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Measurement techniques and procedures for standardized SE(T) testing of linepipe steel

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ABSTRACT

The single edge-notched tension (SENT or SE(T)) test uses a low-constraint specimen geometry to determine the elastic-plastic fracture toughness of relevant linepipe steels. Application of the results include, but are not limited to, design methods, material selection, structural integrity assessment, fitness for service (FFS) and engineering critical assessment (ECA). Until recently, industry and government researchers have developed and published recommended practices without consensus from standard development organizations. A test standard was recently issued in 2014 by the British Standards Institution as BS 8571, and there is an ongoing effort to publish a robust standard test method within the American Society of Testing and Materials (ASTM International). Standardization of any test method should consider the influence of physical measurements on the results of the test. Generically, all measurements have uncertainty, and a standardized test method endeavors to produce results with a minimum uncertainty, as well as known precision and bias so that the results can be intelligently used for their intended purpose. This paper reviews the measurement techniques and procedures from each of the published recommended practices and BS 8571 and provides further guidance on specific techniques and procedures with respect to uncertainty.

1. Introduction

Like most intrinsic material properties, fracture toughness cannot be directly measured and compared to a Base Unit in the International System of Units (SI). The most basic definition of fracture toughness is the ability of a material containing a defect to resist fracture. A variety of physics-based approaches have been applied to describe this ability to resist fracture; these often include a differentiation between initiation and propagation. The details of which approach is applied to different materials or conditions are irrelevant for this review.

The three published industry-recommended practices reviewed here include; *Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain* by Det Norske Veritas (DNV) [1], *Measurement of Crack-Tip Opening Displacement (CTOD) Fracture Resistance Curves Using Single-Edge Notched Tension (SENT) Specimens* by ExxonMobil [2], and *Recommended Practice: Fracture Toughness Testing Using SE(T) Samples with Fixed Grip Loading* by CanmetMATERIALS [3]. While details of the material properties, specimen geometry and testing procedures will impact the results, they can be separated from the measurement techniques and procedures. Considerations of material property variations, specimen geometry and specific testing procedures will be the subject of a subsequent paper, as this review is intended to be the cornerstone for future reviews.

Measurements in each of the recommended practices and BS 8571 [4] can be simplified to the Base Units of the SI for length and the derived unit of the SI for force. Force measurements are universal for each of recommended practices and BS 8571. Length, however, requires a wide mixture of measurement techniques and procedures, since different length definitions and quantities are required in a variety of calculations to include directly measured values and calculated values.

Length measurements within each of the reviewed SE(T) methods, will include directly measured pre-test, in-test and post-test values. Some of the directly measured in-test values will be used to infer other length quantities such as crack extension. Any of these length measurements will be a combination of the technique (instrument and method) and a process. The process includes the technique but also includes the considerations of uncertainty, precision and bias. Uncertainty and error are often used

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interchangeably. However, error is the difference between the measured value and the "true" value, while uncertainty describes the range of values within which the "true" value lies. Uncertainty analysis is a complex subject with many statistical calculations which will not be detailed here; a good reference text was written by Taylor [5]. A comprehensive uncertainty and sensitivity analysis is being conducted per the *Guide to the Expression of Uncertainty in Measurement* (GUM) [16] and the results will be presented in a future publication.

The purpose of this review is to examine each of the physical measurements, to present measurement options and to discuss the measurement uncertainty budget for each of the methods. It is standard practice to calibrate measurement instruments, and it is assumed that the measurements are considered in control; *i.e.*, each measurement represents the true value with variations attributed to a constant system of chance causes. The uncertainties, however, are rarely reported with the results of fracture mechanics tests; owing primarily to the complexity of measurements and calculations necessary to obtain results. Promoting the future work on this subject, evaluation of uncertainties is useful to experimentalists to maintain the quality of the test data and to know the level of confidence in the results for end users. Additionally, an understanding of the propagated uncertainties will provide experimentalists with information on which measurements have the greatest influence on results and therefore may be controlled more closely.

2. Force

Force is a derived unit of the SI. In practice, testing laboratories measure force by use of a force transducer, also referred to as a load cell, that is traceable back to a calibration standard. Typically, testing laboratories are provided a certificate, which reports an uncertainty value for the increments of force that are evaluated. Verification procedures for force transducers used with uniaxial testing machines are well established [6,7]. In summary, force transducers are verified in conjunction with the readout and data-acquisition system, also referred to as an end-to-end verification.

There are many options for force transducers and many causes for uncertainty in force measurement that are outside the control of the experimentalist. Understanding uncertainty and instrument selection however are important aspects of an experimental program. In addition to Standard Development Organizations (SDO), National Metrology Laboratories, such as the National Institute of Standards and Technology (NIST) in the United States or the National Physical Laboratory (NPL) in the United Kingdom, have published excellent references on force measurement [8,9].

For the experimentalist, however, only certain salient points are valuable to ensuring data quality. Selection of a force transducer may not be an option, however, in all circumstances the best practice is to ensure that the transducer be used with the same test machine, electronics and environment in which it was verified.

Additionally, the working range of the force transducer will have been established by the manufacturer but caution is warranted for conducting tests with a force transducer that is not well matched to the range of force measured in the test. At the very least, the uncertainty of the force transducer should be known throughout the expected range of the test. It is common practice to verify load-cells in smaller increments or even use alternate calibration factors or functions for different force ranges. However, most modern force transducers used in test machines employ strain-gages to generate an equivalent force signal. The elastic strain required to generate a low force signal is significantly smaller than the elastic strain required to generate a high force signal and signal noise may become significant for low force measurements. Furthermore, most modern test machines employ analog-to-digital (A/D) converters where the resolution is limited to a specific number of discrete points over the full range.

