ANCOVA analysis of penetration force on Kevlar fabrics used for ballistic protective equipment

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ABSTRACT – REZUMAT

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The paper aims to highlight the existence of significant differences between the variation of the penetration force of three groups of fabrics used for ballistic protective equipment in the function of the deformation arrow, using the ANCOVA mathematical model with a nominal independent variable and a quantitative independent variable. The model included: the dependent variable (Y) – the variation of the penetration force T (N); nominal independent variable – fabric group; quantitative independent variable – deformation arrow, Δl (mm). This paper analyses the effect of the nominal independent variable and the quantitative independent variable on the penetration force variation, using the ANCOVA model. From the results obtained, through Tests of Be-tween-Subjects Effects, it is observed that the effect of the nominal independent variable "fabric group" is significant and also the effect of the covariate "deformation arrow" is significant. Interpreting the value of Sig < 0.05, it can be concluded that there are significant differences between the variation of the penetration force deformation (alternative hypothesis H1 is accepted). This technique can be used later to model the physical and mechanical properties of fabrics and to select the most appropriate fabrics to meet the requirements of a particular field of use.

Keywords: *ANCOVA model, deformation arrow, penetration force, Kevlar fabrics*

Analiza forței de străpungere a țesăturilor din Kevlar folosite pentru echipamente de protecție balistică utilizând modelul ANCOVA

Lucrarea și-a propus să evidențieze existența diferențelor semnificative dintre variația forței de străpungere a unor grupe de țesături destinate confecționării echipamentelor de protecție balistică în funcție de săgeata de deformare, utilizând modelul matematic ANCOVA cu o variabilă independentă nominală și o variabilă independentă cantitativă. În cadrul modelului au fost incluse: variabila dependentă (Y) – variația forței de străpungere T (N); variabila independentă nominală – grupa de țesături; variabila independentă cantitativă – săgeata de deformare, Δl (mm). Această lucrare studiază efectul variabilei independente nominale și a variabilei independente cantitative asupra variației forței de străpungere, utilizând modelul ANCOVA.

Din rezultatele obținute, prin intermediul Tests of Between-Subjects Effects, se observă că efectul variabilei independente nominale "grupa de țesături" este semnificativ și de asemenea, efectul covariabilei "săgeata de deformare" este semnificativ. Interpretând valoarea Sig < 0,05, se poate concluziona că între variația forței de străpungere există diferențe semnificative în funcție de grupele de țesături studiate și săgeata de deformare (se acceptă ipoteza alternativa H1). Această tehnică poate fi folosită ulterior pentru modelarea proprietăților fizico-mecanice ale țesăturilor și pentru selectarea celor mai adecvate țesături privind satisfacerea cerințelor unui anumit domeniu de utilizare.

Cuvinte-cheie: *modelul ANCOVA, săgeata de deformare, forța de străpungere, țesături Kevlar*

INTRODUCTION

Ballistic protection products simultaneously impose two contradictory requirements: ballistic performance requires a large mass and volume of the product, but at the same time the product must be light and comfortable to wear. The factors that are influencing the energy absorption characteristics of ballistic protection systems depend on the properties of the constituent materials, the design parameters of the textile material, the number of layers of textile material, the density of the material and the impact conditions, such as projectile mass, impact velocity and projectile geometry.

In the last decades, a significant research effort has been made to study the ballistic impact mechanisms of bulletproof vests reinforced with textile structures. The traditional method of improving ballistic characteristics is to increase the number of layers [1–7] or, for some applications, to stitch the layers together with an orthogonal pattern or bias pattern [8–10].

The ballistic performance of bulletproof vests/equipment is influenced by different factors, such as the design and structure of textile/non-textile layers, their number, thickness, specific mass and nature of the raw material [11–15].

In order to improve the ballistic performances of the bulletproof equipment's, the computational analysis or the mathematical modelling of the different relevant factors/characteristics are frequently used, among which the most important ones are the penetration resistance and the deformation arrow [16–20]. The mechanisms of energy absorption at ballistic speeds are important in ballistic protection [21, 22]. The primary factors that determine the weight needed to stop a projectile are the specific energy absorption, determined by the tenacity and elongation, and the sonic velocity of fibres, determined by the specific modulus, indicating the area of the fabric to be involved in stopping the projectile [23]. Typical bulletproof vests are made from multiple layers of woven fabric, with the degree of protection being increased as the number of fabric layers increases [24]. These layers are assembled into a 'ballistic panel', which is then inserted into the 'carrier', which is constructed from conventional garment fabrics such as nylon or cotton. The ballistic panel may be permanently sewn into the carrier or maybe removable [25]. Although the overall finished product looks relatively simple in construction, the ballistic panel can be very complex. Even the manner in which the ballistic panels are assembled into a single unit can differ from one product to another [26, 27].

