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Determination Of Impact Resistance Of Aluminum Panels For Machine Guards Using Regressions Of Dataset

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Abstract

An essential requirement for safety of workers consists of retaining ejected workpiece or tool fragments in case of a machinery rupture. Appropriate protective performance of the guard is demonstrated by means of an impact test carried out against a standardized projectile. The impact resistance (IR) is used as quantitative measure of an appropriate protective performance in terms of energy. It is defined as maximum kinetic projectile energy a safeguard can withstand. Based on knowledge of the ballistic limit velocity, an investigation on the statistical dispersion of IR is realized. In order to characterize the sheet's withstanding performance a certain number of test is conducted for different projectile's velocities. In the present study, a probabilistic regression of failed impact tests is proposed for aluminum panels using a procedure already introduced in past research. A normal and a logistic distribution regression are compared in terms of their suitability for modeling the probability of failed impact tests. Logistic regression of the data appears to be less sensitive to the outcome of each test and the number of points used, in comparison to Gaussian regression. According to the findings, the so called "safe ballistic limit" corresponds to a 10% probability of test failure, although there isn't a perfect correspondence between logistic and Gaussian curves. To provide a more physical interpretation of the conducted tests, the new method proposed in this paper should be implemented while considering an energy reduction coefficient. This approach allows the Gaussian phenomenon to maintain the same characteristic. Additional tests are necessary to precisely define the withstanding capacity of the aluminum sheet and determine an appropriate safety factor for material guard design. These conclusions contribute valuable insights for enhancing the design and evaluation of safeguards in industrial settings, emphasizing the importance of continued research to ensure a proper safety of workers in environments prone to ejection risk.

Keywords: safety of machinery, aluminum sheet impact resistance, ballistic limit velocity test

1. Introduction

The Machinery Directive 2006/42/CE (European Parliament and Council, 2006) of the EU specifies safety requirements for the design and construction of machine tools, particularly focusing on safeguards. This includes, among other things, the requirement that no part, i.e., workpiece or tool fragments, "must be ejected," or if they are ejected towards the operator, they should be retained by safeguards. To meet this requirement, international standards such as ISO 14120 (2015) define specific test procedures to verify an adequate level of protection. In these test procedures, a safeguard undergoes a high-velocity impact by a standardized projectile. The damage pattern of the safeguard is subsequently used to assess the test result. A test is considered passed if it leads only to elastic/plastic deformations without fracture through the thickness of the guard. This "limit state" of deformation without through crack is usually called Impact Resistance of a material (IR). As soon as the deformation yields a continuous crack visible on both sides of the safeguard, the test is considered failed. There are several existing probabilistic analysis methods, presented by Tahenti et al. (Tahenti et al.,2017), already used for estimating the distribution of the perforation probability, including the STANAG 2920 method, the Kneubuehl method, the Probit method, the Chi-square and Kolmogorov-Smirnov Goodness of Fit Test, and the Euler-Maruyama Method. All these methods are currently used to determine distribution of probability that a projectile fully perforate a target that is a different (not safe) condition from the one expressed above. Even if the test conditions are different from the IR because the “limit state” in this case is the called V50, those already used methods are interesting for our intent and they will be briefly presented.

The STANAG 2920 method uses the Up and Down technique to approximate the velocity at which the projectile has a 50% probability of perforation (V_{50}). In this case the projectile has 50% probability to fully perforate the target/material without residual velocity (i.e. all the energy is necessary to perforate the target and the projectile remains in the material). The Kneubuehl and Probit methods use different techniques to estimate the mean (V_{50}) and standard deviation of the normal distribution that characterizes the perforation probability as a function of the projectile impact velocity. However, these methods assume normality and may overestimate the interval of velocities for rare events, such as V1 and V99. The Brownian motion approach is an alternative method that leads to a more accurate estimate of the interval of velocities for rare events and avoids the problem of overestimating extreme values. Additionally, the Chi-square and Kolmogorov-Smirnov Goodness of Fit Test and the Euler-Maruyama Method estimate the drift and diffusion coefficients of the developed stochastic differential equation based on the Monte Carlo simulated sample and the experimental one. The following methods are specifically explained. “Euler-Maruyama Method”: this numerical technique is used for solving stochastic differential equations (SDEs) that model the ballistic performance of protection structures. The Euler-Maruyama method provides a computational approach to simulate the behavior of the system over time and space. This last method is defined by the following formula, Eq. (1):

$$X(t) = X(0) + \int_0^t b(s,X) + \int_0^t s(s,X)\,dW(s) \tag{1}$$

where:

- $X(t)$ represents the instantaneous velocity of the projectile;
- $b(s,X)$ is the deceleration of the projectile on the trajectory within the target (drift coefficient);
- $s(s,X)$ is the diffusion coefficient that mathematically translates the observed randomness;
- $W(s)$ denotes the Wiener process, which represents the Brownian motion.

“Chi-square and Kolmogorov-Smirnov Goodness of Fit Test”: these statistical tests are applied to estimate the drift and diffusion coefficients of the developed stochastic differential equation, which describes the motion of the penetrating projectile in the protection structure. It is represented by the equation of motion of the projectile impacting as a rigid body with a known initial condition. The tests involve comparing the simulated sample with the experimental data to assess the accuracy of the model in representing the ballistic behavior of the protection structures. The Chi-square and Kolmogorov-Smirnov tests are defined by specific statistical formulas used to evaluate the goodness of fit of the model to the experimental data. The Chi-square test statistic is calculated using Eq. (2):

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}, \tag{2}$$

where O_i represents the observed frequency and E_i represents the expected frequency in each category, and the Kolmogorov-Smirnov test involves calculating the maximum difference between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution. “Existing Probabilistic Analysis Methods”:

Various established methods, such as the Kneubuehl and Probit methods, rely on the normality assumption to estimate the perforation probability. These methods use specific tools to find the mean and variance of the normal law to quantify the perforation probability. The Probit analysis, for example, is based on a statistical treatment of the sigmoid response curve and is expressed by Eq. (3) also called the Probit function:

$$Z = \Phi(p)^{-1} \tag{3}$$

where Z is the standardized gaussian deviate, and $\Phi(p)^{-1}$ is the inverse of the standard gaussian cumulative distribution function. All those tests are used to give a best fit of probability to be perforated expressed, usually, in terms of impact velocity.

In standardized tests the IR is used as a measure of the protective performance of safeguards (ISO 14120, 2015). It is defined as the maximum kinetic projectile energy (E_{pr}) a safeguard can withstand and is generally determined applying the so-called bisection method. In this method, the IR is estimated by an initially wide interval, which is subsequently narrowed by a series of further impact tests. Although simple in principle, it yields only an interval for the IR, which ultimately depends entirely on the two nearest impact test results and thus is associated with considerable uncertainty (Landi et al., 2022). The results of those tests in terms of residual plastic deformation have also been validated with 3D scanner techniques (Landi et al., 2022b).

An alternative approach to determining the IR was presented by Uhlmann et al. (Uhlmann et al., 2022c), who proposed a statistical evaluation procedure. The statistical method allows a probabilistic description of the IR through the cumulative distribution function (CDF) of a normal distribution. Hence, instead of determining a fixed interval, the IR is described as the probability P of passing an impact test. Uhlmann successfully applied the novel statistical approach to several impact test series on polycarbonate (PC) sheets. Although there has been a theoretical discussion on employing a normal distribution, a thorough analysis of its suitability is yet to be performed. In 2023, the two previous groups of researchers presented together a different statistical approach (Uhlmann et al., 2023) to obtain a proper distribution curve from tests in real conditions (104 different polycarbonate tests in similar test conditions).