The reviewed methods (either directly or by reference) simply state that the test must be conducted within the range of the force transducer in a testing machine conforming to the requirements of ASTM E4 [6], BS EN 10002-2 [10] or ISO 7500-1 [7].

ASTM E1820 [11] also uses the above requirements that comply with ASTM E4, but adds that the individual verification data points shall be within ± 0.2% of a fit to the data, if an elastic compliance method is used. The recommended practices from ExxonMobil and CanmetMATERIALS both cite ASTM E1820 for guidance on force measurement requirements. The DNV recommended practice cites BS 7448-4 [12]. The force measurement requirements are not detailed in the DNV recommended practice, and only a nominal force capacity is described in BS 7448-4. BS 7448-4 does have a normative reference to BS EN 10002-2 and specifies a Class I device having an accuracy of ± 1%. BS 8571 provides no specification for force measurement yet it cites ISO 12135 [13], where a nominal force capacity is described similar to BS 7448-4. The normative reference in ISO 12135 is ISO 7500-1 with no class requirement (Class I assumed for ± 1%). The nominal force capacities described in BS 7448-4 and ISO 12135 are for bend specimens and compact tension specimens, and are obtained by multiplying the estimated maximum force by 1.2.

It is reasonable then, for SE(T) testing, to combine requirements and remain congruent with established fracture toughness test methods. That is, to use the maximum uncertainty (±1% of reading) and imposed linearity (± 0.2% of reading from fit) requirements in conjunction with a nominal force capacity. The multiplier (1.2 ×) is suitable for SE(T) specimens and the nominal force capacity equations would then become a function of the tensile strength of the steel being tested and the initial remaining ligament of the specimen. For side-grooved and plain-sided specimens, the nominal force capacity equations become:

$$P_N = 1.2(W - a_0)B_N\sigma_{TS}, \tag{1}$$

and

$$P_N = 1.2(W - a_0)B\sigma_{TS}, \tag{2}$$

respectively.

Here, P_N is the nominal force capacity, W is the width of the specimen in the direction of crack propagation, B_N and B are the thicknesses of the specimen parallel to the crack front for side-grooved and plane-sided specimens respectively, and σ_{TS} is the ultimate tensile strength of the steel being tested. When testing specimens with notches in the weld center-line (WCL), the tensile strength of the weld metal should be used.

Clearly, using the defined nominal force capacity presents a challenge to the experimentalist when considering the variety of pipeline steels and specimen geometries, because it is often impractical to change experimental equipment for varying test programs. The maximum force capacity is then left to the discretion of the experimentalist if the uncertainty of the transducer up to the nominal force capacity, P_N, is known.

ASTM E1820 further requires a signal resolution of at least 1 part in 4000 of the transducer signal range and a maximum signal noise of ± 4 parts in 4000 of the transducer signal range if the elastic compliance method is used. None of the reviewed SE(T) methods have a force resolution or signal noise requirement for SE(T) testing. To remain consistent with other established fracture toughness standards and to ensure the data quality, the resolution requirement is recommended herein. However, this requirement in ASTM E1820 considers the full range of the transducer signal; which, without other guidance is assumed to be coincident with the full force capacity. It is thereby not related to the maximum force anticipated during the test. It is recommended herein that requirements on minimum resolution and signal noise be related to the nominal force capacity (P_N) and not the working range of the force transducer.

3. Pre-test length measurements

In all the reviewed SE(T) methods, the pre-test measurements are related to the specimen geometry. That is, a measurement traceable to the SI base unit of length. Typical measurement instruments will include calipers and micrometers but a variety of other instruments are available to the experimentalist. In all cases, it is important that the measurement process is statistically in control and the uncertainty is known.

Specimen width, W, thickness, B, and net thickness, B_N, are readily measurable by use of calipers or micrometers. While the ExxonMobil method describes a maximum variation for width and thickness, none of the other reviewed SE(T) methods explicitly define the uncertainty or resolution requirements for these measurements. However, normative references for the reviewed SE(T) methods, ASTM E1820 and ISO 12135, each include requirements. ASTM E1820 specifies that measurement of these dimensions be made to the nearest 0.050 mm (0.002 in) or 0.5% whichever is larger, and resolution is implied to be 0.001 mm in this case. ISO 12135 specifies that these dimensions be measured to ± 0.02 mm or ± 0.2% whichever is larger, and resolution in this case is implied to be 0.01 mm.

The measurement of the net thickness, B_N, of a side-grooved specimen deserves special attention, see Fig. 1. The same uncertainty and resolution requirements from ASTM E1820 and ISO 12135 are applied. Without specific guidance on how the dimension is determined, consideration for the source and magnitude of uncertainty is necessary. Specialized attachments for calipers or micrometers are common for direct measurements; *i.e.*, described as Method 1. Calipers without attachments should never be used for this measurement since the measuring anvils are typically 0.8 mm wide and cannot physically reach the root of the side groove. This would result in a systematic error on the order of +0.4 mm for a commonly specified root radius of 0.5 mm, assuming an ideal geometry.

Method 1—A single direct measurement using anvils that reach the bottom of the side grooves.

To comply with a stated uncertainty budget, the experimentalist must determine the individual uncertainty for B_N. This uncertainty will be the combination of systematic and random errors and it is common practice to combine the stated uncertainty of the instrument and the variance determined from multiple measurements.

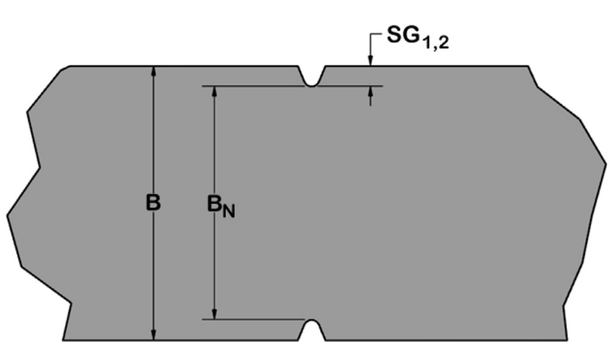

Fig. 1. Schematic representation of the SE(T) thickness with side grooves.

