National Physical Laboratory

NPL REPORT MAT 104

# FRAMEWORK FOR DYNAMIC UNCERTAINTY BUDGET EVOLUTION FOR MODE I FRACTURE TOUGHNESS MEASUREMENTS OF FIBRE-REINFORCED PLASTIC (FRP) COMPOSITES: A USER'S GUIDE TO UNCERTAINTY BUDGET CALCULATION TOOL

N SPETSIERIS & D EDSER

MARCH 2022

Department for
Business, Energy
& Industrial Strategy

FUNDED BY BEIS

# Framework for Dynamic Uncertainty Budget Evolution for Mode I Fracture Toughness Measurements of Fibre-Reinforced Plastic (FRP) Composites: A User's Guide to Uncertainty Budget Calculation Tool

N Spetsieris & D Edser

Department of Engineering
Science & Engineering Directorate

ISSN 1754-2979

DOI: https://doi.org/10.47120/npl.MAT104

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the UK's National Measurement System programmes.



Approved on behalf of NPLML by
Dr Stefanos Giannis
Science Area Leader (Advanced Engineering Materials)

## CONTENTS

# 1 SCOPE

This document details the function of an Excel spreadsheet tool for the calculation of an uncertainty budget for measurements of mode I interlaminar fracture toughness for laminated fibre-reinforced plastic (FRP) composite materials. The approach for the formulation of the uncertainty budget was made according to the Guide to the Expression of Uncertainty in Measurement (GUM) [1].

The work detailed in this report was undertaken within the End-to-End Digitised Materials Testing and Verification project as part of the 2021-2022 Advanced Manufacturing Sector (Materials Metrology) National Measurement System Programme, funded by the Department for Business, Energy and Industrial Strategy (BEIS). The aim of the project is to deliver a digitised materials test and verification framework through an end-to-end (within the measurement environment) provision of high quality, trusted and traceable measure–process–store–disseminate chain of value-added information driven by FAIR (Findability, Accessibility, Interoperability, and Reuse) principles.

The uncertainty budget tool represents a building block enabling future implementation of dynamic uncertainty evaluation as part of the traceability chain of high-fidelity data. The measurement of mode I fracture toughness was chosen as it involves subjective measurements by the user (e.g. crack growth) and/or the use of automated imaging/strain-based measurements, for which the sources of uncertainty are less straight forward than other mechanical characterisation techniques and measurands. The report also considers how the uncertainty model can be implemented in a digital infrastructure as well as novel techniques (e.g. mechanoluminescent coatings) for reducing associated uncertainties.

The tool, in its present form, is a prototype version intended to work as a proof of concept with the aim of enabling a digitalised framework for calculating the uncertainty of a measured quantity (mode I fracture toughness, $G_{IC}$) via contributions from all relevant uncertainty sources entailed in the experiment. For the purpose of monitoring the position of the crack, two methods have been implemented. The first follows the recommendation in ISO 15024 [2] for using a travelling microscope for visual monitoring, with the difference that a camera is hereby mounted on a travelling platform, generating consecutive frames that follow the crack front. The second method involves the use of video extensometry equipment that automatically tracks the crack propagation throughout the test and outputs all required results.

# 2 DEFINITIONS

## 2.1 SOURCES OF UNCERTAINTY

In this section, the applicable sources of uncertainty are described according to their respective category and with regards to their method of definition and quantification.

### 2.1.1 Apparatus

Apparatus uncertainty sources include any uncertainties derived from the equipment used for carrying out the mode I interlaminar fracture toughness test (ILFT), from the initial specimen measurements to the data acquisition of the test results.

- **Load cell resolution:** The precision of the value obtained from the test machine's calibrated load cell. According to [2], the force sensing device shall comply with Grade 1 of ISO 7500-1:2018 [3] (accuracy within ± 1%).
- **Load cell error:** The inherent standard uncertainty of the load sensing device, as specified on the calibration certificate.
- **Micrometer resolution:** The precision of the dimension value obtained from the micrometer.
- **Micrometer error:** The inherent standard uncertainty of the micrometer, as specified on the calibration certificate of the device.
- **Crosshead resolution:** The precision of the value of displacement obtained from the crosshead displacement sensor of the test machine.
- **Crosshead error:** The inherent standard uncertainty of the crosshead displacement sensor, as specified by comparison with readings from a Linear Variable Differential Transducer (LVDT).
- **DAQ transfer error:** The uncertainty induced by any divergence in the output values obtained from the DAQ system compared to the load-cell and crosshead readings.
- **Linear scale resolution:** The precision of the value obtained for the crack length from the linear scale attached to the edge of the specimen.
- **Travelling microscope:** The precision of the value for the crack length, obtained from the frames that the travelling microscope configuration produces. Factors that affect this source include but are not limited to, camera sensor resolution, lens distortion and magnification, working distance, lighting and recording rate.
- **Video extensometer resolution:** The precision of the value for the crack length, obtained from the video extensometry equipment.
- **Video extensometer tracking threshold:** The minimum detectable crack length that can be tracked by the software.

#### 2.1.2 Method

Method uncertainty sources are derived from test procedure parameters that may or may not entail operator error, but do not affect the measurement directly. These are usually covered by the test machine calibration specifications or test standard prerequisites and therefore are often considered negligible from an uncertainty point of view.

- **Alignment:** The uncertainty induced to the load and displacement values due to misalignment of the specimen in the test machine with respect to the intended loading axis. Considered negligible if setup conforms with test standard specifications.
- **Alignment of linear scale:** The uncertainty induced in crack length values due to misalignment of the linear scale attached on the specimen's side.

- **Speed:** The uncertainty induced in the values of load and displacement from the set crosshead speed. Considered negligible if value is within test standard limits.

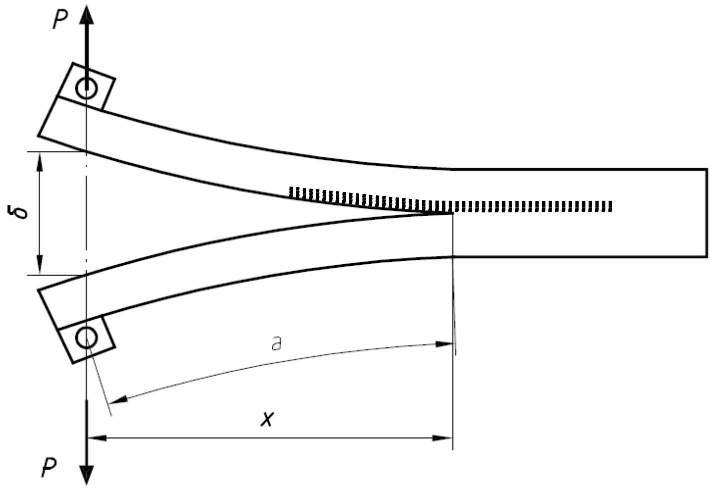


**Figure 1: The Mode I DCB test specimen under loading P, showing displacement δ and crack length a. In the schematic, the linear scale for the tracking of the crack can also be seen. [2]**

### 2.1.3 Environment

Environment uncertainty sources are derived from the effect of the environmental conditions during the test execution. Usually these are considered negligible when within test standard specifications (e.g. 23±2°C, 50±10% relative humidity) and the material is not highly sensitive to changes in temperature or humidity.

- **Ambient temperature:** The uncertainty induced by effect of test ambient temperature on the measurement. Considered negligible when standard room conditions are applied.
- **Relative humidity:** The uncertainty induced by effect of test humidity conditions on the measurement. Considered negligible when standard room conditions are applied.

### 2.1.4 Operator

Operator uncertainty sources account for the effect of human error and subjectivity of certain measured values during the test procedure.

- **Graph interpretation:** The error from the operator's ability to correctly select the load and displacement data points at the instance the load-displacement plot becomes non-linear (NL-point) and other elements from an output graph, in repeated trials. The more dependent the results calculation method is on graph interpretation, the greater the induced uncertainty is.
- **Crack length interpretation:** The error from the operator's ability to follow the crack length from the travelling microscope-generated frames, in repeated trials.

#### 2.1.5 Test Specimen

The test specimen uncertainty sources are derived by errors due to variations in the dimensions of the specimen's unique characteristics that affect the measurand. For the case of mode I, these are the width and the initial crack length.

- **Specimen width:** This error incorporates both the operator error in manually measuring the specimen dimensions in repeated trials, as well as variations in the specimen's width, that should be accordance with the specification given in the standard.
- **Initial Crack Length:** This error incorporates both the operator error in manually measuring the initial crack length in repeated trials, as well as variations in the initial crack, that must comply with the standard's specification. This source directly affects the model's measured quantity of the crack length, as the initial value is the reference for all subsequent length measurements.

## 2.2 MEASURED VALUES

In the context of the mode I ILFT test, where the measurand or output value is the interlaminar fracture toughness $G_{IC}$, the following quantities are measured for the calculation of the measurand and therefore contribute to its uncertainty:

- **Force, P (N)**, measured by the test machine load cell
- **Displacement, δ (mm)**, measured by the test machine's crosshead displacement sensor
- **Width, b (mm)**, measured manually with a micrometer
- **Crack length, α (mm)**, measured either visually, using a travelling microscope configuration or by the video extensometer's pattern recognition capability.

