

QUANTIFYING RISK OF CLASSIFICATION OF PROTECTIVE TEXTILES USING MEASUREMENT UNCERTAINTY

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Abstract: *Laboratories executing performance testing of protective textiles (e.g., CE marking of protective gloves) are obliged to evaluate measurement uncertainty. Currently, this is a challenging task due to the complexity of test methods. In our research, we define this parameter using a newly implemented model of error propagation and use it to assess the risk of performance level classification, which can be interpreted as the proportion of products failing to reach the expected limit value.*

Keywords: *TDM test method, measurement uncertainty, error propagation model, CE marking*

INTRODUCTION

Conformity assessment of protective gloves against mechanical risks includes determination of resistance to cutting by sharp objects (TDM test method), which is described by the standard ISO 13997:1999. The protective equipment's level of performance is defined and classified by the test results. Limit values concerning this product type are specified in the standard EN 388:2016.

The previously unspecified uncertainty values which have been determined during our research are not only informative but also can be used as an indicator of the test method's efficiency as well as for the improvement of components of the measuring system.

THE TEST METHOD AND ITS MEASUREMENT UNCERTAINTY

Principle of test method [1]

One of the appropriate methods is described by the standard ISO 13997:1999, which defines its result by the force that is required to be applied perpendicularly to a blade to cut through the protective material in a blade stroke of length 20 mm.

- After the specimens are mounted on a curved specimen holder, the intact part of the blade is pushed forward while a specified force is being applied to it.
- A blade sharpness correction factor has to be calculated for blades of the same batch by cutting a neoprene calibration material.

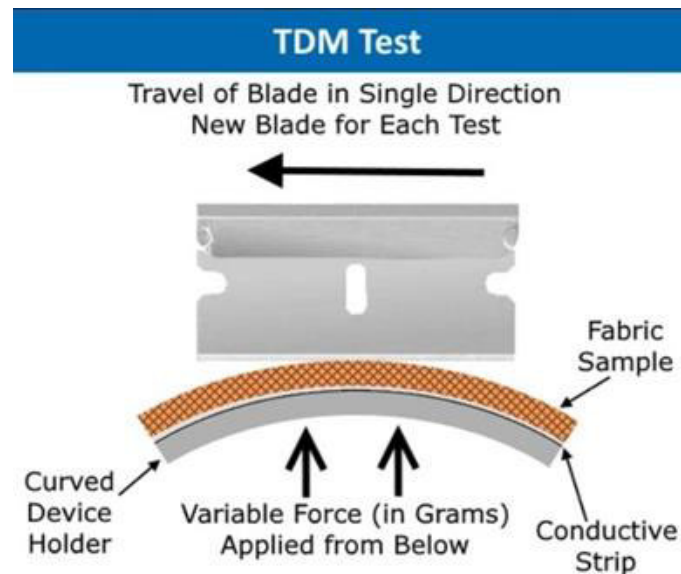


Figure 1: Schematic drawing of the execution of TDM test method

- Test results are multiplied by the correction factor of the respective batch of blades, determining “normalized cutting stroke lengths”. Theoretically, this makes the results comparable with each other, regardless of the manufacturing characteristics of the blade batch. Then, the test procedure continues mostly graphically.
- Normalized cutting stroke lengths are placed on a diagram as a function of the pressure force applied.
- Consequently, the best-fit regression curve is chosen and drawn. (According to the current standard test method, this is a free choice, although a factor of uncertainty in itself.)
- In two turns, adding data from new measurements for improving statistical reliability, the cutting force at the cutting force length of 20 mm is determined using the regression equation of the curve.
- The level of performance of the protective equipment under examination can be defined using this value, following the limit values prescribed in a table of the harmonized standard.