The aim of this paper is to test this new approach on a smaller dataset of new tests to find a small but consistent dataset designed to obtain reliable IR probability distributions. To have consistent tables on safety standards, new test procedures to obtain probability distributions of retaining a given standardized projectile are welcomed (see, for example, material tables of annex B in ISO 23125:2015). It is to notice that these tests are conducted with gas cannons controlled in pressure and different impact velocities are tested. Results are typically expressed in terms of energy (J) with an underlying assumption that the relevant physical quantity to be test is energy not velocity. It the following paragraphs, after a brief description of the gas cannon used for testing and the physical properties of the aluminum material used, the new test procedure will be introduced and the results in terms of logistic and gaussian distribution will be presented. The best fit R&I curve and the already introduced V50 will be found with some high-speed test and utilized to retrieve the upper and lower velocity limits (S_{bl} and $\mathrm{v_{bl}}$) able to highlight the called “gray zone” where subsequent tests must be done as presented in Landi et al. (2022). Using those following tests, it will be possible to define a probabilistic distribution of IR using the same best fitting algorithms used in Uhlmann et al. (2023)

2. Description of the test

Landi et al. (2022) presented impact tests designed to determine the impact resistance of machine guards. These tests involve launching a standardized projectile at a guard with specified thickness and material to establish the impact resistance, denoted as Y. The reference standard governing the testing and validation methodologies for ballistic impact tests on machine guards is ISO 14120, Annex B. However, the current standardized approach has limitations. It includes tests conducted at velocities near or below the impact resistance (Y) or the safe impact resistance (Ysf) until the validation condition stipulated by the reference standard is met. This approach may result in instability of residual velocities near the ballistic limit and might not precisely determine the impact resistance of guards. In response to these limitations, Landi et al. (2022) proposed a new probabilistic method for determining the impact resistance and safe impact resistance of machine guards. This method entails conducting multiple impact tests at varying initial velocities to establish an R&I best-fit curve and a confidence interval for a ballistic limit. Eq. (4) is the base formula in the regression algorithm. The ballistic limit is then utilized to determine the impact resistance by defining a velocity reduction coefficient.

$$\mathrm{v_r} = a(\mathrm{v_i}^p - \mathrm{v_{bl}}^p)^{\frac{1}{p}} \tag{4}$$

With a and p dimensionless parameters where the first is defined as:

$$a = \frac{m_p}{m_p + m_{pl}}$$

and where:

- $\mathrm{v_{bl}}$ is the ballistic limit velocity;
- $\mathrm{v_i}$ is the initial velocity of the projectile;
- $\mathrm{v_r}$ is the residual velocity of the projectile after impact;
- m_p is the mass of the projectile;
- m_{pl} is the mass of the plug ejected from the plate following impact.

In impact tests conducted on machine guards, two potential outcomes, as illustrated in Figure 1, are bulging and penetration. Bulging denotes a permanent deformation of the guard without continuous cracking, whereas penetration happens when the projectile fully pierces through the guard. The crucial energy needed for penetration is termed the penetration energy, and it serves as a valuable parameter for characterizing the impact resistance of the guard.

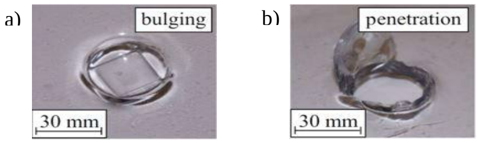

Fig. 1. (a) Bulging; (b) Penetration.

The experimental setup described by Landi et al. (2022) for impact tests comprises an impact test rig. This rig includes a gun barrel designed to accelerate the projectile, propelled by a gas cannon, and a test fixture to secure the guard under examination. The initial velocity of the projectile is regulated by adjusting the operating pressure released from the pressure tank. The impact occurs at a central location on the test fixture. Notably, this setup deviates from the standardized one, as it necessitates the measurement of residual velocity post-impact to achieve the best fit for the Recht and Ipson (R&I) curve, as explained below.