In the constructive technological design of ballistic/bulletproof vest, it is important to know under what conditions the layer structure has maximum/minimum deformation, at what value of the penetration force and what pressure is transmitted to the body during impact. The number and nature of the layers of material in the bulletproof vest directly determine the level of protection provided (according to the NIJ standard), the parameters of comfort, the production of possible traumas or shocks on the human body.

In the present paper, the variation of the penetration force and the corresponding elongation for several variants of Kevlar fabric groups were analysed, using the ANCOVA method.

MATERIALS AND METHODS

The combination of layers chosen for the manufacture of individual ballistic protection equipment must primarily ensure the protection of the body against the action of risk factors, low-level trauma and comfort parameters. Kevlar is a material whose manufacture imposes high costs. The need to use a large number of layers has highlighted the need to combine it with other materials when conditions of use allow. The study included the use of Kevlar layers (5 layers) and their combination with 1 or 2 metallic gauze layers, tested for penetration force and deformation arrow. The tested ballistic packages have the structure and characteristics presented in the table1.

Ballistic performance of the three variants of Kevlar/metallic gauze materials was tested in the Testing Laboratory for Ballistic and Pyrotechnic Protection (LIPBP) within the Scientific Research Centre for Defense CBRN and Ecology in accordance with the NIJ 01.01 04/2000 standard, using the 9 mm Jericho weapon.

Table 1

BULLETPROOF STRUCTURES VARIANTS	
Variants	**Structure**
G1	5 layers of Kevlar
G2	5 layers of Kevlar + 1 layer of metallic gauze
G3	5 layers of Kevlar + 2 layers of metallic gauze

Experimental research was performed on the Marshall Stability Tester. Following the tests performed, the values recorded for the penetration force and the deformation arrow were introduced as variables in the ANCOVA mathematical model.

ANCOVA is a statistical procedure that enables one to compare groups on some quantitative dependent variable while simultaneously controlling for quantitative independent variables [28, 29]. Thus, ANCOVA combines both qualitative and quantitative independent variables. ANCOVA is used because the inclusion of the covariate in the model can increase power to detect group differences and the precision of estimates [30, 31]. With respect to the design, ANCOVA models explain the dependent variable by combining categorical (qualitative) independent variables with continuous (quantitative) variables [32, 33]. The ANCOVA method belongs to a larger family of models called GLM (Generalized Linear Models), as well as Linear Regression and Variance Analysis (ANOVA), with applications in different fields: medicine, psychology, sociology, engineering [34]. AN-COVA checks the correlation between a dependent variable and the covariate independent variables and removes the variability from the dependent variable that can be accounted for by the covariates. Analysis of covariance models combines analysis of variance with regression analysis techniques. There are special extensions to ANCOVA calculations to estimate parameters for both categorical and continuous variables [35, 36]. However, ANCOVA models can also be calculated using multiple regression analysis using a design matrix with a mix of dummy-coded qualitative and quantitative variables [37].

RESULTS AND DISCUSSIONS

The results obtained for testing the materials for penetration force and deformation arrow is presented in table 2.

The processing is performed in the SPSS program (Statistical Package for the Social Sciences) using the stages and statistical tests specific to the ANCOVA regression model following several steps.

Systematization and processing of experimental data

An ANCOVA regression model is constructed with a nominal independent variable and a quantitative

Table 2

RESULTS OF THE EXPERIMENTAL DATA OBTAINED FOR PENETRATION FORCE AND DEFORMATION ARROW								
Fabric groups	**Penetration force T (N)**	**Deformation arrow Δl (mm)**	**Fabric groups**	**Penetration force T (N)**	**Deformation arrow Δl (mm)**	**Fabric groups**	**Penetration force T (N)**	**Deformation arrow Δl (mm)**
	985.80	32.60		842.70	27.60		732.50	18.90
	978.60	31.80		834.50	27.10		725.80	17.80
	981.20	31.90		828.90	27.50		729.40	16.80
G1	985.40	32.10	**G2**	831.80	26.80	**G3**	726.30	18.90
	973.70	31.30		837.50	27.50		730.50	19.00
	977.40	31.60		837.30	26.80		731.90	18.50
	969.70	32.10		840.40	28.10		733.70	18.70

variable in which: the dependent variable (*Y*) – the variation of the penetration force *F* (N); nominal independent variable – fabric group (G1 – 5 layers Kevlar, G2 – 5 layers Kevlar + 1 layer of metallic gauze, G3 – 5 layers Kevlar + 2 layers of metallic gauze; quantitative independent variable: deformation arrow, Δ*l* (mm). Frequency distributions for the variation of the penetration force, *T* [N] depending on the studied fabric groups are represented in the Boxplot diagrams from figures 1–3.

