtained through a series of experiments following appropriate standards, such as EN 2001, ISO 6892-1, ASTM E8/E8M [1–3]. Indeed, for key material parameters in engineering design and materials' development, the current mechanical test methods for measuring the materials are not well established. The available standard of materials testing does not provide an indication of the measurement uncertainty obtained through application of the proposed experimental methods. An accurate knowledge of the engineering value of mechanical properties is vital for design studies, for finite element and modeling calculations and for giving reliable fits to the constitutive equations for stress-strain curve [4].

Geometric characteristics include shape, size, micro-structures, roughness, type and value of the form deviation. The geometric characteristics analysis was used by 3D scanning and vernier caliper of tensile samples. Sources of uncertainty related to measurement object's characteristics could be observed as geometrical, material and optical [5]. Detailed analysis of influence factors, creating mathematical model of measurement system, and uncertainty analysis according to procedures are described in ISO Guide to the Expression of Uncertainty in Measurement [6]. Source of uncertainty related to measurement method includes: configuration, number and distribution of measuring points, sampling, filtering, definition of measurement task, measurement process planning, equipment handling, fixturing, as well as operator's influence [7]. The resolution is usually adjustable and 3D scanner offers different resolution modes. Uncertainty is directly proportional to scanner resolution. Reference [7] suggests that uncertainty is 1/12 of the resolution.

Reference [8] provides a comprehensive review of different techniques of strain measurement during the tensile testing. The criteria that are used to measure deformation of the specimen

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Notations

A_0	initial cross-sectional area, (mm^2)
a_0	original thickness of a sheet type specimen, (mm)
a_u	maximum thickness after fracture, (mm)
a'_u	minimum thickness after fracture, (mm)
b_0	width of the parallel length of a sheet type specimen, (mm)
b_u	maximum width after fracture, (mm)
b'_u	minimum width after fracture, (mm)
E	Young's modulus (GPa)
F	force (kN)
F_m	maximum force (kN)
L_0	initial length
μ_A	Type A measurement uncertainty

depend on the size of specimen, environmental conditions, measurement requirement for accuracy and precision of anticipated strain levels. Consequently, for a given material, the load capacity to failure determined from tensile test depends on the mode of loading (controlled-strain-versus controlled-stress) as well as the criterion selected to define failure.

Fyllingen et al. [9] performed detailed measurement of geometric imperfection, the spatial thickness variation and the spatial materials variation on five high-strength steel batches in order to investigate if the measured variations could be related to the buckling behaviour of dynamically axially crushed top-hat profiles made from these steels. Traditionally, the mechanical properties are analysed by 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 mechanical properties are calculated, and aspects of strain measurement are covered only in brief. There are also 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 [4].

The aforementioned discussion highlights the need to develop a precise methodology and criterion to characterize the tensile testing of metallic materials. This need has promoted researcher to develop methodology that is based on the concept of uncertainty in strain measurement methods until failure occurred in the tensile specimen. This is also the first step towards determining the inherent uncertainty in the strain measurement methods. Measurement results are never exact, nor absolutely free of doubts. Therefore, the measurement uncertainty is a part of the results of a measurement. It is a measure for the accuracy of the result; measurement uncertainty is derived from standard deviations [10]. For example, in specimen from one rod, the repeatability of the yield strength Re was 1% but in specimens made of same type of material's and two hundred different rods, the repeatability was 4%, which was mainly due to materials variety. Reference [11] describes an experiment conducted for five different materials, i.e. two ferritic steels, one austenitic steel and two nickel based alloys. The uncertainties of measurement performed under the same conditions for the same number of specimens ranged from 2.3% to 4.6%. References [10–12] describe the general procedures for the evaluation of uncertainty of measurement results obtained during a tensile strength test, the typical source of uncertainty and their probable influences on the final results for cold-rolled steel.

The objective of this study was to develop a methodology for quantitative comparison of strain measurement techniques concerning tensile test with aspects to the determination of uncertainties. Such methodology, which has a possible systematic application, is associated with advanced metrology concept, aiming a guarantee of methodological reliability to the results of the tensile properties, as well as the possibility of implementation in industrial laboratories, researches center and in the testing laboratory. Although the uncertainty inherent in strain measurement techniques are used for parameter uncertainty quantification, strain measurement uncertainty is rarely included in the evaluation of stochastic parameter identification. One reason for this omission is the lack of strain measurement uncertainty on the stochastic parameter identification in measured structural steel data. The measurement uncertainty associated with other types of calibrations, such as the measurement uncertainty of an assigned quantity value, is specifically not addressed here. In addition, the measurement uncertainty associated with using an indicating measuring instrument for measurement task, such as measuring features on an individual specimen, is considered on this paper. The quality evaluation methodology for strain measurement techniques developed in this paper only applies to the specific case of the performance verification of metrological characteristics of strain measurement instruments.

2. Techniques of strain measurement

Measurement of deformation plays an important role in establishing the mechanical behaviour of materials. The two properties that are measured during a tensile test are load and displacement. The load is measured through a load cell that is installed axially in the test machine within the load path. The accuracy and reliability of displacement measurements are often in question, as the magnitude of displacements is often small. A wide range of methods existing for displacement measurement can be tensile test, including the following methods:

2.1. Technique 1: machine crosshead motion

Simple technique is to use the velocity of the crosshead while tracking the load as a function of time. Electromechanical testing machine of 250 kN was used for the specimen testing, which offers a wider range of crosshead speeds with force measurement accuracy $\leq \pm 0.08\%$, deformation measurement accuracy $\leq \pm 0.5\%$ as well as displacement measurement accuracy 0.001 mm; however, there are continuing advances in the speed control of screw-driven machine. For the load and time data pair, the stress in the specimen and the amount of deformation, or strain, can be calculated. When the displacement of the platen is assumed to be the specimen displacement, an error is introduced by the fact that the entire load frame has been deflected under the stress state. This effect is related to the machine stiffness (i.e. is the amount of deflection in the load frame and grips for each unit of load applied to the specimen). Many research works showed that a significant amount of scatter was found in the measurement of machine stiffness and measurement of strain. This variability can be attributed to relatively small difference in test conditions. The deformation measurement by testing machine, which is the least accurate, may be adequate, while for other materials, one of the remaining methods with higher precision may be necessary in order to obtain test values within acceptable limit.