2.1. Gas cannon description

The gas cannon, shown in Figure 2, measures impact velocity using a standardized projectile. It comprises a cylindrical barrel, a pressure tank storing compressed gas, a valve controlling gas release, a speed sensor measuring projectile velocity, and an impact target. Gas expansion propels the projectile, with total force considering adiabatic gas expansion if the volume of the barrel is negligeable with respect to the volume of the gas tank. Pressure loss occurs due to valve opening, air drag, and barrel friction. Mathematical models presented by Landi et al. (2020) correlate projectile velocity with gas expansion pressure, with experimental measurements crucial for calibration.

It's important to note that as specified in ISO 14120, the impact should be in the center of the sheet and perpendicular to the impacted panel, ensuring accurate velocity measurement and reliable test results. The influence of inclination is decisive, so that inclined impact tests must be rejected for a proper ballistic limit v_{bl} assessment.

As an example, Borvik et al. (2002) and Landi et al. (2019) performed many experimental tests, respectively, on steel and polycarbonate sheets of different thickness

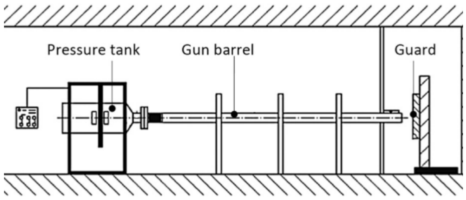

Fig. 2. Equipment for impact tests according to ISO 14120.

3. Material description

In the conducted tests, 3 mm thick aluminum panels measuring 500x500 mm, composed of the 5754 8278 alloy in the H111 state, were employed. The characteristics of the aluminum alloy are detailed in Table 1.

Table 1. Mechanical and physical characteristics of aluminum 5754 (state H111) at 20 °C.

Characteristic (unit)	Value
Thickness (mm)	3
Tensile Strength (N/mm^2)	190
Yield Strength Rp0.2 (N/mm^2)	80
Elongation (N/mm^2) ON 50 mm – A%	16
Hardness HB	52
Density (g/cm^3)	2.65
Thermal Conductivity (W/m C°)	138
Specific Heat (Cal/Kg C°)	0.213
Modulus of elasticity (MPa)	70000

4. Description of the test

In the following paragraphs the test conducted to highlight statistical behavior if IR will be shown and discussed.

4.1. Recht and Ipson

To establish the R&I curve, six tests were conducted, each involving the calibration of the ballistic cannon by adjusting the tank pressure. The primary objective was to provide the projectile with sufficient energy to ensure its ability to penetrate the aluminum sheet. To achieve this, the shot was executed with pressures of over 14.5 bar, resulting in projectile velocities exceeding 89 m/s as suggest by the cannon calibration sheet. A camera, manually triggered for this application, recorded the projectile's videos, capturing the path from the barrel exit to the space behind the aluminum sheet. Speed measurements were extracted from the videos defining four positions along the projectile's path. The impact velocity was determined by measuring the distance (in pixels) of the projectile when positioned at the barrel exit and just before impact, adjusted using the calibration factor and divided by the corresponding time interval. Similarly, the residual velocity was determined using the position right after the impact and the framing extreme. Table 2 describes the main data of the six tests performed to determine the R&I regression.

Table 2. Set1 - impact tests for R&I curve definition.

Test	V_i (impact velocity) (m/s)	V_r (residual velocity) (m/s)	ΔE (lost energy) (J)
All_1	93.41	26.62	400.84
All_2	95.51	35.97	391.42
All_3	89.84	11.09	397.41
All_7	89.48	11.15	393.22
All_8	89.11	14.66	386.28
All_24	91.75	19.15	402.57

The fitting process is conducted with author's routine in MATLAB R2018a, developed by The MathWorks Inc., Natick, USA. Table 3 reports the best fit results with 99% confidence intervals, where $\mathrm{v_{bl}}$ is the best fit value and L_{bl} and U_{bl} are the extremes. Similarly, Figure 3 shows the best fit of R&I curve together with the extreme values of confidence intervals marked as *.

Table 3. Best fit parameters for R&I equation, extremal values of 99% confidence intervals and R^2 values.