That is, the total uncertainty of a measurement will include the uncertainty of the instrument and the uncertainty of the experimentalist. Considering that other influences (*e.g.*, temperature) are included in the uncertainty of the experimentalist. These can be combined like this;

$$u^2(B_N) = u^2(instrument) + u^2(experimentalist). \tag{3}$$

The variance due to the experimentalist can approach zero with enough individual measurements but a balance between the number of measurements and the effect of the variance should be considered for practical and economic considerations. This uncertainty of B_N is then compared to the stated uncertainty budget to determine if the measurement met the requirement.

Method 2—Three direct measurements using a depth or height gauge, with a stylus that reaches the bottom of the two side grooves (independently), and a caliper or micrometer to measure the specimen thickness.

1. Zero the depth or height gauge on the surface of the specimen and measure SG_1.
2. Flip the specimen over and repeat for SG_2.
3. Measure the thickness (B).
4. Subtract SG_1 and SG_2 from B to determine B_N.

The same uncertainty budget is applied to B_N, but in this case, the three individual measurement uncertainties must be considered to determine if the budget requirement is met.

By use of this basic equation:

$$B_N = B - SG_1 - SG_2 \tag{4}$$

the simple propagation of uncertainty can be applied, yielding;

$$u_{B_N}^2 = \left(\frac{\partial B_N}{B}\right)^2 u_B^2 + \left(\frac{\partial B_N}{SG_1}\right)^2 u_{SG_1}^2 + \left(\frac{\partial B_N}{SG_2}\right)^2 u_{SG_2}^2 + 2\left(\frac{\partial B_N}{B}\right) \times \left(\frac{\partial B_N}{SG_1}\right) u_{B,\ SG_1} + 2\left(\frac{\partial B_N}{B}\right)\left(\frac{\partial B_N}{SG_2}\right) u_{B,\ SG_2} + 2\left(\frac{\partial B_N}{SG_1}\right) \times \left(\frac{\partial B_N}{SG_2}\right) u_{\ SG_{1,2}}. \tag{5}$$

The partial derivatives of B_N with respect to all other variables are all equal to one so the squared uncertainty is,

$$u_{B_N}^2 = u_B^2 + u_{SG_1}^2 + u_{SG_2}^2 + 2u_{B,\ SG_1} + 2u_{B,\ SG_2} + 2u_{\ SG_{1,2}}. \tag{6}$$

If each of the measurements are independent from one another then the covariance terms equal zero, leaving a simple addition of individual uncertainties, yielding;

$$u_{B_N}^2 = u_B^2 + u_{SG_1}^2 + u_{SG_2}^2. \tag{7}$$

The experimentalist is then left to determine the individual uncertainties for B, SG_1, and SG_2, the same way as demonstrated in Method 1, by Equation (3). The resultant uncertainty is then compared to the uncertainty budget to determine if the budget requirement is met.

The rigor of this example can be applied similarly to many other measurements necessary. This example should not be taken as the most important measurement in the course of SE(T) testing. It simply illustrates the sources of uncertainty and the considerations necessary in order to comply with stated uncertainty budgets.

The experimentalist is further cautioned to avoid using the inspection report from a machine shop, unless the inspection report has associated uncertainties and can provide current calibration/verification records.

In cases where specific specimen geometry variables can influence the results, it is prudent to document the pre-test condition. Notably, specifications for side-groove geometry, knife-edge geometry, and notch geometry should be verified prior to testing. None of the reviewed SE(T) methods have measurement uncertainty requirements for these; however, none of these dimensions explicitly propagate uncertainty. These are part of the experimental design, and are therefore outside the scope of this review. Each of the reviewed SE(T) methods has a specification for clamped specimens where the distance between the grips (H) is 10W. Only the ExxonMobil method specifies an uncertainty of $\pm 0.1W$, yet the uncertainty would not propagate through the ExxonMobil method. Similarly, the uncertainty on H would not propagate through the CanmetMATERIALS method. This uncertainty would propagate for the DNV and BS 8571 methods, since H is used in the analysis calculations.

The height measurements (h_1 and h_2) of the double clip gauge arrangement, are necessary for the calculation of the crack-tip opening displacement (CTOD) and crack mouth opening displacement (CMOD, assuming $h = 0$). Uncertainties for these measurements propagate through to the test results, yet no uncertainty specification is provided. Since these measurements are made with common instruments used for similar geometric dimensions, it is reasonable to assume that these dimensions are known to $\pm$ 0.2% of the measured value.

4. In-test length measurements

The length measurements captured during the test are used directly in the analysis equations. For this section, only directly measured lengths are considered with direct traceability to a length standard maintained by a National Metrology Laboratory. An alternative electric potential difference method for determining the crack extension will not be considered here but is an active subject of on-going research. Use of this method is more difficult to verify against the SI base unit of length and a standardized method of performing such a verification is unavailable.

Each of the reviewed SE(T) methods use clip gauge type extensometers to measure the opening of the notch. The DNV, ExxonMobil and BS 8571 methods require a double-clip-gauge (DCG) arrangement to calculate the crack-tip opening displacement (CTOD) and crack-mouth opening displacement (CMOD), however, the DNV method allows the use of a single-clip gauge to measure CMOD. The CanmetMATERIALS method only requires a single-clip gauge to measure CMOD. An ideal notch opening geometry can be seen in Fig. 1.