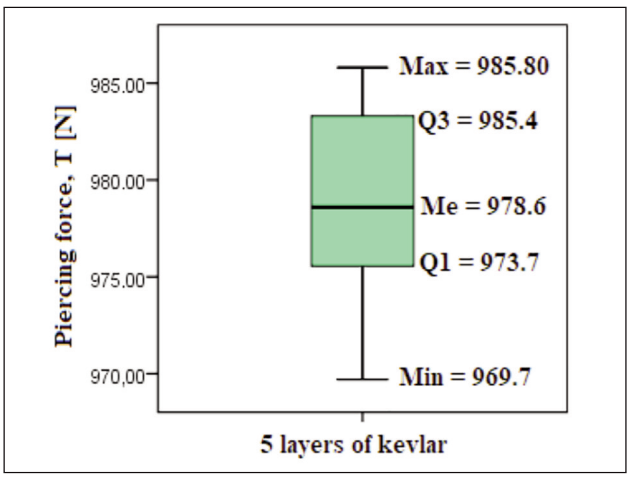


Fig. 1. Boxplot diagram for group G1

These diagrams include the most important statistical characteristics: minimum, maximum, median values, the lower quartile Q1 which delimits the smallest 25% of the measured values and the upper quartile Q3 which delimits the largest 25% of the measured values. A box plot (or box-and-whisker plot) shows the distribution of quantitative data in a way that facilitates comparisons between variables or across levels of a categorical variable. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution, except for points that are determined to be "outliers" using a method that is a function of the inter-quartile range.

Hypothesis formulation

H0 are no significant differences between the variation of the penetration force depending on the groups of fabrics studied and the deformation arrow.
H1: there are significant differences between the variation of the penetration force depending on the groups of fabrics studied and the deformation arrow.

Construction and interpretation of the regression model

Within the ANCOVA regression model, the nominal independent variable "fabric group" has 3 variants, so two dummy variables will be constructed. The reference variant (D1, D2=0) will be the one consisting of

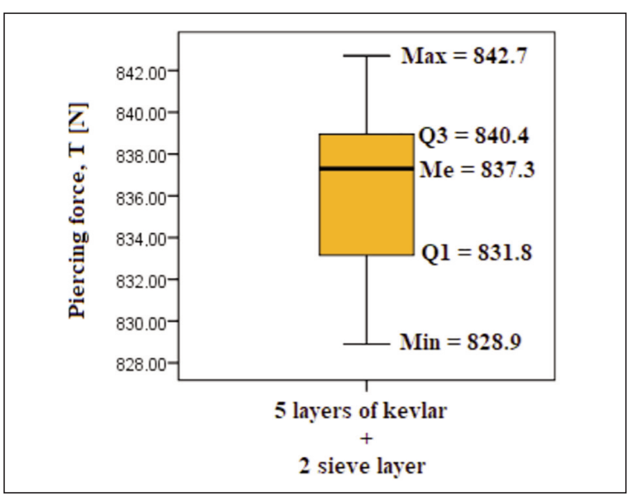


Fig. 2. Boxplot diagram for group G2

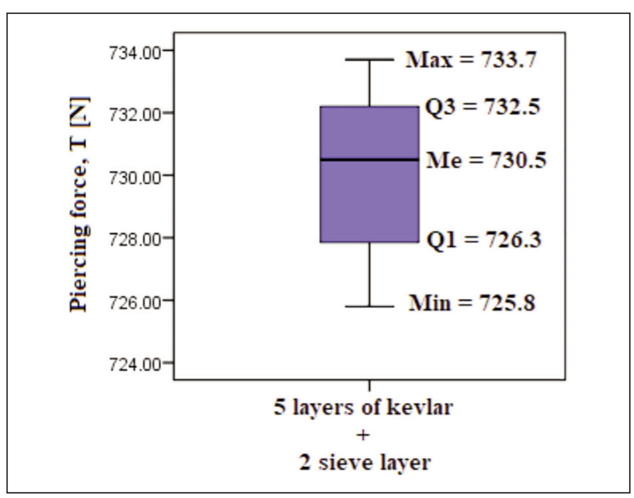
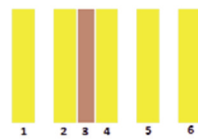


Fig. 3. Boxplot diagram for group G3

Table 3

TRANSFORMING INTO DUMMY VARIABLES											
Group	**D1**	**D2**	**The position of the layers**	**Group**	**D1**	**D2**	**The position of the layers**	**Group**	**D1**	**D2**	**The position of the layers**
G1	0	0	**G1**- 5 Kevlar layers	G2	1	0	 **G2-** 5 Kevlar layers + 1 layer of metallic gauze	G3	0	1	 **G3**- 5 Kevlar layers + 2 layers of metallic gauze

5 layers of Kevlar; therefore, all interpretations will be made in comparison to this category. The transformation into dummy variables is shown in table 3.