Parameter	Value
a	1.0
P	1.84
V_{bl} (m/s)	**88.13**
U_{bl} (m/s)	89.34
L_{bl} (m/s)	86.93
R^2	0.90

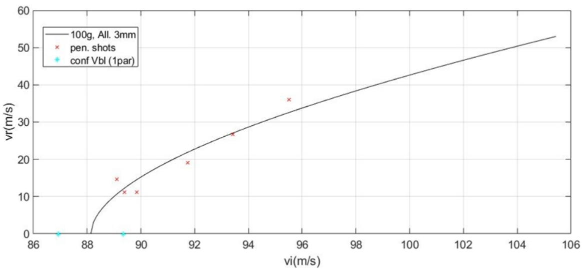

Fig. 3. R&I curve for an aluminum sheet thickness of 3 mm.

Within the scope of this paper, v_{bl} assumes a reference role for characterizing subsequent experiments. Specifically, it represents the velocity imparted to the projectile, ensuring a 50% probability of either perforating or not perforating the sheet (called v_{50} in introduction). Nevertheless, the objective of this research is to discern the probability distribution associated with the projectile inducing a through crack in the aluminum sheet. Following this purpose, according to the theoretical framework already presented in introduction. It is feasible to define a novel region in the R&I diagram, called the velocity gray zone (VGZ). The VGZ is characterized as the velocity interval between the safe ballistic limit (S_{bl}) and the lower ballistic limit (L_{bl}) for a given confidence interval.

The S_{bl} it is to be intended as the energy value (velocity) of the standardized projectile where the standardized penetration test of ISO 14120 can be successfully passed with a desired probability (as an example 90%).

Analysis of tests previously conducted on polycarbonate sheets led to the conclusion that, in order to endow the projectile with a low probability of creating a through crack, a velocity reduction coefficient ($C_{R,v}$) in the range of 1.25-1.28 should be employed. In this paper, the safe ballistic limit has been computed, considering v_{bl} instead of L_{bl}; hence, the speed reduction coefficient has been taken at its maximum 1.28. Eq. (5) is utilized to ascertain S_{bl}:

$$S_{bl} = \frac{v_{bl}}{C_{R,v}} \cong 68.8\ m/s \tag{5}$$

A new set of tests were carried out to impact the projectile with the updated velocity. Table 4 presents the data derived from the subsequent five tests with a desired impact speed of 68.8 m/s It is crucial to note that regulating the pressure to achieve the precise projectile speed as desired is challenging. Consequently, the obtained values will hover around the target speed S_{bl}.

Table 4. Set2 – test results with velocity S_{bl}.

Test	V_i (impact velocity) (m/s)	V_r (residual velocity) (m/s)	ΔE (lost energy) (J)	Crack
All_9	69.83	N/A [a]	243.81	bulging
All_10	69.84	N/A [a]	243.88	bulging
All_11	68.97	N/A [a]	237.85	penetration
All_12	68.16	N/A [a]	232.31	bulging
All_13	68.56	N/A [a]	235.02	bulging

[a] Not available

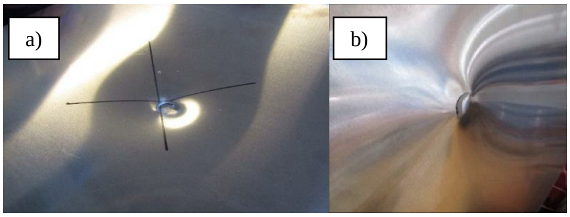

Fig. 4. All_11 test, a) front side b) back side.

As anticipated, none of the projectiles in Table 4 succeeded in penetrating the sheet with a residual velocity, as their velocities were significantly below the v_{bl} threshold. However, from a safety standpoint, at the S_{bl} defined using eq. 5, one out of the five conducted tests (test All_11) resulted in failure due to the formation of a through crack (see Figure 4). To comprehensively assess the probability distribution of failure occurrences across the entire VGZ area, additional tests on the guard were conducted with the projectile velocity expressed by Eq. (6) and (7) as in the following:

$$v_{mid} = S_{bl} + \frac{1}{3}(v_{bl} - S_{bl}) \tag{6}$$

$$v_{high} = S_{bl} + \frac{2}{3}(v_{bl} - S_{bl}) \tag{7}$$

Tables 5 and 6 present the data acquired from the conducted tests.