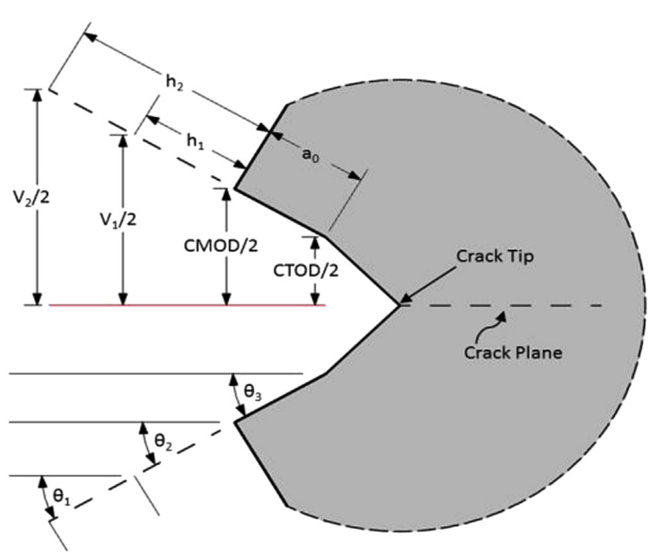

Fig. 2. Schematic representation of the ideal SE(T) notch opening geometry, exaggerated for illustration.

Each of the reviewed SE(T) methods refer to normative standards for details on the clip gauge working range and uncertainty. ASTM E1820 recommends that the working range be less than twice the expected displacement during the test and the uncertainty of any reading shall be within $\pm$ 1% of the full working range with a more restrictive requirement if the elastic compliance method is used. If elastic compliance is used, then the deviation of any individual verification point shall be less than $\pm$ 0.2% of the full working range from a fit to the verification data. Additionally, the resolution should be at least 1 part in 32,000 of the working range, while the signal noise is limited to $\pm$ 2 parts in 32,000 of the working range. BS 7448-4 refers to BS EN 10002-4 [14], where at least a Class I extensometer is to be used. Additional information is provided in BS 7448-4, stating that the verification of the gauge shall be true within $\pm$ 0.003 mm for displacements up to 0.3 mm and $\pm$ 1% of the value for larger displacements. This is identical to the specification provided in ISO 12135 except that ISO 12135 refers to ISO 9513 [15] for calibration requirements. The noteworthy differences between ASTM and ISO uncertainty requirements are that ASTM specifies a value based on the working range of the gauge while ISO uses a fixed value up to 0.3 mm followed by fractional uncertainty based on the individual readings beyond 0.3 mm. The Class I specification in BS EN 10002-4 and ISO 9513 defines the resolution as the larger of 0.001 mm or 0.50% of the reading which is different than the requirement listed in BS 7448-4 and ISO 12135.

Two sources of uncertainty are noteworthy and deserve additional attention since the uncertainties propagate directly into the estimation of crack length (extension), by way of CMOD unloading compliance. Firstly, experimentalists with sufficient experience will have undoubtedly encountered a clip gauge with significant nonlinearity at relatively small opening values. It is important that the experimentalist ensures that the measurement complies with the uncertainty budget. More importantly, the uncertainty budget must be sufficiently restrictive so that the non-linear behavior does not dominate critical results, such as adjusted initial crack length (a_{oq}).

Propagating the uncertainty and performing a sensitivity analysis may be able to provide a recommended uncertainty budget that is more restrictive than what is already stated. However, from a practical perspective a reasonable uncertainty budget can be suggested without the full propagation. For illustration, a typical clip gauge verification is shown in Fig. 3, and the positive uncertainty budgets from the standards are included. To be clear, the verification data presented are the raw values without any linearization or functional adjustment, which are both commonly used in digital acquisition systems. The clip gauge in this illustration had a working range of 6.00 mm and was calibrated on a commercially available digital calibrator. The uncertainty of the calibrator is not super-imposed on the data presented in Fig. 3. It is evident in Fig. 3 that a suggested uncertainty budget should be based on the reading and not the full working range of the clip gauge. Note that the uncertainty budgets considered are computed for each calibration reference value.

The same calibration data, this time with a functional adjustment is presented in Fig. 4 along with a fixed fractional uncertainty budget based on the reading. The suggested uncertainty budget of $\pm$ 0.5% is also shown in Fig. 4.

From the example shown in Fig. 4, the error of the raw instrument readings below ~0.5 mm would not meet the suggested uncertainty budget. In this example, the adjusted data is greatly improved over the whole range. Also, note that the ASTM uncertainty budget did not significantly change between the original

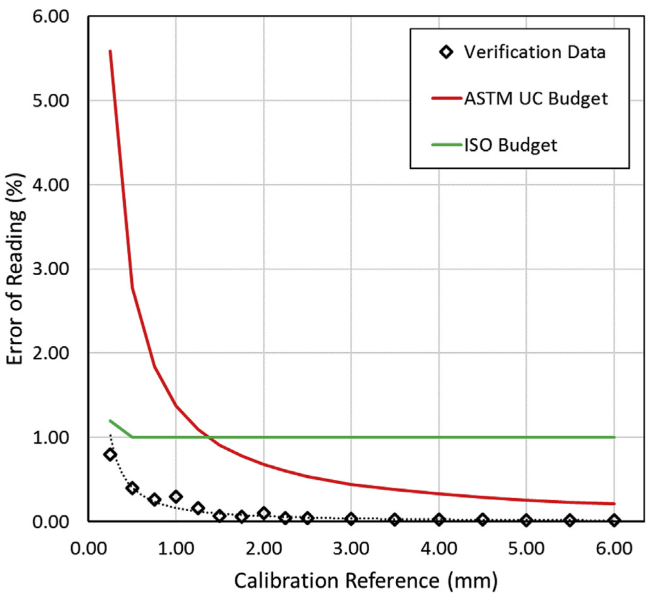

Fig. 3. Plot of Error *vs.* Calibration Reference for a clip gauge showing the positive uncertainty allowances from ASTM and ISO (BS) standards.