The above quantities can be characterized as inputs to the measurement model that calculates the output quantity, $G_{IC}$, which according to [2], is:

$$G_{IC} = \frac{3P\delta}{2ba} \qquad (1)$$

## 2.3 IDENTIFYING UNCERTAINTY CONTRIBUTIONS

It is important to identify what the contribution of various uncertainty sources have on the measurand. Table 1 shows such a correlation, where the uncertainty effect of each source is qualitatively displayed against the measurand and the measurements. A score of 1 infers a major contribution, a score of 2 to a minor contribution and the asterisk (*) denotes an indirect contribution, meaning it does not affect the exact measurement of a specific quantity, but perhaps the measurement of another quantity that affects the former.

**Table 1: The sensitivity table showing the direct or indirect effect the various uncertainty sources have on the measured values and the measurand.**

| Sources of Uncertainty | Measurand and Measurements | | | | |
|---|---|---|---|---|---|
| | $G_{IC}$ | α | b | δ | P |
| **1. Apparatus** | | | | | |
| Load Cell Resolution | *1 | | | | 1 |
| Load Cell Error | | | | | 1 |
| Micrometre Resolution | *2 | | 1 | | |
| Micrometre Error | *2 | | 1 | | |
| Crosshead Resolution | *1 | | | 1 | |
| Crosshead Error | *1 | | | 1 | |
| DAQ Transfer Error | *1 | | | 1 | 1 |
| Linear Scale Resolution | *1 | 1 | | | |
| Travelling Microscope | *1 | 1 | | | |
| Video Extensometer Resolution | *1 | 1 | | | |
| Video Extensometer Tracking Threshold | *1 | 1 | | | |
| **2. Method** | | | | | |
| Alignment | *2 | 1 | | 2 | 2 |
| Alignment of linear scale | *1 | 1 | | | |
| Speed | *2 | | | 2 | 2 |
| **3. Environment** | | | | | |
| Ambient temperature | *2 | | | 2 | 2 |
| Relative Humidity | *2 | | | 2 | 2 |
| **4. Operator** | | | | | |
| Graph Interpretation | *1 | | | 1 | 1 |
| Crack Length Interpretation | *2 | 2 | | | |
| **5. Test Specimen** | | | | | |
| Specimen Measurements | *1 | | 1 | | |
| Initial Crack Length | *1 | 1 | | | |

## 3 METHODOLOGY

The approach to developing an uncertainty budget is split into two stages, as defined by GUM [1] and further described in Procedure for Evaluating Measurement Uncertainty in Mechanical Testing [4] and UNCERT Codes of Practice [5]. These are:

i. The ***formulation*** stage, where a measurement model is adopted, and the measured quantities are categorized as either inputs or outputs in the model. Additionally, the uncertainty sources are identified and information about their contribution to the uncertainty of the measurand is gathered.

ii. The ***calculation*** stage, where the contribution of each uncertainty source is quantified, their individual effects combined and then expanded in order to more accurately represent the uncertainty of the chosen measurand quantity.

The two stages are described in detail in the following sections.

## 3.1 FORMULATION

The steps taken during the formulation stage of the uncertainty budget are:

i. Select a measurement model with defined measured input quantities that can be used to derive the measured output, known as the measurand.

ii. Define all potential sources of uncertainty and classify them according to their type. ***Type A*** uncertainties are those that can be determined by statistical methods (usually through repeated measurements), while ***Type B*** are those that are estimated by other available information, such as calibration certificates and prior knowledge or expert judgement.

iii. Assign an appropriate probability distribution to each uncertainty source and use the corresponding divisor ($k_i$). Typically, Type A sources are characterised by a normal distribution that has a divisor of $k_i$ = 1, while Type B sources are assigned rectangular distributions ($k_i = \sqrt{3}$) in the case of calibration certificates or normal distributions where the divisor takes the value of the coverage factor used in a prior uncertainty evaluation.

iv. Uncertainty values can be handled either as absolute or as a fraction of the measured quantity they are derived from (relative). In the case of the former, appropriate sensitivity coefficients must be calculated to ensure that the uncertainty is in the same units as the measurand they contribute to. If relative uncertainty values are used, then all sensitivity coefficients are equal to 1 and thus, this approach is recommended to simplify the process.

## 3.2 CALCULATION

For the calculation stage of the uncertainty budget, the following quantities are used:

i. **Standard Uncertainty $\boldsymbol{u(x_i)}$:** Calculate the standard uncertainty for each source by dividing the uncertainty value by the divisor $k_i$:

$$u(x_i) = \frac{x_i}{k_i} \tag{2}$$

ii. **Uncertainty Contribution $\boldsymbol{u_i}$:** Calculate the contribution of each source's standard uncertainty by multiplying it with the appropriate sensitivity coefficient $c_i$:

$$u_i = u(x_i)c_i \tag{3}$$

iii. **Combined Standard Uncertainty $u_c$:** Calculate the combined standard uncertainty by taking the square root of the sum of the squared uncertainty contributions. This is known as the *Law of Propagation of Uncertainty* [1]:

$$u_c = \sqrt{\sum_i u_i^2} \tag{4}$$

iv. **Effective Degrees of Freedom $\nu_{eff}$:** Calculate the effective degrees of freedom (DoF) from the individual DoFs for each uncertainty source, where if Type A, the degrees are equal to the number of trials minus one $(n-1)$, while if Type B from a calibration certificate, the DoFs are then considered infinite (∞). The Welch-Satterthwaite formula is used for the calculation:

$$\nu_{eff} = \frac{u_c^4}{\sum_{i=1}^{n} \frac{u_i^4}{\nu_i}} \tag{5}$$

v. **Coverage Factor $k$:** Select the coverage factor for the desired level of confidence from a Student's t-distribution with $\nu_{eff}$ degrees of freedom. This is supported by the Central Limit Theorem (CLT), where it is assumed that despite the different distributions the individual uncertainties may follow, the combined standard uncertainty will always tend towards a normal distribution as the number of uncertainties increase.

vi. **Expanded Uncertainty $u_c$:** Calculate the extended uncertainty by multiplying the combined uncertainty with the coverage factor selected:

$$U_c = ku_c \tag{6}$$

## 3.3 REPORTING UNCERTAINTY

The expanded uncertainty should accompany the measurement result when reported, expressed to the same significant digits, either as absolute or relative, or both. In addition, a brief statement should be included, stating the method of evaluating uncertainty as well as the chosen confidence level and coverage factor.

## 4 IMPLEMENTATION

The following paragraphs describe the process followed for completing the uncertainty budget for a mode I ILFT and calculating the expanded uncertainty through the Excel spreadsheet tool.

In addition, for the monitoring of the crack tip, two methods have been utilized. The first involves the video extensometer's crack monitoring capability that automatically follows the crack tip and provides its length at a specified interval, while the second utilizes the same video extensometry camera with a zooming lens, mounted on a travelling platform configuration, whereas the assessment of the crack length is a subjective measurement performed visually by the test operator. The key differences between the two approaches, both from an experimental set-up aspect, as well as uncertainty calculation, will be highlighted in the following sections.

### 4.1 MEASUREMENT MODEL

According to ISO 15024 [2], the mode I interlaminar fracture toughness for unidirectionally reinforced materials is calculated from the measured values of load (P), the crosshead displacement (δ), the crack length (α) and the specimen width (b):

$$G_{IC} = \frac{3P\delta}{2ba} \tag{7}$$

The measurements for this case study can be found in Table 2. The standard specifies several methods for obtaining the load and displacement values for calculating $G_{IC}$ in both crack initiation and propagation phases. In the present example, the values used (P, δ, α) are for the calculation of the initiation values of $G_I$, following the definition of the non-linear (NL) initiation value given in [2]. Non-linear initiation values inherently come with a larger degree of uncertainty (compared to MAX or $C_{0+5\%}$ initiation values), as the selection of the load and displacement values at the point of divergence from linearity (NL-point) is heavily dependent on the interpretation of the load-displacement plot by the operator.

**Table 2: Measured input quantities for interlaminar fracture toughness test.**

| Input | Measurement device | Value | | Units |
|---|---|---|---|---|
| | | Travelling microscope | Video extensometer | |
| Load, *P* | Load cell | 73.0316 | 76.785 | N |
| Displacement, *δ* | Crosshead sensor | 9.2745 | 11.332 | mm |
| Width, *b* | Micrometer | 19.989 | 19.983 | mm |
| Crack length, *α* | Travelling Microscope / Video Extensometer | 51.645 | 57.938 | mm |

For the specimen width, the value presented is the result of a total of twelve measurements of width: three measurements along the length of the specimen by four different operators, at consistent points each time. Adopting this type of measurement approach means that the uncertainty generated from this Type A measurement, incorporates both the error from the specimen's dimensional variability and the operator error in measuring the width.

As previously stated, for the crack length measurement, two different approaches were followed:

i. <u>Using the Video extensometry system:</u>

The video extensometry system consists of a set of two cameras that feed images to the accompanying software, in order to derive strain measurements, as well as crack length monitoring (Figure 2). The deformation is tracked by means of well-defined targets or features that can be found on the specimen or added artificially. When loaded, by correlating the position of the targets with their previous positions (unloaded state or previous load level/interval), the software can accurately monitor and quantify displacements and translate these to the desired measurement (crack length/position and/or strain).