Contributions to measurement uncertainty and error propagation

Measurement uncertainty is a parameter that is bound integrally to the result of the measurement and shows the natural variance of the series of measurements around the true value of a quantity.⁴ According to ISO/IEC 17025:2017, an accredited laboratory shall analyze and evaluate (but at least estimate) all significant contributions to measurement uncertainty of each and every test procedure used, using an appropriate method. [2]

If test results are given indirectly, using several different measured values and arithmetic calculations (e.g., determination of density by dividing the results of the mass and volume measurements), the error of each measurement result propagates to the calculated results. Using

⁴ JCGM 200:2012 International vocabulary of metrology – Basic and general concepts and associated terms

the function which specifies the correlation between input values and outputs makes it possible to define the result's deviation caused by the change in input values (in this case, the value of random error). The propagation of the u values during the test procedure can therefore be monitored by means of differential calculus. [3]

Interpreting the measuring system of the TDM method as a theoretical measuring element

Distinct units of the measuring system can be summarized as follows:

- specimen holder with the specimen mounted and a circuit detecting cut-through of the specimen,
- blade cutting through the specimen,
- force application system providing constant force between the cutting edge and the specimen,
- cutting-motion system moving the specimen holder and the cutting edge relative to each other and a cut-stroke length measurement system.

To determine the measurement result (as it is described in Chapter x.y), individual series of measurements are performed executing cutting using different forces of the load to achieve cut-through. During the procedure, readings are being done about the length of displacement required to perfect cut-through (dependent variable). Due to the reasons previously described, these lengths show variance, meaning the final result of the measurement is a value of distance, which is the sum of cutting stroke length and random errors at a distinctly set force value. By marking direct measurement results with data points in the diagram, cutting stroke lengths are assigned to the distinct values of force (see regression diagrams later on).

The model of operation of measuring transducers can be represented by a regression curve, reflecting a clear relationship between the set (x) and resulting (y) values. The regression diagram defined should be interpreted as a static characteristic of a transducer's behaviour. In the case of the TDM test method, on account of the velocity of the movement of the cutting edge ($2,5 \pm 0,5$ mm/s) the measurement process is just quasistatic, but this is considered to be one of the disregarded measuring conditions which may be scientifically examined later on but is a fixed data currently due to the standard test method.

Therefore, the "behavior" of our measuring system is expressed by a characteristic curve. To analyze the question, we should consider and use this equation as the "black box" of the measuring system, avoiding the detailed analysis of technically identifiable uncertainty contributions individually.

Identifying the basic concept of the problem

Following the standard principle of testing procedure: "The sample's resistance to cutting by sharp objects is expressed by a cutting force, which is required to be applied to a blade to just

cut through a material in a blade stroke length of 20 mm.”⁵ The sample to be qualified is classified by levels of performance based on this cutting force.

However, cutting force is determined indirectly, using the depiction of cutting stroke lengths produced by different loads and their regression function. Therefore each and every measured value is influenced by all uncertainty contributions caused by the parts of the measuring system.

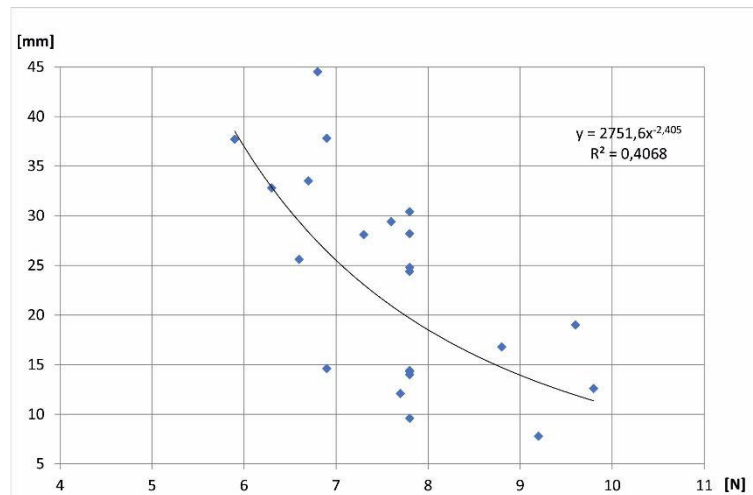


Figure 2: Diagram of the measurement results of a TDM test procedure, with a power regression curve

CALCULATION OF UNCERTAINTY OF THE TDM TEST METHOD USING ERROR PROPAGATION MODEL

In our research, the cumulative effect of each factor is quantified by determining the test procedure’s combined measurement uncertainty.