Table 5. Set3 – test results with velocity v_{mid}.

Test	V_i (impact velocity) (m/s)	V_r (residual velocity) (m/s)	ΔE (lost energy) (J)	Crack
All_14	74.44	N/A [a]	277.07	bulging
All_15	74.82	N/A [a]	279.90	bulging
All_16	75.69	N/A [a]	286.45	penetration
All_17	75.21	N/A [a]	282,83	bulging
All_18	74.64	N/A [a]	278.58	penetration

[a] Not available

Table 6. Set4 – test results with velocity v_{high}.

Test	V_i (impact velocity) (m/s)	V_r (residual velocity) (m/s)	ΔE (lost energy) (J)	Crack
All_19	82.32	N/A [a]	338.83	penetration
All_20	80.33	N/A [a]	322.65	bulging
All_21	81.12	N/A [a]	329.02	bulging
All_22	80.94	N/A [a]	327.56	penetration
All_23	81.69	N/A [a]	333.66	bulging

[a] Not available

Both test sets describe a probability of failure of 40%; however, set – 1 employs a lower projectile velocity, 75.4 m/s, whereas set – 2 utilizes 82.4 m/s. In the second set of trials, a higher failure rate could be expected, given that the imparted velocity is closer to the ballistic limit. It can be concluded that to better understand the distinction in terms of the probability of failure for the adopted velocities, additional tests are required. In order to have a limited set of test for standardization issue more than 20-25 test for a single material of a given thickness is not realistic.

4.2. Logistic and Gaussian best fit

The quantification of protective efficacy is commonly assessed through the metric known as Impact Resistance (IR). This metric signifies the maximal kinetic energy a protective barrier can endure from a projectile. In the investigations conducted by Landi and Uhlmann already introduced, it was determined that both Gaussian and logistic distributions are suitable for analyzing datasets where the continuous variable "Energy" is the input, and the binary outcome of success or failure is the output. While the Gaussian distribution demands extensive data preparation, potentially influencing its outcomes, the logistic distribution presents an advantage over the gaussian distribution by requiring no such data manipulation. Figure 6 displays the points of the dataset used to establish the regressions. As can be seen, when illustrating qualitative data like impact test results, a common practice involves using a binary response variable Y_I, which signifies either a "success" or a "failure" (Montgomery and Runger, 2014). In the current context, a response variable of $Y_I = 0$ indicates a successful impact test, and conversely.

4.2.1. Gaussian regression

Due to the unsuitability of a gaussian distribution for fitting binary data, preprocessing is required for the impact test results. Consequently, the binary data is converted into quantitative data by categorizing the impact test results based on projectile energy E_{pr} into ranges and computing the probability for a failed test. The objective is to generate as many ranges as possible, thereby increasing the number of support points and improving the fit to the gaussian distribution. Figure 5 illustrates the entire dataset categorized into four ranges along with the corresponding number of impact tests for each range. Note that some tests are been excluded because outliers for the VGZ, in particular the test with energy higher from the V_{bl} confidence interval of Figure 3.

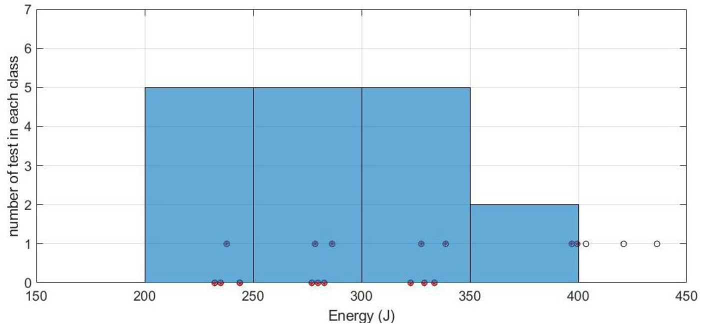

Fig. 5. Number of impact tests of prepared data classified into four ranges.