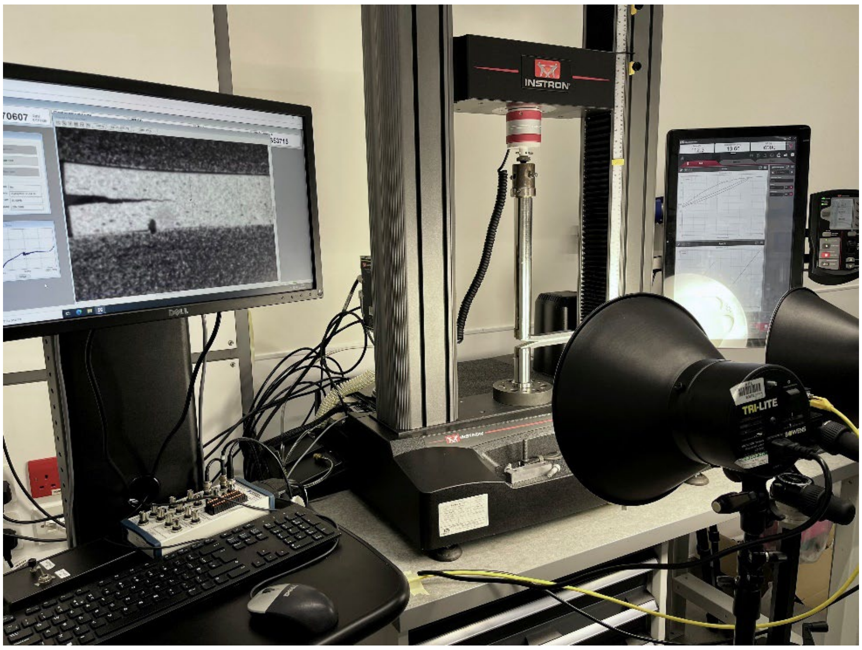


**Figure 2: Experimental set-up for monitoring the crack growth with a video extensometer.**

In order to follow the crack tip position with a video extensometer, specimens need to be carefully prepared prior to test. Having bonded the load-blocks (Figure 3) on the ends of the specimens and marked the initial crack length, the specimens must then be painted with a layer of matt white paint, which provides greater contrast for measurement of the crack position. In addition, for the software to track the crack tip, target areas must be provided. For this reason and due to the limited thickness of specimens, neoprene foam pads are bonded to the upper and lower adherends to provide the necessary surface area for the targets to be applied. The pattern used on the foam pads to allow tracking by the video extensometer is that of speckles, applied on the foam pads with a matte black spray paint after a matte white paint coating. The size and density of the speckle-pattern was as recommended by the video extensometer documentation and was generally defined by the specimen length and the selection of the image resolution. A picture of a mode I double cantilever beam (DCB) specimen used for these measurements is shown in Figure 3.

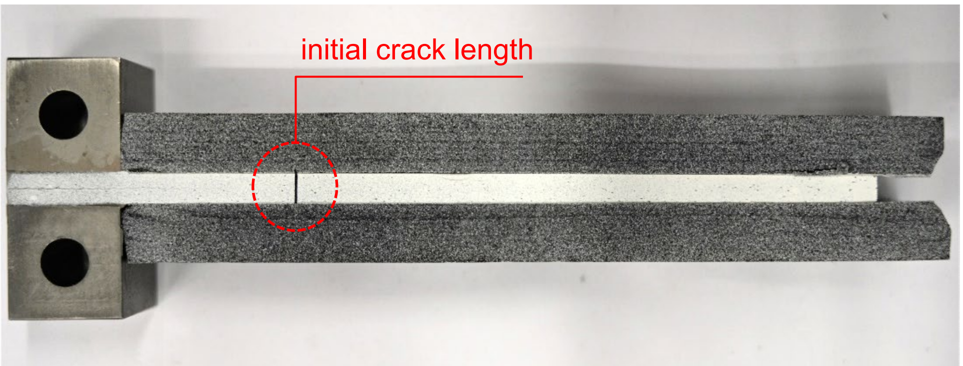


**Figure 3: A typical mode I DCB specimen; crack position monitored using a video extensometer.**

To synchronise the outputs of mechanical test machine and video extensometer, a DAQ unit was utilised to bridge the two systems and correlate the output values. More specifically, the load and displacement values from the test machine were fed into the video extensometer system for subsequent exportation alongside the crack length measurements.

ii. Using a travelling microscope configuration

The test standard specifies that measurement of crack length can be performed with a travelling microscope (instead of following it by eye) in order to improve the accuracy of results. In the present study, a travelling microscope configuration has been used for this purpose and as the benchmark technique for comparison of video extensometer measurements. This approach is adopted to highlight the effect a digitised approach can have on the uncertainty evaluation of the mode I test. The specific configuration used, consists of one the video extensometer cameras mounted on a sliding platform that enables the crack to be followed (Figure 4). The side of the specimen is marked with a graticule; a linear scale of 1 mm intervals used to measure the crack propagated length (Figure 5). A zoom lens is attached to the camera to produce image frames with enhanced precision suitable for reading the crack tip position; shown in the display on the left-side of Figure 4.

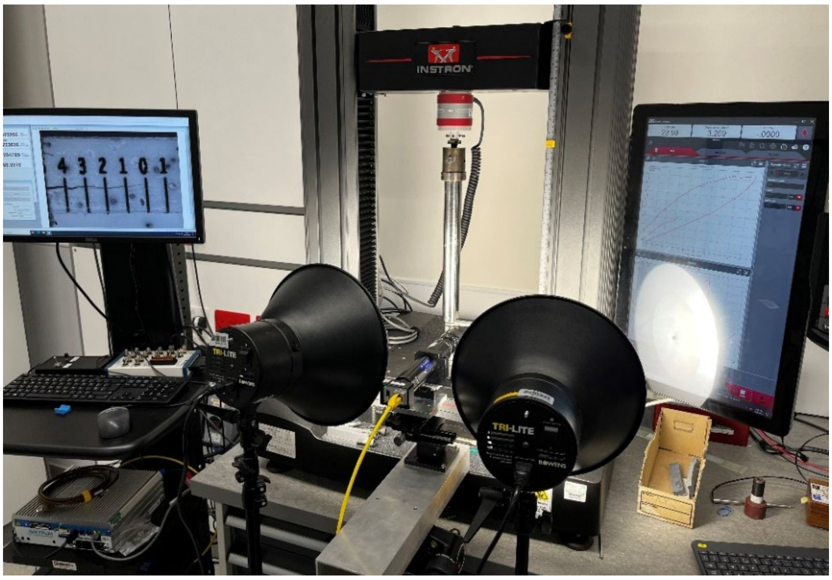


**Figure 4: Experimental set-up for monitoring the crack position with a travelling microscope.**

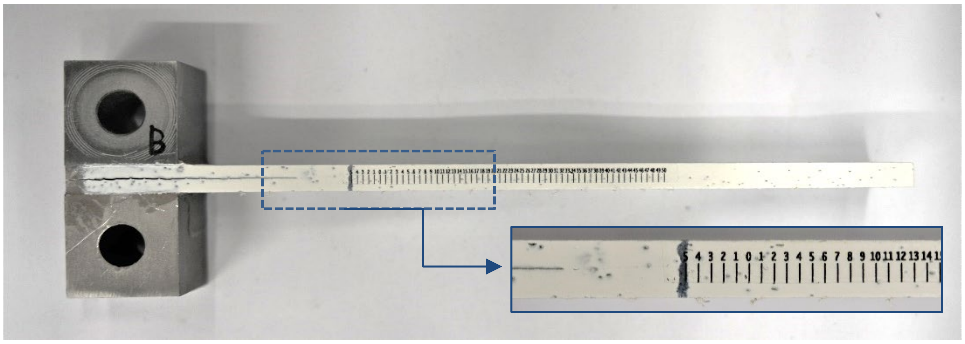

**Figure 5: A typical mode I DCB specimen; crack position monitored using a travelling microscope.**

In this case, the video extensometer software is only used for acquiring the video output from the camera, in order to isolate the frames where crack growth is observed. By extracting the frames at the chosen data acquisition frame rate, each dataset corresponds to a specific frame, simplifying the process of matching the crack length values with those of load and displacement for any given image.

For this case study, the NL-point was chosen as the reference $G_I$ initiation value for the uncertainty budget calculations. The definition of the NL initiation point and the process for extracting the necessary values for input to the model is as per ISO 15024 [2], and the results of both test runs can be found in the Appendix of the present report for the reader's future reference. According the above, the measured values that are used as inputs in the uncertainty model, these can be found in Table 2.

Feeding the above values into Equation 7, the value of the measurand is:

| | Travelling microscope | Video extensometer | Units |
|---|---|---|---|
| $G_{IC}$ | 984.18 | 1127.31 | $J/m^2$ |

## 4.2 UNCERTAINTY SOURCES, VALUE AND PROBABILITY DISTRIBUTION

In the first column of the spreadsheet, all the uncertainties are listed and are categorized based on their wider origin. The five uncertainty categories are:

| | | | | |
|---|---|---|---|---|
| *Apparatus* | *Method* | *Environment* | *Operator* | *Test Specimen* |

### 4.2.1 Apparatus

The measurements are only as accurate and precise as the measuring equipment is. The level of precision the test apparatus provides comes with a contribution to the uncertainty of that measurement, whereas, despite how well calibrated the equipment is, there is always margin for error and thus, for uncertainty. Most of the uncertainty sources in this category have their values defined from specification sheets (e.g. resolution) or from calibration certificates (e.g. standard errors).