To define the value of standard uncertainty (u) and the risk of classification, the following steps were specified by our method.

- 1./ Determination of cutting stroke lengths as a function of a certain load force, using the respective batch of blades on the neoprene calibration material.
- 2./ Using the cutting stroke lengths carrying uncertainties, the standard uncertainty (“ u ”) propagating to the correction factor is determined.
- 3./ Multiplying cutting stroke lengths measured on the test specimen and the known correction factor (which is subject to error) gives the standard uncertainty of linearly connected cutting stroke lengths.

⁵ ISO 13997:1999 Protective clothing — Mechanical properties — Determination of resistance to cutting by sharp objects

- 4./ Knowing the standard uncertainty of normalized cutting stroke lengths, applying the model of error propagation, the uncertainty of the pressure force originating from the regression curve at a given constant (20 mm).

When expressing uncertainty, the basic concept is that the results of length measurement and their content of error at a set load force follow a mathematical distribution due to their randomness. On account of the complexity of the manufacturing processes of the blades, the neoprene and the test samples to be measured on the one hand, and given the various distortive effects of the measurement process, on the other hand, it is safe to assume that in case of a larger number of influencing factors the central limit theorem applies. [4] Taking this into account, measurement results approach a normal distribution. Measurement uncertainty, which can be identified as the random error of measured values, should be a good estimate to be considered equal. However, according to the test procedure's present conditions, this range is estimated through the residual standard deviation of the points deviated from the known regression curve. Naturally, this assumption must be tested with accurate analysis in a validation procedure.

- One of the two factors is the determination of the correction coefficient, in which case the variance of the blade and the calibration neoprene applies.
- The other factor is the measurement series performed on the specimen, where the deviations are caused by the variance of the blade and the test sample.

Therefore, the deviations originated from the previous two factors will be propagating as the random error throughout the calculations performed during the evaluation of the measurement results, as it is prescribed by the test method. Finally, these deviations sum up as the value of combined measurement uncertainty.

An error of the correction factor's determination

The correction factor is defined by repeated measurements, whereby random deviations of the measuring instrument (blade) and the measurand (calibration neoprene) applies the same way as it was stated before. Also, other incidental uncertainty contributions might have an impact as well, so the correction factor possesses its own measurement uncertainty. The correction factor of the respective batch of blades is calculated by using the following equation:

$$C = \frac{20}{\bar{l}_c}$$

where

- C is the correction factor [-],
- $\bar{l}_c$ is the average of the measured cutting stroke lengths [mm],

Indicating the measured data (which was acquired by a previous calibration of a blade batch) as a function, it is apparent that the standard deviation (s) of the measured cutting stroke lengths

- meaning their Type A standard uncertainty ($u=s$) - inflicts a quantifiable uncertainty in the value of the correction factor.