2.2. Technique 2: strain gauges

Strain gauge is one of the tools most often used in strain measurement owing to their apparent accuracy, low cost, and ease of use; however, they are frequently misused, and the causes of their

measurement uncertainty are badly estimated [13]. There are two reasons for measurement uncertainty: the first is due to the measurand, and the second is due to the uncertainty introduced by the measuring system. It is also important to note that systematic errors have an effect on the global accuracy of the measuring system, while random errors affect the system's precision and consequently its accuracy [14]. The quality of raw data involves the use of a model of measurement to determine the uncertainty associated with the best estimate of the value of the quality to be measured [15]. Error sources in resistance strain gauges measuring system are numerous; for example, error due to the transverse sensitivity of the strain gauges, error due to temperature, error due to misalignment, and error due to the Wheatstone bridge's non-linearity. Detailed mathematical description of these errors refer to [16]. The variation of the factors involved in the problem, as well as the mean value is a prime concern. Nevertheless, the right interpretation of the results requires the knowledge about possible sources. The proper functioning of a strain gauge is completely dependent on the contact into the testing specimen. If the contact does not faithfully transmit the strain from the test piece to wire or foil of the gauge, the results obtained cannot be accurate. Failure to contact over even a minute area of the gauge will result in incorrect strain indications. Strain gauge gives the reliable value only in elastic region, in plastic region, strain gauge loses the contact with test piece and shows no value or inaccurate value due to the bonding problem. The greatest weakness in the entire technique of strain measurement by means of strain gauge is in the bonding of the gauge to the test piece. HBM half bridge circuit, Y series strain gauges are used for the displacement measurement.

2.3. Technique 3: extensometer

The related ASTM standards [17,18] recommended the use of an extensometer for accurate measurement of strain. For the highest possible accuracy, a class 0.2 averaging high-resolution extensometer, calibrated according to EN ISO 9513 [19] over the restricted strain range appropriate to the test, is recommended for modulus measurement. But class 0.2 and 0.5 extensometers are not widely available, so in many cases class 1 and 2 extensometers are used. In contrast, clip-on extensometer of class 0.5 is used and has fixed gage length 50 mm, attached to a test specimen to measure elongation or strain as the load is applied. For 0.5 class extensometer, calibration protocol provides the total bias error of ±1% or 25 μm, whichever is the greater, and this can lead to significant errors at the low strain over which the mechanical properties are measured. The bias error associated with the various classes of extensometer, according to EN ISO 9543, is summarised in Table 1. This is particularly important for metals and similar materials that exhibit high stiffness.

Fig. 1 shows the variation in measured modulus data generated on the BCR Nimonic 75 tensile. There is quite a large variation in the measured values, and clear differences between individual bars and organizations. Lab 5 was the only participant that used a special high resolution averaging extensometer, and the reduced scatter and repeatability of the measurement (the uncertainty was ±2% compared with ±12% for all tests) illustrate the importance of the test set-up and strain measurement in particular [11]. But [20] found some issues when measuring the tensile strain of steel chords with a clip-on extensometer, listed as follows: the extensometer might be damaged when the specimen broke, the geometry of the chord surface had an influence on the mounting of the extensometer, and the weight of the extensometer made the chord bend considerably when the force was small.

Table 1
Bias error associated with various class of extensometer [18].

Class of extensometer	Bias error	
	100× Relative error	Absolute/μm
0.2	±0.2	±0.6
0.5	±0.5	±1.5
1	±1.0	±3.0
2	±2.0	±6.0

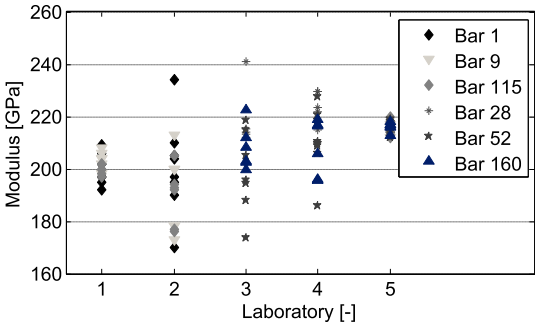

Fig. 1. Variation in the modulus measurement [4].

3. Uncertainty analysis of stress and strain measurement

Measurement uncertainty estimation in strain measurement is necessary if one is interested in evaluating the materials inherent variability in terms of spatial property distribution or manufacturing repeatability on the steel structures, but this is not always carried out and still rarely reported. For the tensile test, it is reasonably straightforward to make some estimate of the uncertainties associated with the test methods, and this is an approach that should be encouraged as it can also help to identify which experimental parameters or aspects of the test contribute most to the uncertainty in the measurement. The force, cross sectional area and dimensions of samples are measured to a high degree of accuracy to ensure an accurate calculation of stress-strain. In the case of indirect measurements, for example, measurement of stresses in a tensile strength test, when the quantity measured is a function of many variables $y = f(x_i)$ and $i = 1,2,\ldots,n$, the absolute and relative limiting errors are determined by means of following relationships:

$$\Delta y_g = \sum_{i=1}^{n} \left| \frac{\partial f}{\partial x_i} \Delta x_{gi} \right| \tag{1}$$

Maximum error of the tensile strength R_m of one specimen with a rectangular cross-sectional area A_0 is calculated in the way described below. For example, if the maximum force acting on the specimen F_m is 75 kN and specimen dimension, thickness $(a_0) = 8$ mm and breadth $(b_0) = 20$ mm, then the tensile strength is: $R_m = f_m/a_0 \cdot b_0 \rightarrow R_m = 468.75$ MPa.