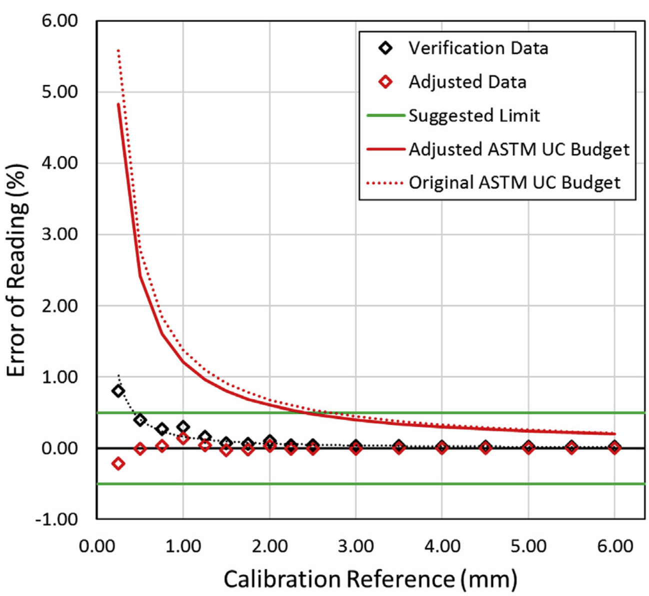

Fig. 4. Plot of Error *vs.* Calibration Reference for a clip gauge showing the aw and adjusted verification data, the suggested uncertainty budget, along with the ASTM unloading compliance uncertainty budget (positive) as a function of the original and adjusted data.

deviation from fit and the deviation from fit of the adjusted data.

At this point the suggested uncertainty budget is without foundation from a propagation or sensitivity perspective. It has a practical basis in terms of what is possible (shown only for one case) and if the verification data can be shown to be repeatable. The case can then be made, that the level of uncertainty may be less important than the repeatability of the instrument, *i.e.*, the magnitude and slope or shape of the verification data is repeatable. The point is made because initial compliance calculations rely on the difference in CMOD measurement values from zero to ~0.1 mm. As presented, calibration verification data is not available for this range of CMOD values. The value of 0.1 mm was chosen as an example based on data collected during an SE(T) test where five elastic unloading cycles were performed and the maximum elastic CMOD (in that test) was less than 0.1 mm.

Regarding the resolution requirements, ASTM requires 1 part in 32,000 of the full working range and ISO requires the larger of 0.001 mm or 0.50% of the reading. A hypothetical, value of the clip gauge reading is needed to discuss the differences, therefore, consider 0.1 mm. From ASTM, 1 part in 32,000 of 6.00 mm is equal to 0.0002 mm and the larger of the ISO equivalent is 0.001 mm.

The same SE(T) results, specifically, the unloading data from the first cycle were examined; which included 50 data points in the range of 0.0334 mm–0.0201 mm. Since linear regression aims to minimize the total squared error in the vertical direction, it is assumed that all the error is in the *y*-variable. A linear regression was performed on the clip gauge output *vs.* the data index (no error) and the maximum deviation of any individual data point from the fit was 0.0002 mm and the standard error of the slope from the regression was ±0.00003 mm/index. The 0.0002 mm matches the resolution requirement of ASTM and equates to 1% but the deviation from the fit is appropriately associated with signal noise which cannot be separated from bias. The bias, accounted for by adjusting the verification data, is not completely removed and is evident in the regression example here by a *y*-intercept of 0.00003 mm (± 1E-6 mm). For all practical purposes, this is insignificant and of no real concern for the experimentalist. Moreover, the non-linearity of the response over 0.0334 mm and 0.0201 mm, which is currently unknown, resulted in a negligible uncertainty in the slope over the same range.

The 0.0002 mm deviation from the fit, is outside the suggested uncertainty budget of ± 0.5%, but to resolve ± 0.5% on a 0.02 mm signal, the resolution of the analog-to-digital converter would have a resolution of 0.0001 mm or 1 part in 60,000 for a 6.00 mm working range. This is within the capability of modern data acquisition equipment and commercially available calibration equipment, however, is not the suggested resolution requirement herein. Only the full propagation of uncertainties and sensitivity analysis will determine if the uncertainty of the results can be significantly improved with a more restrictive uncertainty budget on clip gauge measurements. Additional caution is prudent here because signal noise is typically larger than the resolution so an uncertainty based on resolution alone ignores signal noise and it is indeed a component of uncertainty. The ASTM requirement for signal noise is 2 parts in 32,000 over the working range, or 0.0004 mm for 6.00 mm. At a hypothetical clip gauge measurement of 0.08 mm, the ASTM noise requirement matches the suggested uncertainty budget of ± 0.5%. In contrast the ISO uncertainty budget for a 0.08 mm signal is ± 3.75%. Until the full uncertainty propagation and sensitivity analysis is complete, the suggested uncertainty budget of ± 0.5% of individual readings will remain.

The second source of uncertainty which is superimposed on the calibration verification is from material/mechanical responses that cannot be adequately captured by the clip gauges. The clip gauge (opening) measurements at $h = 0$ mm, $h = 2$ mm and $h = 8$ mm (as an example) cannot discern between asymmetric openings (with respect to the crack plane) nor a mixed mode component of the opening measurements. The mixed mode component of the opening measurements is primarily associated with high plasticity and is especially prevalent in specimens that are notched in the heat affected zone (HAZ) of a weld. The former, poses no great risk to the results as the symmetry is not specifically required for a valid test. The latter is not specifically a consideration for crack path deviation (angle), but rather an uncertainty based on the knife edges departing from a virtual vertical plane. The effect is clear in Fig. 5, which is a side-view photograph of an SE(T) specimen captured after the test. The clip gauges have been removed from the DCG fixture and the photograph was analyzed by digital image correlation (DIC) to show significant shear and an obvious out of