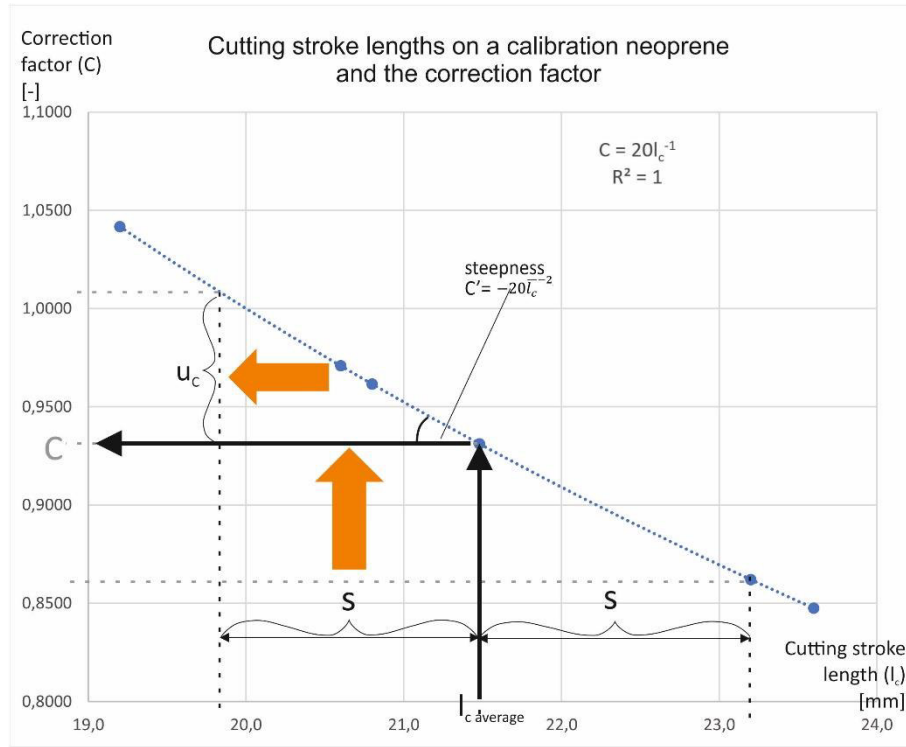


Figure 3: Error propagation applied to the determination of the correction factor (example)

According to the model describing the correlation, the standard deviation of cutting stroke lengths causes a standard uncertainty propagating to the correction factor, depending on the slope of the function. The slope of the function (thus the extent of propagation) is defined by deriving the regression curve:

$$C = 20 \cdot l_c^{-1}$$

$$C' = -20 \cdot l_c^{-2}$$

As a result, the standard uncertainty (u_c) of the correction factor originated from the measured lengths is defined by the following equation:

$$u_c = s_l \cdot (-20 l_c^{-2})$$

An error of the determination of normalized cutting stroke lengths

Normalized⁶ cutting stroke lengths (l_n) are defined following the test procedure: the measured and recorded cutting stroke lengths (l_m) are multiplied by the correction factor indicating the sharpness of the blade (C), meaning

$$l_n = l_m \cdot C$$

According to our estimations, the value l_{meas} displayed by the measuring device is not subject to significant error on the part of the measuring equipment or the environment. However, the standard uncertainty of the preciously determined correction factor (u_c) propagates linearly to the normalized cutting stroke lengths, as it is shown on the figure down below.