Thus, the absolute maximum error of stress for rectangular specimens is:

$$\Delta R = \pm \left[\left| \frac{\partial R}{\partial F} \Delta F \right| + \left| \frac{\partial R}{\partial a_0} \Delta a_0 \right| + \left| \frac{\partial R}{\partial b_0} \Delta b_0 \right| \right] \tag{2}$$

where: ΔF-the limiting error of the measured value of the force, Δa_0, Δb_0 – the limiting error of the specimen cross-sectional dimensions. The measurement error for each dimension of specimen cross-section should not exceed ±0.5%. The cross-sectional area A_u after fracture at the point of greatest necking is calculated from the equation [21]:

$$A_u = 0.25(a_u + a'_u)(b_u + b'_u) \tag{3}$$

where a_u and a'_u – the maximum and minimum thickness of the specimen at fracture point respectively, b_u and b'_u – the maximum and minimum width of the specimen at fracture point respectively, as shown in Fig. 2.The maximum error of the percentage necking Z of a specimen with a rectangular cross-section is determined as follows:

$$Z = \frac{A_u - A_0}{A_0}\cdot 100\%; \quad S_u = a_{us}\cdot b_{us}; \quad a_{us} = \frac{a_u + a'_u}{2}; \quad b_{us} = \frac{b_u + b'_u}{2} \tag{4}$$

$A_0 = a_0 \cdot b_0$, the necking is:

$$Z = \frac{a_{us}\cdot b_{us} - a_0\cdot b_0}{a_0\cdot b_0}\cdot 100\% \tag{5}$$

whereas the maximum error is:

$$\Delta Z = \pm\left[\frac{\partial Z}{\partial a_0}\Delta a_0 + \frac{\partial Z}{\partial b_0}\Delta b_0 + \frac{\partial Z}{\partial a_{us}}\Delta a_{us} + \frac{\partial Z}{\partial b_{us}}\Delta b_{us}\right]\cdot 100\% \tag{6}$$

$$= \pm\left[\left|\frac{-b_0\cdot a_{us}\cdot b_{us}}{a_0^2\cdot b_0^2}\right|\Delta a_0 + \left|\frac{-a_0\cdot a_{us}\cdot b_{us}}{a_0^2\cdot b_0^2}\right|\Delta b_0 + \left|\frac{b_{us}}{a_0\cdot b_0}\right|\Delta a_{us} + \left|\frac{a_{us}}{a_0\cdot b_0}\right|\Delta b_{us}\right]\cdot 100\% \tag{7}$$

The estimation of uncertainty in the series of tensile test on steel coupons is determined in compliance with the [6,22–24]. In this report, the uncertainty of a measurand is called the standard uncertainty of the measurand. Moreover, it is assumed that the measurand is characterised by a normal probability distribution with the measured value as mean value and with the standard uncertainty as standard deviation. The ISO Guide distinguishes between type A and type B uncertainties. Evaluation of type A uncertainty is by calculation from a repeated measurements, and of type B from scientific judgment based on the available information on the possible variability of the quantity. In either case, knowledge can be represented by probability density function. The pool of information may include previous measurement data, experience with or general knowledge of the behaviour and properties of relevant materials and instruments, manufacture's specifications, calibration certificate data and uncertainties assigned to reference data taken from ISO Guide [6]. In the case of direct measurements, the type A standard uncertainty is determined on the basis of results of a series of measurements:

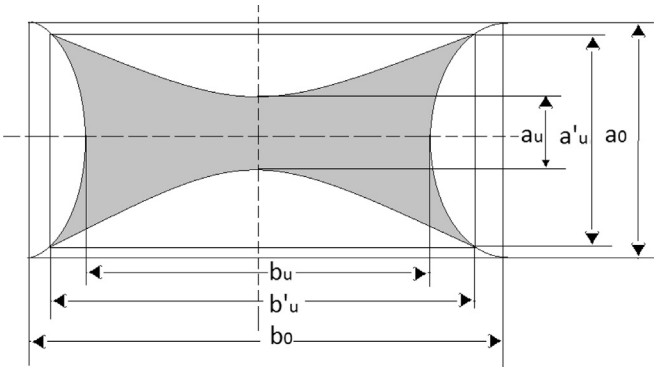

Fig. 2. Dimensions of the rectangular specimen at fracture point; a_0 – thickness of the specimen before fracture; b_0 – width of the specimen before fracture; a_u and a'_u – the minimum and maximum thickness of the specimen at fracture point respectively; b_u and b'_u – the minimum and maximum width of the specimen at fracture point respectively [21].

$$\mu_A = \overline{S}_{\overline{x}} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{8}$$

where: x_i is the value of the i-th measurement, $\overline{x}$-mean value, n-number of measurements. The expanded uncertainty μ_c for determining the limit of the confidence interval is:

$$\mu_c = k_\alpha \cdot \mu_a = k_A(\alpha)\cdot \mu_A \tag{9}$$

where $k(\alpha)$ is coverage factor, which value is dependent upon the degree of freedom of experiments [6].