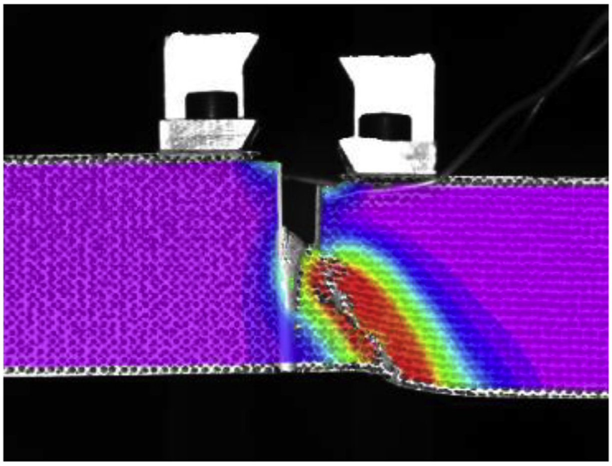

Fig. 5. A post-test DIC analyzed photograph of a SE(T) with a notch in the HAZ of the weld, the photo demonstrates significant shear and the out of plane measurements from the clip gauges.

plane shift of the specimen.

This example is shown to illustrate that clip gauge opening data alone cannot capture this effect and separate the notch opening from the shear displacement. This material/mechanical response does not match the ideal notch opening shown in Fig. 2. CMOD unloading compliance methods to determine the crack length (extension) are compromised, especially rotation corrected compliance. While this case demonstrates, what can be encountered during SE(T) testing, it is an extreme case in the author's experience. Further discussion of how to deal with such an anomaly is outside the scope of this paper. However, the point is made that situations such as this are encountered and further work is necessary to avoid this sort of response from being analyzed the same way as more ideal material/mechanical responses by any test method.

5. Post-test length measurements

Each of the reviewed SE(T) methods require post-test measurements of the initial and final crack lengths. These measurements are used directly in the analysis equations and are also used in comparison to the crack validity requirements of size and shape. Here, only uncertainty in the measurements will be discussed. A wide range of tools are available to the experimentalist, with many commercially available integrated systems or more simple separated systems of imaging and analysis.

None of the reviewed SE(T) methods have measurement uncertainty requirements for post-test measurements. Such requirements are found in the normative references. ASTM E1820 requires the instrument to have an accuracy of 0.025 mm (0.001 in). BS 7448-4 requires that the measurement be within the greater of ± 0.25% (of *a*) or ± 0.05 mm and ISO 12135 requires that the instrument be accurate to within the greater of ± 0.1% or 0.025 mm. Both ASTM E1820 and ISO 12135 explicitly state that the uncertainty limit is placed on the instrument and therefore applied to each individual measurement combined in the nine-point average method. BS 7448-4 can be interpreted either way, but only the individual measurements will be considered for the purposes of propagating uncertainty.

6. Uncertainty budgets

This section presents the uncertainty budgets as published from the referenced test methods and normative references. Resolution and noise requirements are not presented here, but the experimentalist is encouraged to review resolution and noise requirements to compare with existing test equipment or to assist in selecting future instrumentation. The uncertainty budgets for each measurement shown in Table 1, are condensed into a single suggested uncertainty budget and is shown in Table 2. The tightest uncertainty budgets from each of the methods are presented. However, the suggested uncertainty budget from clip gauge measurements is presented, as discussed in the In-Test Measurement section.

7. Uncertainty propagation

This section will review some calculations made in each of the reviewed SE(T) methods and discuss the strategy to propagate the measurement uncertainties. Referring to the *Guide to the Expression of Uncertainty in Measurement* (GUM) [16], we'll consider these uncertainties as Type B; *i.e.*, an estimate of uncertainty based on judgement, experience, manufacturer's specification, and calibration certificates. In contrast, a Type An uncertainty is based on multiple measurements under the same conditions where an average value has a statistically relevant standard deviation.

The Type B evaluations can apply to both random error and bias. Random errors cannot be corrected, and theoretically, biases can be eliminated from the result. This is the basis for adjusting raw clip gauge signals to reduce the uncertainty of the measurement and assumes that the raw data is repeatable, that is, the bias is the same for every verification performed.

There are numerous resources on uncertainty propagation and it is not within the scope of this paper to review all the assumptions and validations. However, in general, the validity of using

Table 1
Directly measured uncertainty budget.

Measured Value (unit)	Maximum Allowed Uncertainty by Method			
	DNV	ExxonMobil	CanmetMATERIALS	BS 8571
P (N)	±1%	±0.2%	±0.2%	±1%
B (mm)	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.02 (±0.2%)[a]
B_N (mm)	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.02 (±0.2%)[a]
W (mm)	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.050 (±0.5%)[a]	0.02 (±0.2%)[a]
CMOD (mm)	±1%		±0.2% (of range)	±1%
h_1 (mm)	±0.2%	±0.2%		±0.2%
h_2 (mm)	±0.2%	±0.2%		±0.2%
V_1 (mm)	±1% [b]	±0.2% (of range)		±1% [b]
V_2 (mm)	±1% [b]	±0.2% (of range)		±1% [b]
a_0^i (mm)	0.05 (±0.25%)[a]	±0.025	±0.025	0.025 (±0.1%)[a]
a_p^i (mm)	0.05 (±0.25%)[a]	±0.025	±0.025	0.025 (±0.1%)[a]

[a] The larger of the absolute or relative value.
[b] The normative references have tighter uncertainty requirements.

Table 2
Condensed uncertainty budget for directly measured values.