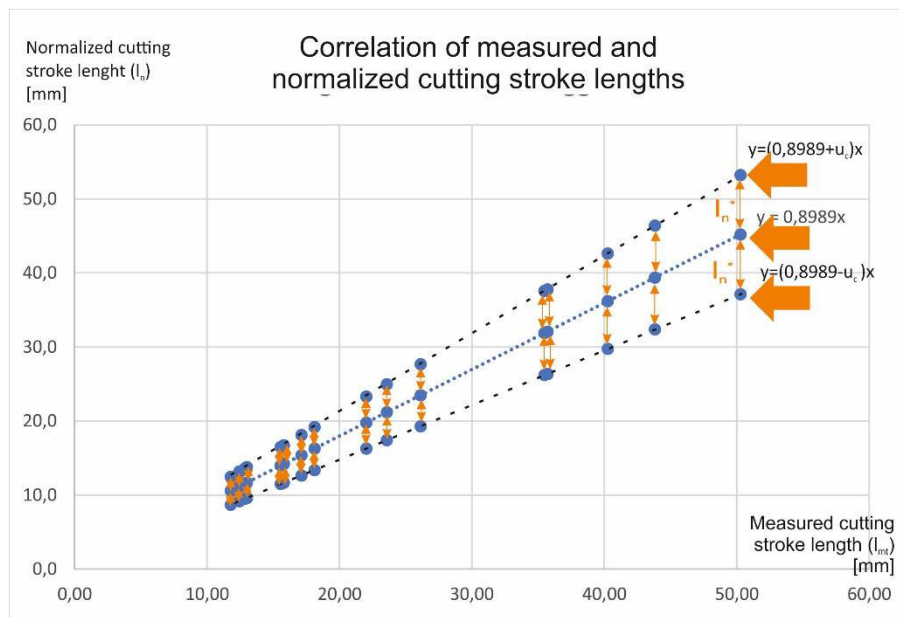


Figure 4: Propagation of error of the determination of normalized cutting stroke lengths

The l_n 'values subject to error are define by the following equation:

$$l_n^* = (C \pm u_c) \cdot l_m$$

The values l_n^* and l_n change linearly, therefore the uncertainty of determining the normalized cutting stroke lengths is identified by averaging the elements on both ends or the known ones in between (u_{ln}):

⁶ Normalization of cutting stroke lengths means multiplying by the correction factor, according to the terminology used in ISO 13997:1999.

$$u_{ln} = \frac{\sum_{i=1}^n |l_{ni}^* - l_{ni}|}{2n}$$

This random error is estimated by the measurements of the correction factor and can be considered general; it propagates to each and every normalized cutting stroke length. When estimating u_{ln} , only half of the absolute linear deviation values are taken into account, as the extent of the variance here includes deviations further from the regression curve.

Regression curves and the related calculations

According to the standard procedure, the best fit curve shall be drawn of the force-cutting stroke length point pairs, which enables to calculate of the cutting force at a cutting stroke length of 20 mm.

The regression equation represents the correlation between the load force and its inflicted cutting stroke length, as it has been elaborated at the idea of the theoretical measuring transducer. Therefore, during the following steps of the test procedure, our calculations will be based on this function (as a conceptual static characteristic), using the possibilities given by the model of error propagation on uncertain variables and the connecting uncertainty values.

When the model of error propagation was being made, an example of a frequently used power function was used. Nevertheless, by using the following method, the principle presented can be applied to other functional relationships as well.

Uncertainty of the regression curve

As the next step of the test procedure, we need to quantify the deviations (“errors”) compared to the regression curve to represent the variation of measurement results on the final test result. For this purpose, the residual standard deviation (S_r) of the experimental pair of value is used, which is calculated by using the following equation:

$$S_{r1} = \sqrt{\frac{\sum_{i=1}^n (l_{ni} - \widehat{l_{ni}})^2}{n-2}}, \text{ where}$$

- l_{ni} normalized cutting stroke lengths determined by “real” measurements (indicating as a function of load force used for the measurement),
- $\widehat{l_{ni}}$ the cutting stroke lengths belonging to the respective load forces, estimated by the regression equation
- n the number of measurements.

The uncertainty components expounded in the previous chapters (l_n and C) are randomly combined, therefore, their standard deviation sums up given the square root of the sum of their variance. That is why the combined uncertainty of the regression curve (u_{r1}) arises from the sum of squares of the two deviation values:

$$u_{r1} = \sqrt{u_{ln}^2 + S_{r1}^2}$$

The u_{r1} value continues to be expressed in the dimension of cutting stroke lengths [mm].

The propagation of the error of cutting stroke lengths onto the cutting force

The test procedure's following step is to calculate the cutting force value belonging to a cutting stroke length of 20 mm, using the regression curve. This propagates the random error applicable to the previously determined cutting stroke lengths, to the value of the cutting force. The way to do this is also determined by the functional relationship described by the equation.