In the case of indirect measurements, for instance, stress measurements, the type A uncertainty is evaluated using the results of a series of measurements performed separately for each quantity. It is necessary to determine the mean values $\overline{x_i}$ and the standard uncertainty μ_A. The standard uncertainty for the mean $\overline{y}$ is calculated from the formula:

$$\mu_{A\overline{y}} = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial \overline{x_i}}\right)^2 \mu_{Ai}^2} \tag{10}$$

For the mean value $\overline{y}$ of the quantity Y measured in an indirect way and its standard uncertainty $\mu_{A\overline{y}}$, the expanded uncertainty is:

$$\mu_{Ac} = k_A(\alpha)\mu_{A\overline{y}}. \tag{11}$$

The combined uncertainty of type A and type B is calculated from the formula:

$$\mu_{y_i} = \sqrt{\mu_{A_{y_i}}^2 + \mu_{B_{y_i}}^2}. \tag{12}$$

The standard uncertainty related to the tensile strength is calculated from equation (12) is:

$$\mu_{R_m} = \sqrt{\left(\frac{\partial R_m}{\partial F_0}\right)^2 \mu_{(F)}^2 + \left(\frac{\partial R_m}{\partial a}\right)^2 \mu_{(a)}^2 + \left(\frac{\partial R_m}{\partial b}\right)^2 \mu_{(b)}^2} \tag{13}$$

The standard uncertainty related to the elastic modulus is calculated from equation (14) is:

$$E = \left(\frac{\Delta f}{A_0}\right) / \left(\frac{\Delta l}{L_0}\right) \tag{14}$$

Young's modulus is calculated from the force increment and corresponding extension increment between two points on the line as far apart as possible, by use of following equation:

$$\mu_s^2(E) = \left(\frac{\partial E_s}{\partial F}\right)^2 \mu_{(F)}^2 + \left(\frac{-\partial E_s}{\partial a^2}\right)^2 \mu_{(a)}^2 + \left(\frac{-\partial E_s}{\partial b^2}\right)^2 \mu_{(b)}^2 + \left(\frac{\partial E_s}{\partial l}\right)^2 \mu_{(l)}^2 + \left(\frac{-\partial E_s}{\partial \Delta l}\right)^2 \mu_{(\Delta l)}^2 \tag{15}$$

The key document is the ISO Guide to the expression of uncertainty in measurement [6], but this can be a little over-complicated, therefore other publications [22–24] are recommended. A Code of Practice (CoP) for determining the uncertainties associated with the tensile testing technique was provided by [24]. CoP promotes

traceability and uncertainty evaluation for a range of mechanical tests, including the uniaxial tensile test, taking into account, technical development such as computer-controlled test machines. Table 2 shows an example of uncertainty calculation of measurement of young modulus using strain measurement data.

The 'Expanded Uncertainty' calculated at approximately 95% confidence level are shown graphically in Fig. 3, with a simple power law trend line plotted through the data. Thus it can be seen that the estimated measurement uncertainties range from ±2.3% up to ±4.6% at approximately 95% confidence level. Thus, two laboratories testing in accordance with *EN*10002 Part1, but controlling their machines at the extreme ends of the permitted tolerance ranges, may produce tensile results with differences up to 4.6–9.2% depending upon the material being tested. The estimated uncertainties do not take into account the inherent scatter attributable to material inhomogeneity [11]. Detailed description of experimental data analysis and mathematical model of strain measurement are gigen in references [25,26].

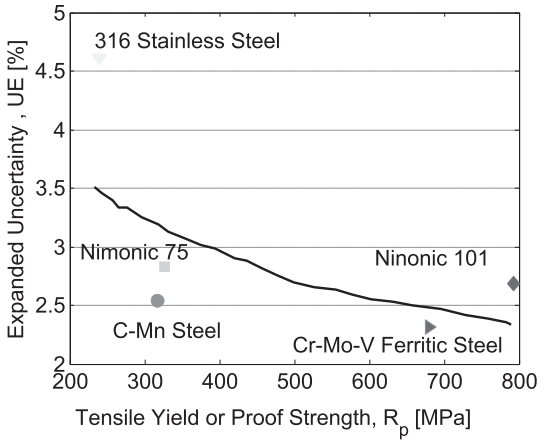

Fig. 3. Expanded Measurement Uncertainties at the 95% confidence level for Proof or Yield Strengths selected materials tested in accordance with EN 10002 Part 1 [11].

4. Materials and methods

4.1. Review of testing procedure

The tensile testing procedure presented in ISO 6892-1:2009 [2] was reviewed in conjunction with the modifications recommended by [4]. From the review, revised tensile testing procedure was drafted. Electromechanical tensile testing machine of 250 kN was calibrated for both load and displacement and the expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%. The tests were conducted at room temperature, and the crosshead speed rate was ranging from slow, middle and fast at 0.00007 s^{-1}, 0.00016 s^{-1} and 0.00025 s^{-1}, respectively, strain rate and determination of E, $R_{p0.2}$, then displacement control at equivalent 0.00025 s^{-1} strain rate up to failure and determination of R_{eL} and R_m.

4.2. Materials and specimen geometry

The samples used for this study were structural steel, S 235(IPE 360 and IPE 400 section, in longitudinal and transverse direction, as shown in Fig. 4) procured from European hot rolled profile, ArcelorMittal Steel. The samples were sectioned to produce the desired specimens, according to Annex D of the [2], using an abrasive water cutting. Table 3 shows the chemical composition of the S 235 steel. The nominal thickness of samples were 8.00 mm and 8.60 mm of IPE 360 and IPE 400 steel, respectively and specimen, testing apparatus and different strain measurement devices were as shown in Fig. 6. Four groups of specimens were tested to compare the three strain measurement techniques individually and in the fourth group, to compare all three techniques simultaneously. The

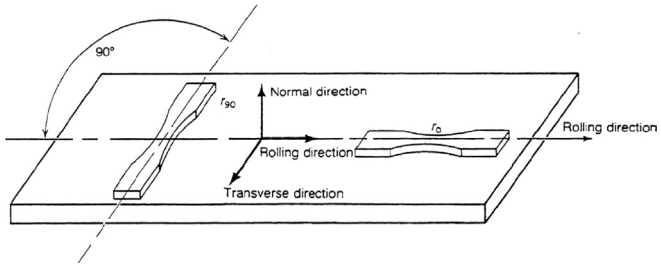

Fig. 4. Tensile specimen orientation to determine r_0, and r_{90} in rolled sheet.

