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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 $\leq\pm0.08\%$, deformation measurement accuracy $\leq\pm0.5\%$ 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