For the crosshead standard error, a comparative analysis was carried out, as no calibration certificate was available to define it for the required displacement range. For this reason, an LVDT set-up (Figure 6) was utilized to measure values of displacement as a calibration reference. Three test runs were performed, and the percentage errors were calculated for the whole range of displacement, as seen in Figure 7. To filter out outlier values, an effective range of 20-80% of the full range of displacement was chosen for the calculation of the mean percentage error, which was then used as the relative uncertainty value in the budget.

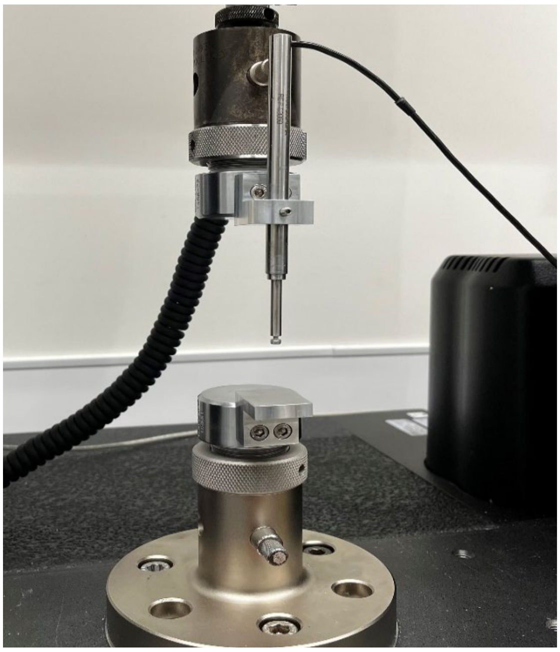

**Figure 6: The LVDT set-up used for defining the standard error value of the crosshead.**

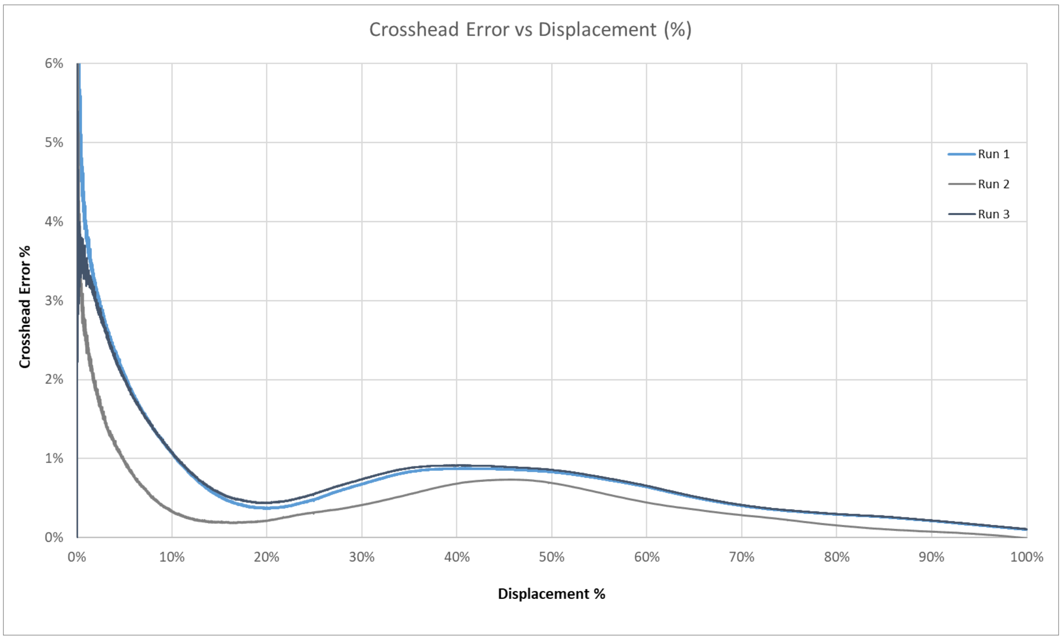


**Figure 7: Fluctuation of the crosshead standard error over the displacement range, as a percentage, for three test runs using the LVDT set-up.**

For the DAQ transfer error, a comparative test run was undertaken using test machine readings as the reference calibration values. The error percentages were calculated for the whole displacement range of the ILFT experiment, and the mean of the percentage errors for the effective displacement range of 20-80% was selected as the relative uncertainty value. This was done for both the load and displacement readings, as both quantities are transferred to the video extensometer through the DAQ unit. It is worth pointing out that the mean divergence in load readings is more than three times higher than those of displacement, resulting in a significant uncertainty contribution altogether.

A summary of uncertainty values for various sources relating to apparatus, derived using the abovementioned process, are presented in Tables 3 and 4. The tables summarise the uncertainty type of each source, together with the probability distribution and the divisor that is assigned according to [1]. The green cells indicate user-defined parameters.

**Table 3: Uncertainty values for apparatus-related sources for the travelling microscope test**

| Source | Value | | Units | Measurement Affected | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor $k_i$ |
|---|---|---|---|---|---|---|---|---|---|
| | absolute | relative | | | | | | | |
| **1. Apparatus** | | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0034% | N | P | 73.032 | N | B | Rectangular | √3 |
| Load Cell Error | 0.13876 | 0.1900% | N | P | 73.032 | N | B | Normal | 2 |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | b | 19.989 | mm | B | Rectangular | √3 |
| Micrometer Error | 0.00008 | 0.0004% | mm | b | 19.989 | mm | B | Normal | 2 |
| Crosshead Resolution | 0.00010 | 0.0011% | mm | δ | 9.275 | mm | B | Rectangular | √3 |
| Crosshead Error | 0.05379 | 0.58% | mm | δ | 9.275 | mm | A | Normal | 1 |
| DAQ Transfer Error | 2.00 | 2.74% | N | P | 73.032 | N | A | Normal | 1 |
| | 0.07420 | 0.80% | mm | δ | 9.275 | nn | A | Normal | 1 |
| Linear Scale Resolution | 0.50000 | 0.9681% | mm | a | 51.645 | mm | B | Rectangular | √3 |

### 4.2.2 Method

As stated previously, the alignment of the specimen in the test machine and the loading rate are two parameters that could potentially lead to uncertainty sources with significant contribution. However, for the purpose of the present study, [2] assumes an aligned test set-up, therefore suggesting that the contribution of said sources, in a compliant test run, would be negligible.

**Table 4: Uncertainty values for apparatus-related sources for the video extensometer test**

| Source | Value | | Units | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor |
|---|---|---|---|---|---|---|---|---|
| | absolute | relative | | | | | | $k_i$ |
| **1. Apparatus** | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0033% | N | 76.758 | N | B | Rectangular | √3 |
| Load Cell Error | 0.14589 | 0.1900% | N | 76.758 | N | B | Normal | 2 |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | 19.983 | mm | B | Rectangular | √3 |
| Micrometer Error | 0.00008 | 0.0004% | mm | 19.983 | mm | B | Normal | 2 |
| Crosshead Resolution | 0.00010 | 0.0009% | mm | 11.332 | mm | B | Rectangular | √3 |
| Crosshead Error | 0.06572 | 0.58% | mm | 11.332 | mm | A | Normal | 1 |
| DAQ Transfer Error | 2.10 | 2.74% | N | 76.758 | N | A | Normal | 1 |
| | 0.09065 | 0.80% | mm | 11.332 | nn | A | Normal | 1 |
| Video Extensometer Resolution | 0.00010 | 0.0002% | mm | 57.938 | mm | B | Rectangular | √3 |
| Video Extensometer Tracking Threshold | 0.06500 | 0.1122% | mm | 57.938 | mm | B | Rectangular | √3 |

For tests in which the travelling microscope was used, there is an additional error source that affects the uncertainty in measuring the crack length. This is the alignment of the linear graticule that is placed on the side of the specimen. Assuming the crack propagates horizontally and parallel to the length of the specimen, any misalignment (angle θ) of the graticule creates an artificial crack length measurement $a_A$, instead of the actual propagated length $a$. By measuring the angle of deviation and applying trigonometry, the actual value can be calculated and the percentage error of the two can be quantified and used as the relative

**Table 5: Uncertainty values for method-related sources for the two types of tests; travelling microscope (top table) and video extensometer (bottom table)**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **2. Method** | | | | | | | | | |
| Alignment | - | - | mm | P,δ | - | N,mm | B | Rectangular | √3 |
| Alignment of lin. scale | 0.00027 | 0.0005% | mm | a | 51.645 | mm | B | Rectangular | √3 |
| Speed | 1.00 | - | mm/min | P,δ | - | N,mm | B | Rectangular | √3 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **2. Method** | | | | | | | | | |
| Alignment | - | - | mm | P,δ | - | N,mm | B | Rectangular | √3 |
| Speed | 1.00 | - | mm/min | P,δ | - | N,mm | B | Rectangular | √3 |

uncertainty value. For measurement of θ, an electronic optical microscopy system has been utilised. Table 5 details the "Method" segment of the budget for the two crack length monitoring methods.

### 4.2.3 Environment

The environmental conditions of the test are other factors that can potentially influence the uncertainty. These are defined by ISO 15024 [2] and as the tests reported here were conducted within the prescribed tolerances for temperature and humidity, and measured throughout, their contribution to uncertainty was considered negligible.

### 4.2.4 Operator

The operator-related uncertainty sources mainly comprise of the ability to extract data from the measured load-displacement curves. Especially for the selection of the NL-point that is used to define the initiation value of $G_{IC}$, the exact pair of load and displacement values relies on the subjectivity of the user deciding when the curve begins to deviate from the linear behaviour it initially exhibits (Figure 8). For this reason, the uncertainty value is derived from the data selections made by four different operators for each test run.