specimen length and the gage length were changed to reflect the procedures stated in the standard, as shown in Table 4. The geometry of the specimen was measured and analysed using 3D laser scanner and caliper. Indeed, sources of uncertainty related to measurement object as well as measurement method were analysed. These uncertainties are considered in this paper and the quantification of these uncertainties is not trivial; these uncertainties analysed with mathematic model of 3D scanning measurement uncertainty will be considered in the next paper. Results represented in Fig. 5 show the deviation between the 3D scanned real part and the nominal breadth and thickness of samples. The vernier caliper measured data deviation are larger than 3D scanning. The focus of this paper is not the quantification of all the error sources in 3D scanning and vernier caliper but to develop a methodology to assess the validity of the strain measurement by systematically accounting for the various sources of uncertainty and error.

The error and uncertainty terms considered in this paper adequately illustrate the various techniques for uncertainty

Table 2
Example uncertainty budget for the tensile modulus test: According to [6,11]

Source of uncertainty	Uncertainty	Measured value	100× Relative uncertainty μ	Probability distribution	Divisor	100× $\mu(E_{spec})$
Force, *F*	From load	cell calibration certificate	0.34	Normal	1	0.34
Area, *A*	0.041 mm^2	160 mm^2	1.60	Rectangular	$\sqrt{3}$	0.92
Accuracy of strain measurement	25$\mu\varepsilon$	1000$\mu\varepsilon$	1.00	Rectangular	$\sqrt{3}$	0.58
Modulus analysis method	0.25 GPa	200 GPa	0.20	Rectangular	$\sqrt{3}$	0.12
Repeatability of *E* measurement	2.0 GPa	200.0 GPa	0.95	Normal	1	0.95
				Combined standard	uncertainty	1.48
				Expanded uncertainty	($k = 2.95\%$)	2.97

Table 3
Chemical composition of steel S 235: According to Stahlwerk Thüringen, ArcelorMlttal (Schneldbetrieb GmbH).

Weight Percentage (%)	Carbon C	Manganese Mn	Silicon Si	Phosphor P	Sulphur S	Aluminum Al	Nitrogen N
Max	0.20	1.60	0.55	0.025	0.024	0.069	0.005
Min	–	–	–	–	–	–	–

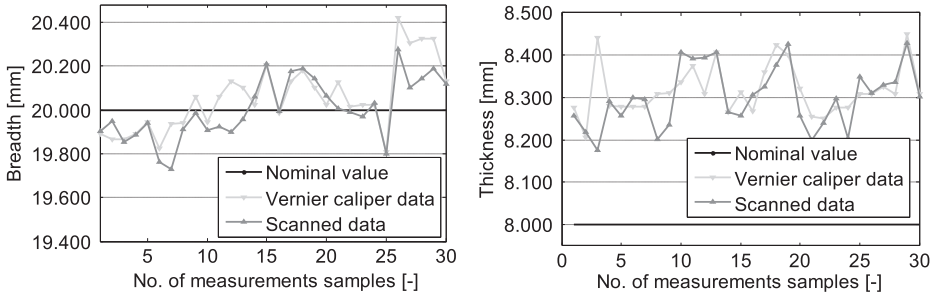

Fig. 5. Results of the 20 mm breadth and 8 mm thickness gauge block scanning 30 different samples.

quantification, probabilistic materials modeling and quality assessment of strain measurement.

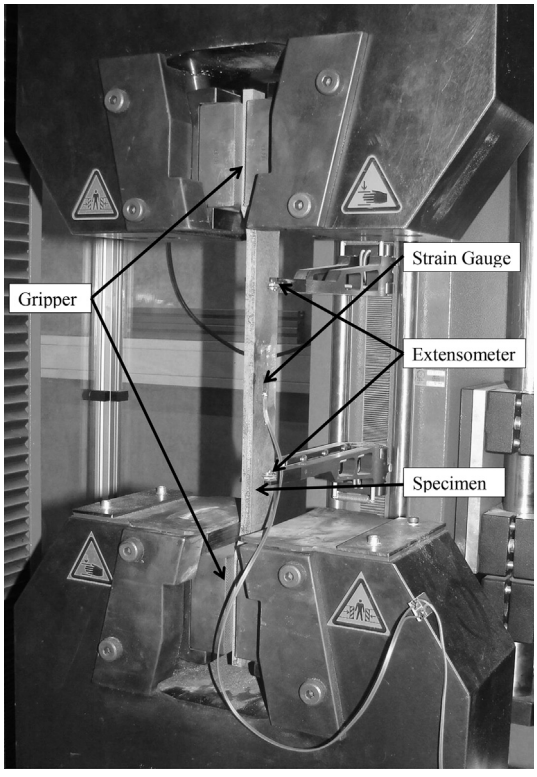

Fig. 6. Testing apparatus for evaluating strain using three different strain measuring devices.

5. Results and discussion

The average and standard deviations were calculated for all the results in Groups 1, 2, 3 and 4. Extensometer was set as the control group. An F-test was used to determine equal or unequal variances between the groups and a two-sample *T*-test was used to establish significance in the results. A *T*-test with a *p*-value less than 0.05 (one-tail) was considered to be statistically significant.