In the series of test procedures that were used as an example for our analysis, the approximation was made with a power function, so the general equation of the correlation (F_v still indicating the cutting force and l_n stands for cutting stroke lengths): Parameters a and b apply to the respective test samples in question in case of a power regression.

$$F_1(l_n) = a \cdot F_v^b$$

The figure below illustrates through the measurement results of an actual TDM test procedure how the deviation (u_r) determined on the vertical axis is projected on the horizontal axis. The error arisen on axis y propagates to axis x. The steeper the part of the curve coming from the y-axis (subject to an error of a given size), the smaller the error propagating to the x-axis will be. Consequently, if we know the measurement uncertainty of the input characteristic (cutting stroke length) (u_r), and the steepness of the curve $-l(F)^{-}$, we are able to calculate the output characteristic's (cutting force) error and standard uncertainty (u_{Fv1}).

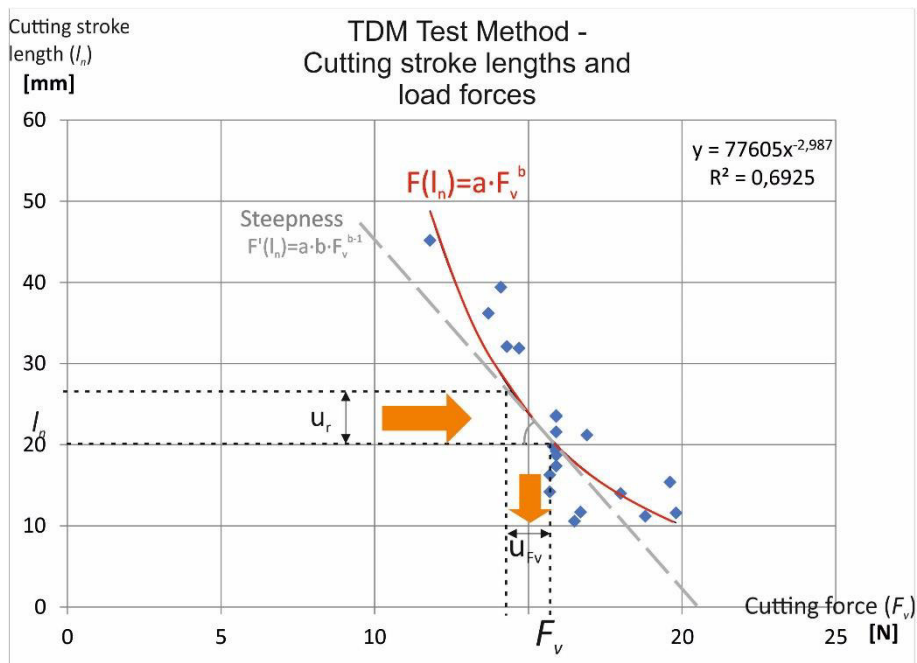


Figure 5: Example of error propagation on the regression curve

By deriving the regression function, we get the equation describing the slope of the curve at the point in question:

$$F(l_n) = a \cdot F_v^b$$

$$F'(l_n) = a \cdot b \cdot F_v^{b-1}$$

Using the slope and rearranging the equation the uncertainty of the cutting force is the following (u_{Fv}):

$$u_{Fv} = \frac{u_r}{a \cdot b \cdot F_v^{b-1}}$$

where

- u_{Fv} is the uncertainty of the cutting force belonging to a cutting stroke length of 20 mm [N],
- u_r is the combined uncertainty of the regression curve [mm],
- a and b are the coefficients of the regression equation,
- F_v calculated cutting force at the cutting stroke length of 20 mm [N].

Regression curve supplemented by the new measurement results

After using the curve drawn first, we determined the cutting force; we have to perform another 5 or 10 measurements with the given load, which, in addition to the results shown above, we need to determine the cutting force again at 20 mm using a refined regression curve. This will be the final result of the test procedure.