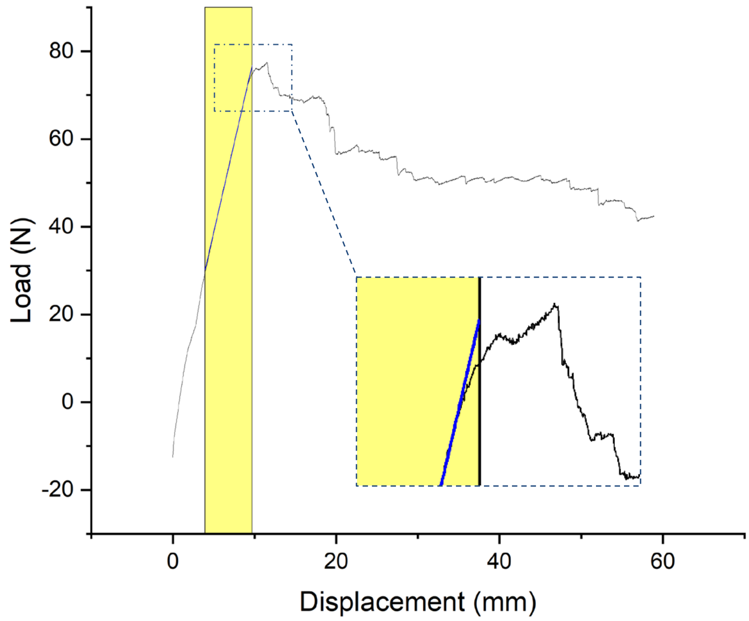


**Figure 8: A typical load-displacement curve with a linear fit and the NL-point region.**

Table 6 shows the calculation of the uncertainty values for the load and displacement for one of the specimens, following the process described.

**Table 6: Calculation of uncertainty for the interpretation of the load-displacement curve.**

| | Operator 1 | Operator 2 | Operator 3 | Operator 4 | Mean | St. Dev | Uncert |
|---|---|---|---|---|---|---|---|
| **Load** | 72.8256 | 73.32 | 73.1552 | 72.8256 | **73.032** | **0.247** | **0.338%** |
| **Displacement** | 9.23581 | 9.33468 | 9.29184 | 9.23581 | **9.275** | **0.048** | **0.518%** |

In addition to the interpretation of the NL-point initiation point, for the case of monitoring the crack length using the travelling microscope operator uncertainty also stems from the definition of the specific crack length value from the available frames. However, since initiation is the chosen crack growth phase for this study, there is minimum variation in the crack length for adjacent datasets and therefore the uncertainty contribution is considered negligible.

**Table 7: Uncertainty values for operator-related sources for the two types of tests; travelling microscope (top table) and video extensometer (bottom table)**

| 4. Operator | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Graph Interpretation | 0.24720 | 0.3385% | N | P | 73.032 | N | A | Normal | 1 |
| | 0.04801 | 0.5177% | mm | δ | 9.275 | mm | A | Normal | 1 |
| Crack Length Interpretation | - | - | mm | a | 51.645 | mm | A | Normal | 1 |

| 4. Operator | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Graph Interpretation | 0.15011 | 0.1955% | N | P | 76.758 | N | A | Normal | 1 |
| | 0.05008 | 0.4420% | mm | δ | 11.332 | mm | A | Normal | 1 |

### 4.2.5 Test Specimen

This category of uncertainty sources relates to the contribution of the various dimensional variations of the specimens and specifically, the width and initial crack length that directly affect the uncertainty of the measurand.

For the calculation of its uncertainty, multiple measurements were taken from multiple operators, in order to account both for the dimensional variation and the operator error in measurement. Table 8 shows an example of this approach:

**Table 8: Calculation of the uncertainty in measuring the width of the specimen**

| | Operator 1 | | | Operator 2 | | | Operator 3 | | | Operator 4 | | | Mean | St. Dev | Uncert |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Width | 19.975 | 19.998 | 19.996 | 19.976 | 19.983 | 19.994 | 19.978 | 19.99 | 19.996 | 19.978 | 20.01 | 19.995 | **19.989** | **0.011** | **0.055%** |

**Table 9: Uncertainty values for specimen-related sources for the two types of tests; travelling microscope (top table) and video extensometer (bottom table)**

| 5. Test Specimen | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Specimen Measurements | 0.01099 | 0.055% | mm | b | 19.989 | mm | A | Normal | 1 |
| Initial Crack Length | 0.01808 | 0.035% | mm | a | 51.645 | mm | B | Rectangular | √3 |

| 5. Test Specimen | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Specimen Measurements | 0.02796 | 0.140% | mm | b | 19.983 | mm | A | Normal | 1 |
| Initial Crack Length | 0.00811 | 0.014% | mm | a | 57.938 | mm | B | Rectangular | √3 |

**Table 10: The complete uncertainty table for traveling microscope tests, prior to the calculation phase**

| Source | Value | | Units | Measurement Affected | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor |
|---|---|---|---|---|---|---|---|---|---|
| | absolute | relative | | | | | | | $k_i$ |
| **1. Apparatus** | | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0034% | N | P | 73.032 | N | B | Rectangular | √3 |
| Load Cell Error | 0.13876 | 0.1900% | N | P | 73.032 | N | B | Normal | 2 |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | b | 19.989 | mm | B | Rectangular | √3 |
| Micrometer Error | 0.00008 | 0.0004% | mm | b | 19.989 | mm | B | Normal | 2 |
| Crosshead Resolution | 0.00010 | 0.0011% | mm | δ | 9.275 | mm | B | Rectangular | √3 |
| Crosshead Error | 0.05379 | 0.58% | mm | δ | 9.275 | mm | A | Normal | 1 |
| DAQ Transfer Error | 2.00 | 2.74% | N | P | 73.032 | N | A | Normal | 1 |
| | 0.07420 | 0.80% | mm | δ | 9.275 | nn | A | Normal | 1 |
| Linear Scale Resolution | 0.50000 | 0.9681% | mm | a | 51.645 | mm | B | Rectangular | √3 |
| **2. Method** | | | | | | | | | |
| Alignment | - | - | mm | P,δ | - | N,mm | B | Rectangular | √3 |
| Alignment of lin. scale | 0.00027 | 0.0005% | mm | a | 51.645 | mm | B | Rectangular | √3 |
| Speed | 1.00 | - | mm/min | P,δ | - | N,mm | B | Rectangular | √3 |
| **3. Environment** | | | | | | | | | |
| Ambient temperature | 20.00 | | °C | P,δ | | N,mm | B | Rectangular | √3 |
| Relative Humidity | | 50% | - | P,δ | | N,mm | B | Rectangular | √3 |
| **4. Operator** | | | | | | | | | |
| Graph Interpretation | 0.24720 | 0.3385% | N | P | 73.032 | N | A | Normal | 1 |
| | 0.04801 | 0.5177% | mm | δ | 9.275 | mm | A | Normal | 1 |
| Crack Length Interpretation | - | - | mm | a | 51.645 | mm | A | Normal | 1 |
| **5. Test Specimen** | | | | | | | | | |
| Specimen Measurements | 0.01099 | 0.055% | mm | b | 19.989 | mm | A | Normal | 1 |
| Initial Crack Length | 0.01808 | 0.035% | mm | a | 51.645 | mm | B | Rectangular | √3 |

**Table 11: The complete uncertainty table for the video extensometer tests, prior to the calculation phase**

| Source | Value | | Units | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor |
|---|---|---|---|---|---|---|---|---|
| | absolute | relative | | | | | | $k_i$ |
| **1. Apparatus** | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0033% | N | 76.758 | N | B | Rectangular | √3 |
| Load Cell Error | 0.14589 | 0.1900% | N | 76.758 | N | B | Normal | 2 |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | 19.983 | mm | B | Rectangular | √3 |
| Micrometer Error | 0.00008 | 0.0004% | mm | 19.983 | mm | B | Normal | 2 |
| Crosshead Resolution | 0.00010 | 0.0009% | mm | 11.332 | mm | B | Rectangular | √3 |
| Crosshead Error | 0.06572 | 0.58% | mm | 11.332 | mm | A | Normal | 1 |
| DAQ Transfer Error | 2.10 | 2.74% | N | 76.758 | N | A | Normal | 1 |
| | 0.09065 | 0.80% | mm | 11.332 | nn | A | Normal | 1 |
| Video Extensometer Resolution | 0.00010 | 0.0002% | mm | 57.938 | mm | B | Rectangular | √3 |
| Video Extensometer Tracking Threshold | 0.06500 | 0.1122% | mm | 57.938 | mm | B | Rectangular | √3 |
| **2. Method** | | | | | | | | |
| Alignment | - | - | mm | - | N,mm | B | Rectangular | √3 |
| Speed | 1.00 | - | mm/min | - | N,mm | B | Rectangular | √3 |
| **3. Environment** | | | | | | | | |
| Ambient temperature | 20.00 | | °C | | N,mm | B | Rectangular | √3 |
| Relative Humidity | | 50% | - | | N,mm | B | Rectangular | √3 |
| **4. Operator** | | | | | | | | |
| Graph Interpretation | 0.15011 | 0.1955% | N | 76.758 | N | A | Normal | 1 |
| | 0.05008 | 0.4420% | mm | 11.332 | mm | A | Normal | 1 |
| **5. Test Specimen** | | | | | | | | |
| Specimen Measurements | 0.02796 | 0.140% | mm | 19.983 | mm | A | Normal | 1 |
| Initial Crack Length | 0.00811 | 0.014% | mm | 57.938 | mm | B | Rectangular | √3 |

## 4.3 CALCULATION OF EXPANDED UNCERTAINTY $U_C$

In this section, the complete process for the calculation of the expanded uncertainty of the mode I interlaminar fracture toughness test is demonstrated in detail, for one of the sources of the budget, which serves as an example to show the process that occurs in the background of the spreadsheet for every source listed.