Fig. 7 shows a close-up of the engineering stress-strain graph of the difference in strain measured from strain gauge, extensometer and displacement by machine crosshead motion in three different strain rates. The values obtained from machine crosshead motion were in disagreement with the values determined from the extensometer and strain gauges. By referring to Fig. 7, the strain values determined by the extensometer and the strain gauge method were close to each other and stress–strain curve fits with reality within the elastic region. The extensometer reported significantly lower *p*-values of elongation than the other two strain measurement techniques ($p < 0.001$ and $p = 0.002$ and 0.006 for the strain gauge and crosshead respectively, $n = 20$) as, shown in Fig. 8. It is believed that slipping of the knife-edges as the extensometer was unloaded may be the cause of this finding. Larger error in machine crosshead motion may occur because of the influence of alignment, machine and surface finish of the test piece and testing speed. Due to the gripping system, the system may not apply uniform strain across the sample cross-section or along its length. This may occur due to misalignment, or deficiencies in clamping or precision of grip components. The effects may include side-to-side or lengthwise variation in the clamping or pinning arrangement, the gripping system introduces a non-linear element in the load strain and this may be responsible for unexpected departures from the specified strain rates during the test. Therefore, measured displacement machine crosshead motion can not be used to determine strain, because either gage length of sample is not necessarily a known value or the displacement measurement is not

Table 4
Test procedure summery for group, strain device and length.

	Strain devices	Sample length (mm)	Gage length (mm)	Test speed s^{-1}
Group 1(IPE360, L)	Three technique	298.00	80.00	$7 \times 10^{-5}s^{-1}; 1.6 \times 10^{-4}s^{-1}; 2.5 \times 10^{-4}s^{-1}$
Group 2(IPE360, T)	Three technique	270.00	98.00	$7 \times 10^{-5}s^{-1}; 1.6 \times 10^{-4}s^{-1}; 2.51 \times 0^{-4}s^{-1}$
Group 3(IPE400, L)	Three technique	450.00	226.00	$7 \times 10^{-5}s^{-1}; 1.6 \times 10^{-4}s^{-1}; 2.5 \times 10^{-4}s^{-1}$
Group 4(IPE400, T)	Three technique	315.00	135.00	$7 \times 10^{-5}s^{-1}; 1.6 \times 10^{-4}s^{-1}; 2.5 \times 10^{-4}s^{-1}$

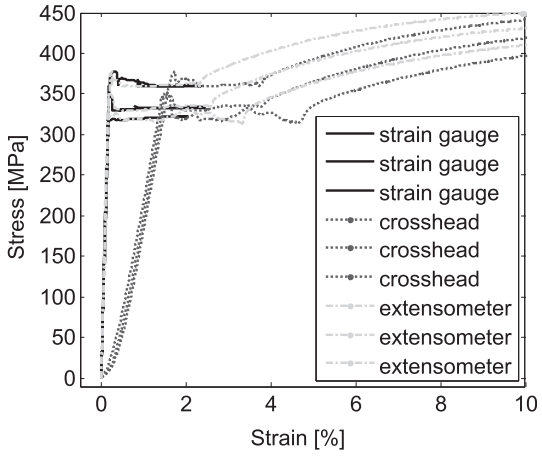

Fig. 7. A systematic diagram of the stress strain curve, showing the expected Young' modulus value and values calculated and recorded from the tensile tests conducted.

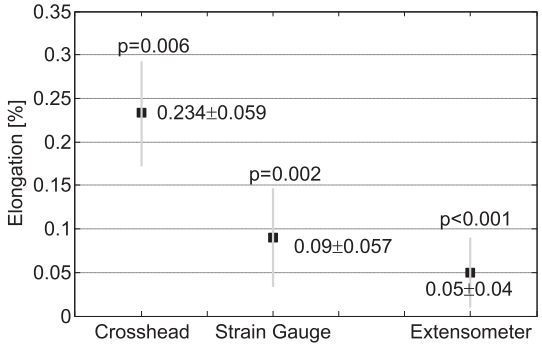

Fig. 8. Elongation results for three different strain measurement techniques. The strain calculated from crosshead strain were significantly greater than the strain gauge and extensometer ($p < 0.001$, $p = 0.002$, and $p = 0.006$ respectively, $n = 20$).

a measure of the change in length of the sample within the gage length.

Fig. 9 (left side) plots the strain gauge output against the extensometer output, while same Figure in right side plots the extensometer against machine crosshead motion. As shown in figure, the strain gauge and extensometer give identical results, however, in practice there is a 0.7% difference between strain gauge and extensometer. In contrast, the strain variability between extensometer and machine crosshead motion is large, which is not an acceptable range. Simply, R^2 of the trend-line demonstrated that in the relationship between two strain measurement method, over a 0.05% strain range, the errors were larger. Due to this reason the strain measurement using the traditional corosshead does not give the reliable strain output during the tensile testing.

Fig. 10 shows the data, which include results from measurement using strain gauges and extensometer from sixty different samples.

The results show excellent repeatability with a mean value of E modulus from the thirty tests of 199.30 GPa for strain gauge and sixty tests of 201.40 GPa for extensometer. Fig. 10 shows that they are significant differences between predicted Young's modulus variability using strain gauge strain measurement and extensometer strain measurement. For the coefficient of variation, the strain gauge measured data is 0.048, which corresponds to a standard deviation of 9.5 GPa, that is 4.7% variation in the modulus. For the coefficient of variation, the extensometer measured data is 0.024, which corresponds to a standard deviation of 4.8 GPa, that is 2.4% variation in the modulus. Furthermore, there was no significant difference in either modulus calculation between the extensometer and strain ($p = 0.208$ and 0.456, respectively, $n = 20$); however, there were significant differences between the extensometer and the crosshead strain ($p = 0.021$ and $p = 1.236$, respectively, $n = 20$). By referring to the comparison of the modulus of elasticity determined by the two methods mentioned above, the extensometer strain measurement methods had been achieved better than the other method. Uncertainties based on a statistical analysis of series on measurements obtained in repeatability conditions to each method were calculated according to the uncertainty budget calculation for the measurement of modulus of elasticity shown in Table 2. Typically the variation in modulus expressed by the range is 4%–5% and based on the modulus values, a corresponding range values for $R_{p0.1}$ and $R_{p0.2}$ calculated, which is used of a certified reference materials as a quality check and is recommended in references.