Measured Value (unit)	Uncertainty Budget
P (N)	±0.2% (of nominal force capacity)
B (mm)	±0.2% (of reading value)
B_N (mm)	±0.2% (of reading value)
W (mm)	±0.2% (of reading value)
CMOD (mm)	±0.5% (of reading value)
h_1 (mm)	±0.2% (of reading value)
h_2 (mm)	±0.2% (of reading value)
V_1 (mm)	±0.5% (of reading value)
V_2 (mm)	±0.5% (of reading value)
a_0^i (mm)	±0.1% (of reading value)
a_p^i (mm)	±0.1% (of reading value)

uncertainty propagation assumes that the uncertainty is small compared to the measurement of the true value, and it is also a linear approximation of the expanded uncertainty. However, the latter does not preclude non-linear functions in the propagation. The propagation is greatly simplified in the cases where the measurements and calculated variables are independent from one another, *i.e.*, variance is the standard uncertainty and covariance is zero. A very simple example of a propagation is given by Equation (5) through Equation (7). In this case, the uncertainties are small compared to the measured value and the individual measurements are independent of one another.

Conversely, CMOD unloading compliance, which is seemingly simple presents challenges for the propagation of uncertainty. In the simplest form, the unloading compliance is the change in CMOD with respect to the change in force acquired at the same time. The CMOD can be directly measured by use of a single clip gauge or calculated by use of two clip gauges, see Fig. 2. For discussion, here, in the simplest form, the change in CMOD is given by

$$\Delta\delta_m = \delta_i - \delta_{i-1}. \tag{8}$$

The same is true for the change in force, given by

$$\Delta P = P_i - P_{i-1}, \tag{9}$$

and the compliance (C) is given by

$$C = \frac{\Delta\delta_m}{\Delta P} \tag{10}$$

However, in practice this is not how the compliance is determined (chord). In practice, the slope of the range of CMOD values with respect to the range of force values is determined most commonly by linear regression. Recall that simple linear regression aims to reduce the total squared error in the y-direction and assumes no error in the abscissa. This assumption fails for the situation at hand. It is reasonable to assume that this method does yield a meaningful result with low uncertainty, yet the expanded uncertainty must include covariance since the two variables are no longer independent.

Another instance where a fit is used to calculate the result from independent measurements is embedded in the incremental crack length calculations found in all methods except the DNV method. All the equations take the form

$$a_i/W = \sum_{j=0}^{p} \beta_j \vartheta_i^j \tag{11}$$

where, β_j is from a set of constants provided in the test methods determined from a fit, and will have covariance associated with them. Because u is used here as standard uncertainty, the variable ϑ replaces instances where the variable symbol u appears in the referenced equations. Here also, the size of the polynomial (p) differs between methods. The variance of each β_j and their covariances here are not known, as they were not published with the test methods nor were they found in the source references of those methods. It is reasonable to assume that they are small but unreasonable to assume that they are zero, hence it will remain a consideration.

The smallest polynomial function for a_i/W is found in the ExxonMobil method. There are six terms for the fifth-order polynomial, and since the incremental crack length (a_i) is the value of interest we multiply both sides by the width (W), and is shown as,

$$a_i = W\left(\beta_0 + \beta_1\vartheta_i + \beta_2\vartheta_i^2 + \beta_3\vartheta_i^3 + \beta_4\vartheta_i^4 + \beta_5\vartheta_i^5\right). \tag{12}$$

If W and ϑ_i are not correlated with β_j then the uncertainty can be expressed as,

$$\begin{aligned} u_{a_i}^2 = {} & \left(\frac{\partial a_i}{W}\right)^2 u_W^2 + \left(\frac{\partial a_i}{\vartheta_i}\right)^2 u_{\vartheta_i}^2 + 2\left(\frac{\partial a_i}{W}\right)\left(\frac{\partial a_i}{\vartheta_i}\right) u_{W,\vartheta_i} + \left(\frac{\partial a_i}{\beta_0}\right)^2 u_{\beta_0}^2 \\ & + \left(\frac{\partial a_i}{\beta_1}\right)^2 u_{\beta_1}^2 + \left(\frac{\partial a_i}{\beta_2}\right)^2 u_{\beta_2}^2 + \left(\frac{\partial a_i}{\beta_3}\right)^2 u_{\beta_3}^2 + \left(\frac{\partial a_i}{\beta_4}\right)^2 u_{\beta_4}^2 \\ & + \left(\frac{\partial a_i}{\beta_5}\right)^2 u_{\beta_5}^2 + 2\left(\frac{\partial a_i}{\beta_0}\right)\left(\frac{\partial a_i}{\beta_1}\right) u_{\beta_0,\beta_1} + 2\left(\frac{\partial a_i}{\beta_0}\right)\left(\frac{\partial a_i}{\beta_2}\right) u_{\beta_0,\beta_2} \\ & + 2\left(\frac{\partial a_i}{\beta_0}\right)\left(\frac{\partial a_i}{\beta_3}\right) u_{\beta_0,\beta_3} + 2\left(\frac{\partial a_i}{\beta_0}\right)\left(\frac{\partial a_i}{\beta_4}\right) u_{\beta_0,\beta_4} + \\ & 2\left(\frac{\partial a_i}{\beta_0}\right)\left(\frac{\partial a_i}{\beta_5}\right) u_{\beta_0,\beta_5} + 2\left(\frac{\partial a_i}{\beta_1}\right)\left(\frac{\partial a_i}{\beta_2}\right) u_{\beta_1,\beta_2} + 2\left(\frac{\partial a_i}{\beta_1}\right)\left(\frac{\partial a_i}{\beta_3}\right) u_{\beta_1,\beta_3} + 2\left(\frac{\partial a_i}{\beta_1}\right)\left(\frac{\partial a_i}{\beta_4}\right) u_{\beta_1,\beta_4} + \\ & 2\left(\frac{\partial a_i}{\beta_1}\right)\left(\frac{\partial a_i}{\beta_5}\right) u_{\beta_1,\beta_5} + 2\left(\frac{\partial a_i}{\beta_2}\right)\left(\frac{\partial a_i}{\beta_3}\right) u_{\beta_2,\beta_3} + 2\left(\frac{\partial a_i}{\beta_2}\right)\left(\frac{\partial a_i}{\beta_4}\right) u_{\beta_2,\beta_4} + 2\left(\frac{\partial a_i}{\beta_2}\right)\left(\frac{\partial a_i}{\beta_5}\right) u_{\beta_2,\beta_5} + \\ & 2\left(\frac{\partial a_i}{\beta_3}\right)\left(\frac{\partial a_i}{\beta_4}\right) u_{\beta_3,\beta_4} + 2\left(\frac{\partial a_i}{\beta_3}\right)\left(\frac{\partial a_i}{\beta_5}\right) u_{\beta_3,\beta_5} + 2\left(\frac{\partial a_i}{\beta_4}\right)\left(\frac{\partial a_i}{\beta_5}\right) u_{\beta_4,\beta_5}. \end{aligned} \tag{13}$$