### 4.3.1 Sensitivity Coefficients

Since the tool operates with relative uncertainty values instead of absolute, this step in the calculation can be excluded as, according to GUM [1], the sensitivity coefficients for relative uncertainties are set to 1.

For the case in which absolute uncertainty values are used, the sensitivity coefficients are calculated as the partial derivative of the selected input quantity with respect to the output quantity.

For example, in the case of the load-related uncertainties this would be:

$$G_{IC} = \frac{3P\delta}{2ba} \quad (1)$$

$$c_P = \frac{\partial G_{IC}}{\partial P} = \frac{3\delta}{2ba} = \frac{3 \times 9.275}{2 \times 19.989 \times 51.645} = 0.013$$

### 4.3.2 Standard Uncertainty contributions

These are calculated for each source according to Equations (2) and (3), with data from Tables 10 and 11.

For example, the standard uncertainty contribution of the load cell resolution would be:

$$u(x_{LCRes}) = \frac{0.0034}{\sqrt{3}} = 0.0020\%$$

$$u_{LCRes} = u(x_{LCRes}) \times c_P = 0.0020 \times 1 = 0.0020\%$$

and so, the rest of the contributions are calculated for the listed uncertainty sources, as shown in Tables 12 and 13, for the test cases using a travelling microscope and video extensometer.

**Table 12: Calculated standard uncertainty contributions for the travelling microscope test runs.**

| Source | Standard Uncertainty $u(x_i)$ | | Sensitivity Coefficient $c_i$ | Uncertainty Contribution $u_i$ |
|---|---|---|---|---|
| | absolute | relative | | |
| **1. Apparatus** | | | | |
| Load Cell Resolution | 0.001 | 0.0020% | 1 | 0.0020% |
| Load Cell Error | 0.069 | 0.10% | 1 | 0.0950% |
| Micrometer Resolution | 0.006 | 0.03% | 1 | 0.0289% |
| Micrometer Error | 0.000 | 0.00% | 1 | 0.0002% |
| Crosshead Resolution | 0.000 | 0.00% | 1 | 0.0006% |
| Crosshead Error | 0.054 | 0.58% | 1 | 0.5800% |
| DAQ Transfer Error | 2.001 | 2.74% | 1 | 2.7400% |
| | 0.074 | 0.80% | 1 | 0.8000% |
| Linear Scale Resolution | 0.289 | 0.56% | 1 | 0.5590% |
| **2. Method** | | | | |
| Alignment | | | | *negligible* |
| Alignment of lin. scale | 0.000 | 0.00% | 1 | 0.0003% |
| Speed | | | | *negligible* |
| **3. Environment** | | | | |
| Ambient temperature | | | | *negligible* |
| Relative Humidity | | | | *negligible* |
| **4. Operator** | | | | |
| Graph Interpretation | 0.247 | 0.34% | 1 | 0.3385% |
| | 0.048 | 0.52% | 1 | 0.5177% |
| Crack Length Interpretation | | | | *negligible* |
| **5. Test Specimen** | | | | |
| Specimen Measurements | 0.011 | 0.06% | 1 | 0.0550% |
| Initial Crack Length | 0.010 | 0.02% | 1 | 0.0202% |

**Table 13: Calculated standard uncertainty contributions for the video extensometer runs.**

| Source | Standard Uncertainty $u(x_i)$ | | Sensitivity Coefficient $c_i$ | Uncertainty Contribution $u_i$ |
|---|---|---|---|---|
| | absolute | relative | | |
| **1. Apparatus** | | | | |
| Load Cell Resolution | 0.001 | 0.00% | 1 | 0.0012% |
| Load Cell Error | 0.111 | 0.10% | 1 | 0.0950% |
| Micrometer Resolution | 0.006 | 0.03% | 1 | 0.0289% |
| Micrometer Error | 0.000 | 0.00% | 1 | 0.0002% |
| Crosshead Resolution | 0.000 | 0.00% | 1 | 0.0005% |
| Crosshead Error | 0.066 | 0.58% | 1 | 0.5800% |
| DAQ Transfer Error | 3.200 | 2.74% | 1 | 2.7400% |
| | 0.091 | 0.80% | 1 | 0.8000% |
| Video Extensometer Resolution | 0.000 | 0.00% | 1 | 0.0001% |
| Video Extensometer Tracking Threshold | 0.038 | 0.06% | 1 | 0.0648% |
| **2. Method** | | | | |
| Alignment | | | | *negligible* |
| Speed | | | | *negligible* |
| **3. Environment** | | | | |
| Ambient temperature | | | | *negligible* |
| Relative Humidity | | | | *negligible* |
| **4. Operator** | | | | |
| Graph Interpretation | 0.228 | 0.20% | 1 | 0.1955% |
| | 0.050 | 0.44% | 1 | 0.4420% |
| **5. Test Specimen** | | | | |
| Specimen Measurements | 0.028 | 0.14% | 1 | 0.1399% |
| Initial Crack Length | 0.005 | 0.01% | 1 | 0.0081% |

### 4.3.3 Combined Standard Uncertainty

For the calculation of the combined standard uncertainty, the Law of Propagation (Eq. 4) is used, meaning the square root of the sum of the squared values of the individual standard uncertainty contributions. That would be:

- For travelling microscope test runs:

$$u_c = \sqrt{u_{LCRes}^2 + u_{LCErr}^2 + u_{MRes}^2 + u_{MErr}^2 + u_{CRes}^2 + u_{CErr}^2 + u_{DAQ}^2 + u_{LSRes}^2}$$

$$+ \sqrt{u_{LSAl}^2 + u_{GIP}^2 + u_{GI\delta}^2 + u_{SpMb}^2 + u_{SpMa0}^2} = \mathbf{3.032}\%$$

- For video extensometer runs:

$$u_c = \sqrt{u_{LCRes}^2 + u_{LCErr}^2 + u_{MRes}^2 + u_{MErr}^2 + u_{CRes}^2 + u_{CErr}^2 + u_{DAQ}^2 + u_{iMRes}^2 + u_{iMTT}^2}$$

$$+ \sqrt{u_{GIP}^2 + u_{GI\delta}^2 + u_{SpMb}^2 + u_{SpMa0}^2} = \mathbf{2.958}\%$$

### 4.3.4 Effective Degrees of Freedom and Coverage Factor

The degrees of freedom (DoF) for each individual uncertainty source are assigned based on their uncertainty type (A or B). For Type A uncertainties, the DoF are one less than the number of the repeated measurements or trials made. For Type B, they are assumed to be infinite, due to the confidence shown in the definition of their uncertainty values (calibration certificates, manufacturer specification etc).

As previously stated, the effective DoF are calculated by using the Welch-Satterthwaite formula (Eq. 5). This is also within the capabilities of the budget tool and for the two test runs the results are:

| | Travelling microscope | Video extensometer |
|---|---|---|
| **$v_{eff}$** | 2.968 | 2.691 |

And since the DoF quantity must be an integer, for both cases they were set **equal to 3**.

For the estimation of the coverage factor, a confidence level must first be chosen. For the purpose of this study, a 95% confidence level was selected and therefore, the coverage factor is derived from the 2.5th percentile of a Student's t-distribution with $\nu = \nu_{eff} = 3$.

The coverage factor is $\boldsymbol{k} = \mathbf{3.18}$.

### 4.3.5 Expanded Uncertainty

The last step in the calculation of the measurands uncertainty is that of the expanded uncertainty $U_C$, which is derived by the multiplication of the combined standard uncertainty with the coverage factor.

**Table 14: Results of the uncertainty budget for both test runs.**

| | | Video Extensometer | Travelling Microscope |
|---|---|---|---|
| Combined Standard Uncertainty | $u_c$ | 2.958% | 3.032% |
| Effective Degrees of Freedom | $\nu_{eff}$ | 3 | |
| Coverage Factor | $k$ | 3.18 | |
| Expanded Uncertainty | $U_c$ | 9.407% | 9.641% |

## 4.4 REPORTING THE UNCERTAINTY OF $G_{IC}$

- For the travelling microscope runs

$$G_{IC} = 984.18 \frac{J}{m^2} \pm 94.89 \frac{J}{m^2} \quad (9.64\%)$$

*The reported expanded uncertainty is calculated by multiplying the combined uncertainty with a coverage factor $k = 3.18$, corresponding to a confidence level of 95%.*

*This evaluation was carried out according to the Guide to the Expression of Uncertainty in Measurement (GUM) [1].*

- For the video extensometer runs

$$G_{IC} = 1127.31 \frac{J}{m^2} \pm 106.05 \frac{J}{m^2} \quad (9.41\%)$$

*The reported expanded uncertainty is calculated by multiplying the combined uncertainty with a coverage factor $k = 3.18$, corresponding to a confidence level of 95%.*

*This evaluation was carried out according to the Guide to the Expression of Uncertainty in Measurement (GUM) [1].*