In the case of redrawing the refined, more precise regression curve, we have to recalculate the u_{ln} associated with the determination of the normalized cutting stroke lengths, as well as the residual standard deviation of the new curve (S_{r2}). Therefore the combined uncertainty (u_{r2}) of the second regression curve will be given by the sum of squares of the two previous factors:

$$u_{r2} = \sqrt{u_{ln2}^2 + S_{r2}^2}$$

The u_{r2} value is expressed in the dimension of cutting stroke lengths [mm].

Measurement uncertainty of the final result

The final result of the test procedure is given by the cutting force belonging to a cutting stroke length of 20 mm. As the last step of the application of the model of error propagation, in accordance with Chapter x.y, the combined uncertainty of the regression curve shall be projected to axis x as described above, using the following equation:

$$u_{Fv2} = \frac{u_{r2}}{a_2 \cdot b_2 \cdot F_{v2}^{(b_2-1)}}$$

The value obtained (u_{Fv2}) is the Type A, combined measurement uncertainty value, specific to the particular test sample and test.

RISK OF PERFORMANCE CLASSIFICATION

Based on the combined measurement uncertainty value (u_e) calculated by the above-mentioned model of error propagation, we have made further suggestions regarding the application of the result (Besides being an obligation for accredited laboratories)

This value can also be used in the course of the classification of the tested protective equipment according to the performance level by a probability risk model. This is because the test result is also a probability variable, and according to an earlier train of thought, this will also deviate according to normal distribution around the designated force value. As the deviation can be interpreted as the previously defined standard uncertainty (u_e), limit values of the performance levels can be shown and visualized on the same diagram as the probability density function.

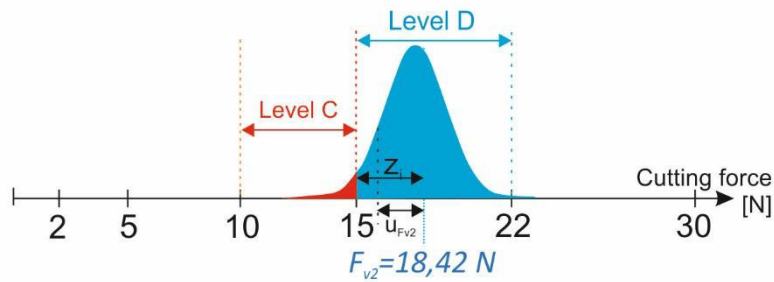


Figure 6: The expected ratio of products that are non-compliant (red) with their level of performance due to their test results and uncertainty values (see performance levels in EN 388:2016)

In this case, we only take into account the lower limit value of the result (to its left), as it is a question of product certification of protective equipment. The risk is now identified with the probability of the product not reaching the lower limit of the given performance level, posing a threat to the user.

The limit value (F_{min}) between level C and D is at 15 N. As an example, a test result (F_{v2}) of 18,42 N is given as the average, and its combined measurement uncertainty (u_{Fv2}) is at 2,31 N. To define the normalized z_i value:

$$z_i = \frac{F_{v2} - F_{min}}{u_{Fv2}}; \text{ i.e. } -1,48$$

Based on the value of z_i , the probability (given by the distribution function) to not reaching 15 N is 1-0,9306. Therefore the risk of misclassification of the tested product regarding the category of 15-22 N is 6.94% – in case the representativeness of the sample was provided. [5]

SUGGESTIONS AND FURTHER OBJECTIVES

When developing the test method (and the standard), it is worth simplifying the procedure for evaluating the results. Of course, this decision would require further consideration of aspects.

It is essential to assess the effect of the chosen type of regression curve on the final result, its uncertainty, and the classification risk, as the choice of curves is not sufficiently regulated at the moment for laboratories.

In case it is possible to identify the proportions of individual uncertainty components – for example, which part of the combined u value is caused by the blade and which is caused by the internal variance of the test specimen –, more accurate conclusions can be drawn regarding the test result's evaluation procedure.

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