The probability of a failed impact test is utilized as supporting points to fit a gaussian distribution. The fitting process is conducted using MATLAB R2018a, employing a least square fit based on the Levenberg-Marquardt algorithm (Nocedal and Wright, 2019). A gaussian distribution is characterized by its mean $\overline{x}$ and its standard deviation (STD) s; both parameters are derived by fitting the cumulative distribution function (CDF). The outcome of the fitting process is illustrated in Figure 6, and the corresponding results are presented in Table 7.

4.2.2 Logistic regression

An alternative representation of the probability for observing the failure of an impact test is provided by the logistic distribution. A logistic function is a monotonically increasing S-shaped function whose optimal fit regression is achieved by minimizing the log-likelihood estimator determining the best values for the parameters. Figure 6 depicts the comparison of the two regressions realized in relation to the experimental points and failure percentages for each class. Take note that the extreme energy value, 400 J, corresponds to the ballistic limit for our tests. Summary data for the regressions are presented in Table 7.

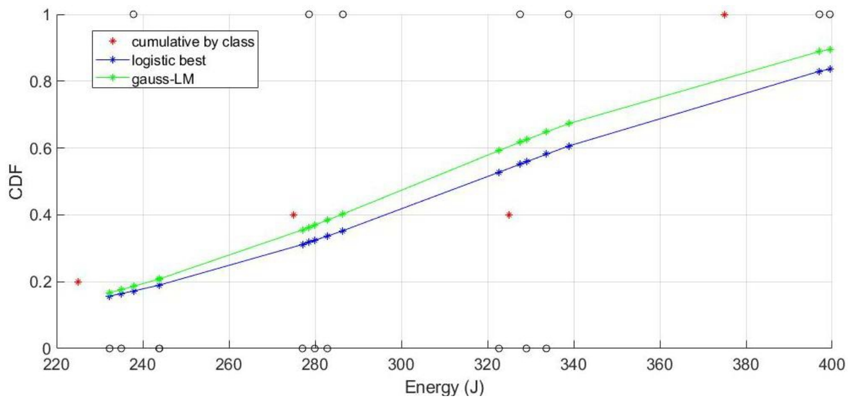

Fig. 6. Comparison of gaussian and logistic distribution fit.

Table 7. Best fit regression data.

Fitting parameter	Gaussian regression	Logistic regression
Mean	300.0	317.1
Std	55.9	50.5
LL	-21.8	-9.8
R^2	0.72	0.75
CDF (1%)	170.0	85.2
CDF (5%)	208.1	168.5
CDF (10%)	228.4	206.2

5. Conclusion

In this paper, the authors introduced novel tests procedure based on 3mm aluminum sheet panels, investigating the statistical distribution of VGZ based on knowledge of the ballistic limit velocity. Lower projectile velocities exhibit a lower probability of failure; however, to thoroughly characterize the sheet's withstanding performance, a considerable number of tests should be conducted at the desired velocities. Logistic regression of the data appears to be less sensitive to the outcome of each test and the number of points used, in comparison to Gaussian regression. According to the findings, the safe ballistic limit of 68.8 m/s (236 J with a standardized projectile weight of 100g) corresponds at about a 10% probability of test failure, although there isn't a perfect alignment between logistic and Gaussian curves. To provide a more physical interpretation of the conducted tests, the method proposed in this paper should be implemented while considering an energy reduction coefficient for testing. The authors believe that the penetration phenomenon is to be evaluated in terms of energy and not in terms of velocity as proposed by other authors is previous works. If only the V_{bl} value is desired the two approaches are equivalent but if the physical meaning of the phenomenon under observation must be taken into due account the dispersion of it has to be evaluated in terms of energy. Elasto-plastic deformation work and Deformation energy of material to failure are considered relevant for this problem from authors and not velocities.

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