**Table 15: The Uncertainty budget through the spreadsheet tool for the travelling microscope test runs**

| Sources of Uncertainty | | | | Measurements | | Uncertainties | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Value | | Units | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor | Standard Uncertainty $u(x_i)$ | | Sensitivity Coefficient $c_i$ | Uncertainty Contribution $u_i$ | Degrees of Freedom $\nu_i$ |
| | absolute | relative | | | | | | $k_i$ | absolute | relative | | | |
| **1. Apparatus** | | | | | | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0034% | N | 73.032 | N | B | Rectangular | √3 | 0.001 | 0.0020% | 1 | 0.0020% | ∞ |
| Load Cell Error | 0.13876 | 0.1900% | N | 73.032 | N | B | Normal | 2 | 0.069 | 0.10% | 1 | 0.0950% | ∞ |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | 19.989 | mm | B | Rectangular | √3 | 0.006 | 0.03% | 1 | 0.0289% | ∞ |
| Micrometer Error | 0.00008 | 0.0004% | mm | 19.989 | mm | B | Normal | 2 | 0.000 | 0.00% | 1 | 0.0002% | ∞ |
| Crosshead Resolution | 0.00010 | 0.0011% | mm | 9.275 | mm | B | Rectangular | √3 | 0.000 | 0.00% | 1 | 0.0006% | ∞ |
| Crosshead Error | 0.05379 | 0.58% | mm | 9.275 | mm | A | Normal | 1 | 0.054 | 0.58% | 1 | 0.5800% | 2 |
| DAQ Transfer Error | 2.00 | 2.74% | N | 73.032 | N | A | Normal | 1 | 2.001 | 2.74% | 1 | 2.7400% | 2 |
| | 0.07420 | 0.80% | mm | 9.275 | nn | A | Normal | 1 | 0.074 | 0.80% | 1 | 0.8000% | 2 |
| Linear Scale Resolution | 0.50000 | 0.9681% | mm | 51.645 | mm | B | Rectangular | √3 | 0.289 | 0.56% | 1 | 0.5590% | ∞ |
| **2. Method** | | | | | | | | | | | | | |
| Alignment | - | - | mm | - | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| Alignment of lin. scale | 0.00027 | 0.0005% | mm | 51.645 | mm | B | Rectangular | √3 | 0.000 | 0.00% | 1 | 0.0003% | ∞ |
| Speed | 1.00 | - | mm/min | - | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **3. Environment** | | | | | | | | | | | | | |
| Ambient temperature | 20.00 | | °C | | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| Relative Humidity | | 50% | - | | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| **4. Operator** | | | | | | | | | | | | | |
| Graph Interpretation | 0.24720 | 0.3385% | N | 73.032 | N | A | Normal | 1 | 0.247 | 0.34% | 1 | 0.3385% | 3 |
| | 0.04801 | 0.5177% | mm | 9.275 | mm | A | Normal | 1 | 0.048 | 0.52% | 1 | 0.5177% | 3 |
| Crack Length Interpretation | - | - | mm | 51.645 | mm | A | Normal | 1 | | | | *negligible* | 3 |
| **5. Test Specimen** | | | | | | | | | | | | | |
| Specimen Measurements | 0.01099 | 0.055% | mm | 19.989 | mm | A | Normal | 1 | 0.011 | 0.06% | 1 | 0.0550% | 11 |
| Initial Crack Length | 0.01808 | 0.035% | mm | 51.645 | mm | B | Rectangular | √3 | 0.010 | 0.02% | 1 | 0.0202% | ∞ |

| INPUT | VALUE | UNIT |
|---|---|---|
| **Load, P** | 73.032 | N |
| **Displacement, δ** | 9.275 | mm |
| **Width, b** | 19.989 | mm |
| **Crack Length, α** | 51.645 | mm |

| MEASURAND | VALUE | UNIT |
|---|---|---|
| **ILFT, $G_{IC}$** | 984.18 | J/m^2 |
| **$U_C$** | **94.89** | J/m^2 |

| | | |
|---|---|---|
| **Combined Standard Uncertainty** | $u_c$ | **3.032%** |
| **Effective Degrees of Freedom** | $\nu_{eff}$ | **3** |
| **Coverage Factor** | $k$ | **3.18** |
| **Expanded Uncertainty** | $U_c$ | **9.64%** |

**Table 16: The Uncertainty budget through the spreadsheet tool for the video extensometer test**

| Sources of Uncertainty | | | | Measurements | | Uncertainties | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | Value | | Units | Nominal or Averaged Value | Units | Type | Probability Distribution | Divisor | Standard Uncertainty $u(x_i)$ | | Sensitivity Coefficient $c_i$ | Uncertainty Contribution $u_i$ | Degrees of Freedom $\nu_i$ |
| | absolute | relative | | | | | | $k_i$ | absolute | relative | | | |
| **1. Apparatus** | | | | | | | | | | | | | |
| Load Cell Resolution | 0.00250 | 0.0033% | N | 76.758 | N | B | Rectangular | √3 | 0.001 | 0.00% | 1 | 0.0012% | ∞ |
| Load Cell Error | 0.14589 | 0.1900% | N | 76.758 | N | B | Normal | 2 | 0.111 | 0.10% | 1 | 0.0950% | ∞ |
| Micrometer Resolution | 0.01000 | 0.0500% | mm | 19.983 | mm | B | Rectangular | √3 | 0.006 | 0.03% | 1 | 0.0289% | ∞ |
| Micrometer Error | 0.00008 | 0.0004% | mm | 19.983 | mm | B | Normal | 2 | 0.000 | 0.00% | 1 | 0.0002% | ∞ |
| Crosshead Resolution | 0.00010 | 0.0009% | mm | 11.332 | mm | B | Rectangular | √3 | 0.000 | 0.00% | 1 | 0.0005% | ∞ |
| Crosshead Error | 0.06572 | 0.58% | mm | 11.332 | mm | A | Normal | 1 | 0.066 | 0.58% | 1 | 0.5800% | 2 |
| DAQ Transfer Error | 2.10 | 2.74% | N | 76.758 | N | A | Normal | 1 | 3.200 | 2.74% | 1 | 2.7400% | 2 |
| | 0.09065 | 0.80% | mm | 11.332 | nn | A | Normal | 1 | 0.091 | 0.80% | 1 | 0.8000% | 2 |
| Video Extensometer Resolution | 0.00010 | 0.0002% | mm | 57.938 | mm | B | Rectangular | √3 | 0.000 | 0.00% | 1 | 0.0001% | ∞ |
| Video Extensometer Tracking Threshold | 0.06500 | 0.1122% | mm | 57.938 | mm | B | Rectangular | √3 | 0.038 | 0.06% | 1 | 0.0648% | ∞ |
| **2. Method** | | | | | | | | | | | | | |
| Alignment | - | - | mm | - | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| Speed | 1.00 | - | mm/min | - | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **3. Environment** | | | | | | | | | | | | | |
| Ambient temperature | 20.00 | | °C | | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| Relative Humidity | | 50% | - | | N,mm | B | Rectangular | √3 | | | | *negligible* | ∞ |
| **4. Operator** | | | | | | | | | | | | | |
| Graph Interpretation | 0.15011 | 0.1955% | N | 116.785 | N | A | Normal | 1 | 0.228 | 0.20% | 1 | 0.1955% | 3 |
| | 0.05008 | 0.4420% | mm | 11.332 | mm | A | Normal | 1 | 0.050 | 0.44% | 1 | 0.4420% | 3 |
| **5. Test Specimen** | | | | | | | | | | | | | |
| Specimen Measurements | 0.02796 | 0.140% | mm | 19.983 | mm | A | Normal | 1 | 0.028 | 0.14% | 1 | 0.1399% | 11 |
| Initial Crack Length | 0.00811 | 0.014% | mm | 57.938 | mm | B | Rectangular | √3 | 0.005 | 0.01% | 1 | 0.0081% | ∞ |

| INPUT | VALUE | UNIT |
|---|---|---|
| **Load, P** | 76.78475 | N |
| **Displacement, δ** | 11.33175 | mm |
| **Width, b** | 19.983 | mm |
| **Crack Length, α** | 57.9375 | mm |

| MEASURAND | VALUE | UNIT |
|---|---|---|
| **ILFT, $G_{IC}$** | 1127.308 | J/m^2 |
| **$U_C$** | 106.048 | J/m^2 |

| | | |
|---|---|---|
| **Combined Standard Uncertainty** | $u_c$ | **2.958%** |
| **Effective Degrees of Freedom** | $\nu_{eff}$ | **3** |
| **Coverage Factor** | $k$ | **3.18** |
| **Expanded Uncertainty** | $U_c$ | **9.4%** |

## 5 CONCLUSIONS AND FUTURE WORK

In this report, the operation of an uncertainty budget calculation tool has been described in detail. In this first iteration of the tool, the execution has been performed via an Excel spreadsheet, where the key features and capabilities were realised and tested.

For the test purposes, an interlaminar fracture toughness experiment was adopted and more specifically, two methods for measuring crack length were applied to further highlight the effect of digitalisation in the evaluation of the measurement uncertainty. The tool has successfully been demonstrated in calculating the uncertainty for both test runs and has provided a proof of concept for the next version to build-up on.

Regarding the evolution of the tool, it is anticipated that the Uncertainty Budget Tool will eventually develop into a standalone piece of software, capable of closely and directly linking multiple digital resources and allowing for faster and more efficient uncertainty budget calculations. A significant milestone towards that goal would be the incorporation of the tool with the Laboratory Information Management System (LIMS) that will be implemented throughout the National Physical Laboratory's Mechanical Testing Facility (MTF).