The increase in the uncertainty in modulus values in the strain rate range of 0.00007 s^{-1} to 0.00025 s^{-1} is rather small but at higher strain rates, the increment becomes quite notable (the slope of the σ vs. $\dot{\varepsilon}$ curve becomes steeper), which is shown in Fig. 11. The uncertainties in the measured modulus values from two strain measurement methods were alarmingly large, but the mean modulus values for a particular direction of sample and specimen dimension were generally very good, and in agreement with what might be expected for the particular specimen dimension and longitudinal and transverse directions of specimen. The lowest uncertainties were obtained with specimens Group 1 (gage length 80 m and strain measured by extensometer) and some of the highest from tests on high strain rate Group 3 (gauge length 226 mm and strain measured by strain gauge. The data gave the highest uncertainties 23% in strain gauge of large gage length specimen of higher rate testing speed. For the same conditions, tests on the different directions and specimens showed less scatter and variability, and lower uncertainties probably as a result of better alignment of the specimen. From a practical point of view the

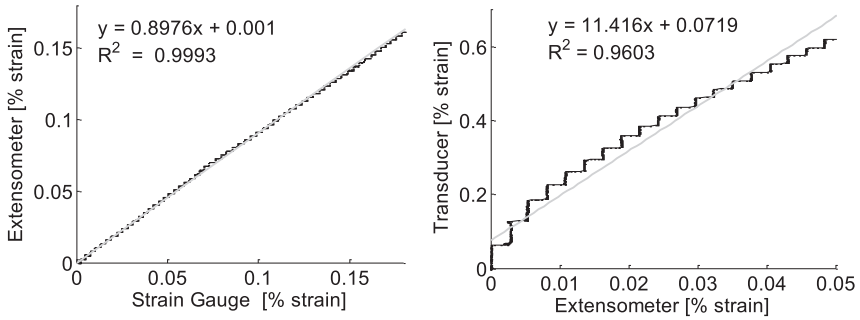

Fig. 9. Expressing regressing uncertainty of different stain measurement methods, showing the expected Young' modulus value and values calculated and recorded from the tensile tests conducted.

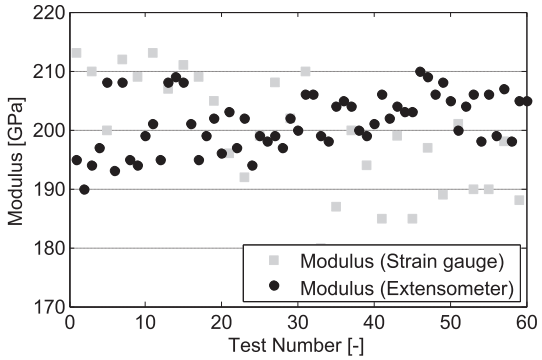

Fig. 10. Variation in modulus, measured in Lab and different methods of strain measurement.

strain rate dependence of the Young's modulus may also be important. If, for example, the modulus value that is used as a material property in the design phase of a component was determined at a much lower strain rate than experienced by the material in the actual forming process, the amount of IPE355 would be overestimated. The precision at which strain device is able to control the system to achieve 1.5% strain will ultimately affect residual strain and the modulus.

Tensile strength is calculated at the peak load value on the stress-strain curve. In the comparison of tensile strength, it is seen that the machine crosshead motion results are slightly lower than the extensometer results ($p = 0.012$, $n = 20$), but these results were not statistically significant. This may be the assumption that because the extensometer is a contacting strain measurement device, the stress concentrations that occur where the knife-edges attach to the specimen may cause premature failure, especially on thin wire and small diameter tubing. In addition, this finding may not be related to extensometer, but rather to the fact that the length of the specimen varied between the group. The longer specimens that were used for measuring crosshead strain have a greater surface for material defects that may be the cause for a lower reported strength value. The system compliance will cause an increase in the strain derived from crosshead extension and cause tensile strength values also to be greater than expected.

There were no significant differences reported in either upper yield strength (R_{eH}) (Fig. 12) and lower yield strength (R_{eL}). *P*-values for the R_{eH} were equal to 0.179, 0.213 and 0.297 for extensometer, strain gauge and crosshead techniques, respectively ($n = 20$). *P*-values for the R_{eL} were 0.198, o.321 and 0.408 for extensometer, strain gauge and machine crosshead strain, respectively ($n = 20$). The specimen used in this experiment had consistently flat, therefore, the single point calculation was not affected by difference in strain measurement. It should be noted that for materials where the are not flat, R_{eH} and R_{eL} will be affected when using crosshead strain because of the overshoot at 4% strain and resulting overshoot at 0.2% and 2% strain values required for the R_{eH} and R_{eL} calculations.

Increase in the gage length of the test piece at maximum force is expressed as a percentage of the original gage length (Lo), which is shown in Fig. 13. The percentage elongations at maximum force measured with the use of extensometer and machine crosshead were recorded on average 6.8% and 9.4% variation respectively in repeated testing. However, the percentage elongations at maximum force from extensometer and machine crosshead were 24.8% and 25.6% higher than the reference values. *P*-values for the extensometer were equal to 0.199 and 0.326 for the corsshead strain, respectively ($n = 20$). This higher variation might be due to the influence of the residual stress, for example: mechanical twinning, creep, phase transformations. In addition, in the experimental investigation, it is found that specimens are cambered due to the hot and cold bending. The extensometer strain measurement method was found to be capable to measure the strain in higher quality compared to crosshead. In contrast, the strain gauge is not capable to measure strain beyond yield point, due to the no contact between the sample and strain gauge. This is disadvantage of strain gauge. Indeed, at the same time the deformation of testing machine is the main source of the specimen extension error. In fact, the sources of the specimen extension error are complex and relative stiffness is the key, that is, when the specimen is weak in relation to the testing system, the grip is the main source of **error**, but if the specimen is much stronger the influence of the system compliance will become significant.