Given that the uncertainties in each constant, β_j, and the covariance between them due to fitting, are unknown, a substitution is suggested to replace their impact on the result. Let S_β, be a new variable which is also uncorrelated to W and ϑ_i.

The substitution would then yield,

$$u_{a_i}^2 = \left(\frac{\partial a_i}{W}\right)^2 u_W^2 + \left(\frac{\partial a_i}{\vartheta_i}\right)^2 u_{\vartheta_i}^2 + \left(\frac{\partial a_i}{S_\beta}\right)^2 u_{S_\beta}^2 + 2\left(\frac{\partial a_i}{W}\right)\left(\frac{\partial a_i}{\vartheta_i}\right) \times \left(\frac{\partial a_i}{S_\beta}\right) u_{W,\vartheta_i,S_\beta}. \quad (14)$$

Once again, the partial derivatives of a_i with respect to the other variables are equal to one and the covariance between variables is zero so the resultant uncertainty equation for a_i becomes,

$$u_{a_i}^2 = u_W^2 + u_{\vartheta_i}^2 + u_{S_\beta}^2. \quad (15)$$

The size of the polynomial (fully substituted here) may influence the uncertainty associated with S_β. The uncertainty can be estimated with sufficient rigor, and the original authors are encouraged to provide such results. However, even when known, it is unclear if the value will significantly influence the total uncertainty, for this example in a_i. In this case a sensitivity analysis will prove helpful.

For unknown uncertainties, like that of S_β, a sensitivity analysis can be performed using the Monte Carlo method on the uncertainty equations to determine the impact of reasonable uncertainty values. The definition of reasonable values here is simply one that would coincide with the results of a similar regression analysis.

Another method to evaluate total uncertainty is also by Monte Carlo simulations. In this method, the analysis equations from each of the test methods are used to calculate a result from the measurement values, incrementally changed within the standard uncertainty budget. While the Monte Carlo simulations can be computationally rigorous, a separate (from above) sensitivity analysis can be performed at the same time to elucidate the measurement uncertainties with the most impact on the result. Another advantage of the Monte Carlo method is that non-linear relationships between uncertainties are intrinsically accounted for.

The examples presented here are the simplest in comparison with the many complex equations found in the test methods. Each method and each equation is being carefully considered, to perform the uncertainty propagation according to the GUM. A concurrent effort is to write the code and with analysis equations to perform the Monte Carlo simulations.

Working in reverse, by applying a desired uncertainty limit on the result, an uncertainty budget may be calculated for each of the measurements using the same propagation equations and even from the Monte Carlo simulation. However, the calculated uncertainty budget may be too unreasonable for the experimentalist to achieve. At present, the condensed uncertainty budget presented in Table 2 is reasonable since the budget for each of these measurements was taken from existing and established standards. In the case of the clip gauge measurements where ± 0.5% of the reading is suggested, the suggested value has no justification from an uncertainty propagation perspective; yet is both achievable and improved over existing standard requirements.

8. Conclusions

The available published SE(T) test methods, characterized by a variety of measurement uncertainty budgets, have been reviewed. A condensed uncertainty budget specific to SE(T) testing has been suggested that accounts for all the available normative references. Additionally, this review specifically highlighted two measurement uncertainty budgets that can be improved upon for future definition and standard language of the uncertainty budgets.

ASTM E1820 tightens the uncertainty budget of clip gauge measurements when the CMOD unloading compliance method is used to estimate the incremental crack length. Clip gauge measurement uncertainty is commonly reported based on the reading of the instrument as opposed to the range of the instrument. Assuming a fixed resolution based on the range of the instrument, the relative errors associated with small instrument readings can be high, leading to more uncertainty in the compliance especially at the beginning of the test. An uncertainty budget based on the individual readings has been suggested. The suggested uncertainty budget has been shown to be achievable from a practical perspective but is not justified from a propagation of errors. This will be further examined by the propagation of errors and Monte Carlo simulations in progress.

Since unloading compliance is also determined from the force measurement record, the uncertainty budget should be sufficiently tight and with the actual uncertainty being known over the range of the test record. Condensing the guidance provided from referenced normative standards, it is suggested that the uncertainty budget be applied to the nominal force capacity of the test.

In general, the following conclusions will be useful to any experimental program involving SE(T) testing and should be considered for ongoing standardization efforts or updates to current methods:

1. Physical measurements should be traceably verified to base SI units.
2. Uncertainty budgets for physical measurements should follow those shown in Table 2.
3. Uncertainty budgets should be used to determine resolution requirements and noise limits, and not the reverse.
4. The uncertainty budget for force should be based on the nominal force capacity for the test and not the working range of the load cell.
5. The uncertainty budgets for length measurements should be fractional.

A thorough and rigorous application of the GUM method for the propagation of errors is currently being conducted in concurrence with a Monte Carlo simulation to determine the measurement or measurements that have the highest impact to the uncertainty of the final results of SE(T) testing.

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