LIMS will provide central storage for the calibration certificates of the test equipment used in mechanical test measurements. This will allow the user to select the applicable equipment for each test set-up and subsequently acquire the relevant calibration information, so that the derived uncertainty values can automatically be added into the uncertainty budget.

For equipment where the uncertainty is the same across the entire measurement range, such as micrometres and vernier callipers, this should involve a simple script. However, it is also anticipated that where the uncertainty is not uniform across the entire range of the measurement device, such as for a load cell, the uncertainty budget tool will be able to calculate an uncertainty based on the measurement range of the test.

Apart from calibration information, LIMS will record and store information on the laboratory environment including temperature and humidity. This will enable the user to ensure that the measurement takes place in an environment which is either compliant with the relevant standard or in agreement with customer specifications.

LIMS will also store past-experimental data, including images and logs of the equipment used. This will enable users to maintain a consistent approach to testing and reduce the possibility of increased uncertainty as a result of user error. The results of previous tests will be stored in LIMS in an easily accessible way so that cumulative uncertainty based on an increasing number of tests can be utilised, if appropriate.

## 6 REFERENCES

[1] BIPM, IEC, IFC, ILAC, ISO, IUPAC, IUPAP and OIML, *Evaluation of data – Guide to the expression of uncertainty in measurement (GUM:1995 with minor corrections)*, Bureau International des Poids et Mesures, JCGM 100:2008

[2] BS ISO 15024:2001, *Fibre-reinforced plastic composites – Determination of the mode I interlaminar fracture toughness $G_{IC}$, for unidirectionally reinforced materials*, 2001

[3] BS ISO 7500-1:2018, *Metallic materials - Calibration and verification of static uniaxial testing machines - Part 1: Tension/compression testing machines - Calibration and verification of the force-measuring system*, 2018

[4] *Procedure for evaluating measurement uncertainty in mechanical testing*, National Physical Laboratory, 2020

[5] *SM&T Manual of Codes of Practice for the determination of uncertainties in mechanical tests on metallic materials*, Project UNCERT, EU Contract SMT4-CT97-2165, Standards Measurement & Testing Programme, 2000

## APPENDIX

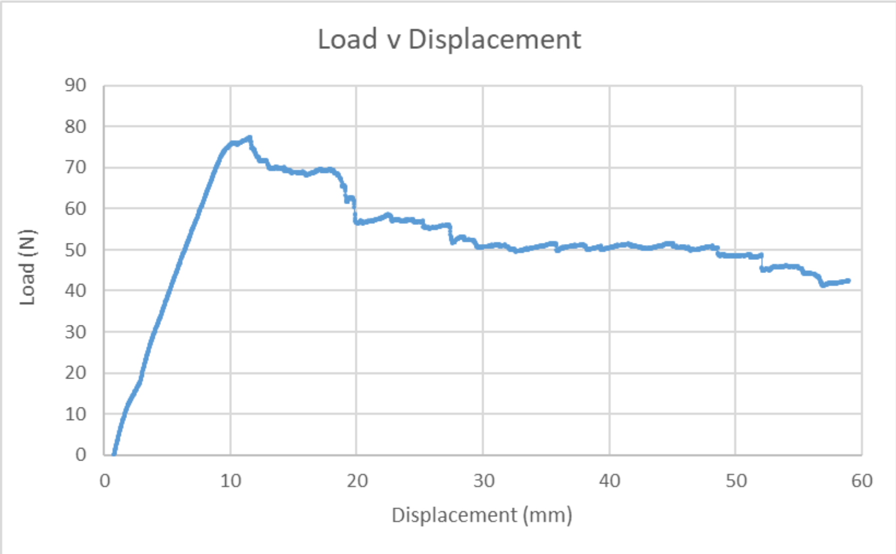


**Figure 9: The load-displacement curve for the travelling microscope (TM) test run of this study.**

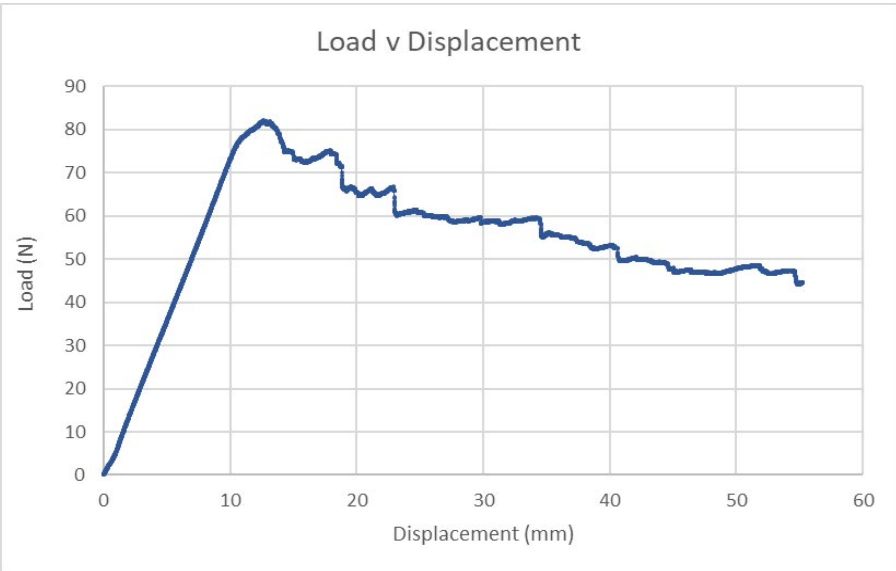


**Figure 10: The load-displacement curve for the video extensometer test run of this study.**

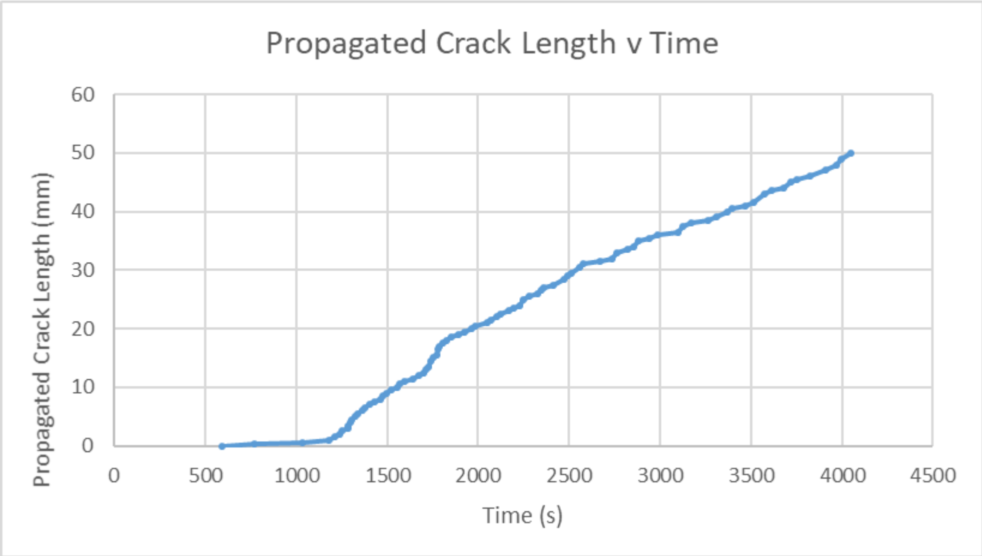


**Figure 11: The propagated crack length vs. time curve for the travelling microscope (TM) test run of this study.**

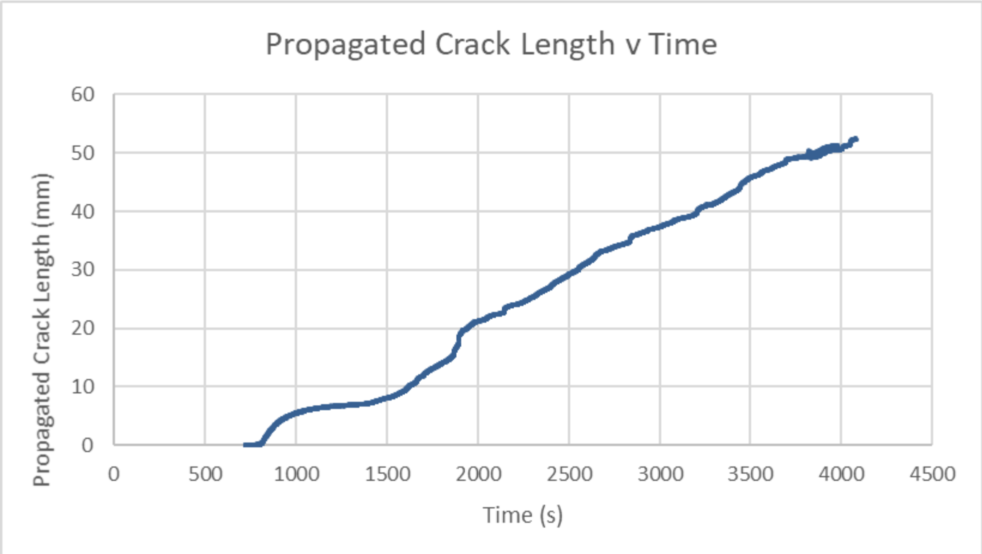


**Figure 12: The propagated crack length vs. time curve for the video extensometer test run of this study.**