In the all above examples, the uncertainty in the mechanical properties of metals depends on the uncertainty in the force measurement. There will be a contribution associated with measuring the specimen dimensions. The accuracy and resolution of the strain measurement technique are also important. The data in this paper presented are based on the typical uncertainty in the strain measurement technique. From the different laboratory proficiency tests, it is also found that test set-up has been derived from the consideration of accuracy and resolution of the strain reading. According to this calculation, it is the largest contributing factor to the uncertainty in the measurement. A factor has been included to cover the uncertainty associated with the ASCII data and uncertainty in the ability to fit a line to the linear part of the stress-strain curve, together with variability associated with repeated tests and this might be either on

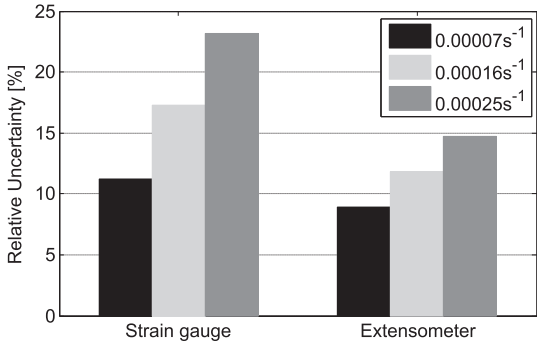

Fig. 11. Uncertainty in modulus: two strain measurement methods and three test conditions for group 1 specimens.

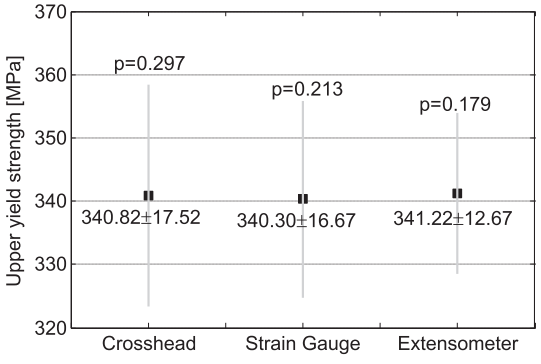

Fig. 12. R_{eH} for three different strain measurement techniques. There was no significant difference between methods ($p = 0.179$ and $p = 0.213$ for the extensometer and strain gauge, respectively, $n = 10$, for Group 4 and strain rate of 7×10^{-5} s^{-1}.

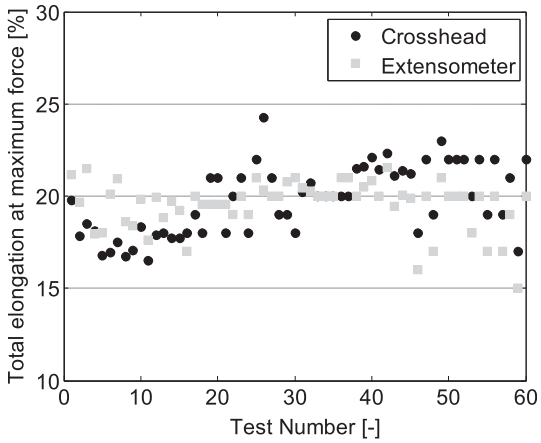

Fig. 13. Percentage elongation at maximum force:two strain measurement techniques.

same sample or on different samples from a batch of material. It is important that the uncertainty is reported and for the example above the calculated Young's modulus value should be reported as $E_{\text{extensometer}} = (201.0 \pm 4.5)$ and $E_{\text{straingauge}} = (200.00 \pm 5.55)$ to a confidence level of 95%, with the note that expanded uncertainty of measurement is based on the standard uncertainty of measurement multiplied by the coverage facor [27,28].

The differing specimen dimensions, different orientations on the prior rolling directions, residual stress and loading speed have effects on the obtained mechanical properties. These effects are not considered in this paper and the quantification of these effects is not trivial; these effects will be considered in the future work.

6. Conclusions

An analysis of the uncertainty sources incorporated during strain measurements using different techniques of the material mechanical properties has been performed. Although not all sources of uncertainty have been investigated in detail, examples illustrate the importance of uncertainty sources relevant to the variability of the parameters measured from a series of tests on coupons from the same batch. Focus should be put on discriminating the uncertainty introduced through the use of measurement devices and the measurement techniques from the inherent variability of the materials and the variability introduced through manufacturing processes. This is possible, as shown, through application of the techniques for estimation of the uncertainty in measurements and quality evaluation in strain measurement techniques, which are increasingly developed and adopted by testing laboratories active in the field of material mechanical testing.

In summary, an extensometer is highly recommended for testing steel specimen in accordance with [2]. The extensometer allows for better control and achievement of the 3% turnaround point defined in the methothology and it also allows for more accurate calculation of results based on the strain as compared with strain gauge and machine crosshead motion. Bonding strain gauges to a specimen are the standard way to generate high quality and reliable strain measurement in testing, however, applying strain gauge and use are both time consuming and require high levels of skill and training. Strain measurement in elastic region by strain gauge technique gave reliable output but in the plastic region, there is no more bonding with specimen and could not provide the reliable strain. The machine crosshead motion showed high variability in the strain measurement. The Young's modulus values were not in acceptable range. Therefore, the machine crosshead technique is not used for modulus measurement techniques. The extensometer technique of measuring strain could both save time and reduce costs, but the technique demostrated relatively lower variability to the strain measurement. Also, development of uncertainty budgets for the mechanical properties will help to identify particular areas of the test set-up that contribute most of the scatter and variability. The need to assure measurement quality is, therefore, a main issue to consider.

Thus, metrology probabilistic approach has mathematical and computational tools particularly suited to improve the quality of measurement thus fulfilling the growing technological demands of the modern society.

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