The ANCOVA model is defined by the relation:

$$Y = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \beta_1 X_1 + \varepsilon \qquad (1)$$

Conditional average: $M(Y/D) = \alpha_0$; $D_1, D_2 = 0$; $M(Y/D) = (\alpha_0 + \alpha_2) + \beta_1 X_1$; $D_1 = 0, D_2 = 1$; $M(Y/D) = (\alpha_0 + \alpha_1) + \beta_1 X_1$; $D_1 = 1, D_2 = 0$.

The Levene's test is used to test the homogeneity of the variation within the model. Levene test result $F(2.18) = 1.807$, Sig. = 0.193 ($p < 0.05$) is statistically insignificant, therefore, the homogeneity condition of the variants is met. The effect of the nominal independent variable "fabric group" is significant, $F(2.17) = 410.790$, Sig. = 0.000, $p < 0.05$ and also, the effect of the covariate "deformation arrow" is significant, $F(1.17) = 2.676$, Sig. = 0.020, $p < 0.05$, as seen in table 4.

Also, the evaluation of the impact of the independent variables on the dependent variable based on the Type III analysis, shows that the probability F is much stronger for the fabric group (F = 410.790), compared to the tear deformation arrow (F = 2.676) on the variation penetration force.

The graph of the ANCOVA model is presented in figure 4, covariates appearing in the model are evaluated at the following values: deformation arrow = 25.8762 mm. The results show that the penetration force estimates for the three groups of fabrics are statistically related to the deformation arrow. Thus, as we introduce one or two layers of metallic gauze, the penetration force decreases in proportion to the deformation arrow.

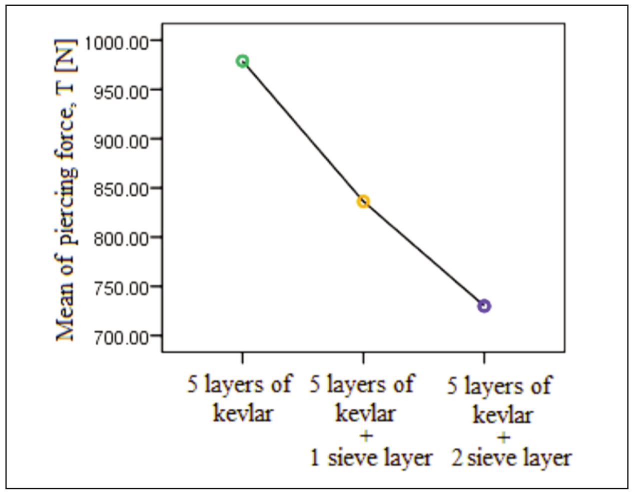


Fig. 4. ANCOVA chart for fabric groups

The coefficients of the ANCOVA model are calculated in table 4. The model estimates are: $\alpha_0 = 273.628$; $\alpha_1 = -40.037$; $\alpha_2 = 49.167$; $\beta_1 = 22{,}166$.

The regression model is:

$$Y = 273.628 - 40.037D_1 + 49.167D_2 + 22.166X_1 \qquad (2)$$

Model interpretation:

a) $\alpha_0 = 273.628$, $D_1, D_2 = 0$, represents the average value estimated for the variation of the penetration force depending on the group of G1 fabrics and the deformation arrow;

b) $\alpha_0 + \alpha_1 = 273.628 - 40.037 = 233.591$ represents the average value estimated for the variation of the penetration force depending on the group of G2 fabrics and the deformation arrow;

Table 4

TESTS OF BETWEEN-SUBJECTS EFFECTS					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	218291.452	3	72763.817	3553.18	0.000
Intercept	5546.617	1	5546.617	270.851	0.000
Fabric group	16824.733	2	8412.367	410.790	0.000
Deformation arrow	54.805	1	54.805	2.676	0.020
Error	348.135	17	20.479	-	-
Total	15331697.92	21	-	-	-

Table 5

MODEL COEFFICIENTS					
Model 1	**Unstandardized coefficients**		**Standardized coefficients**	**t**	**Sig.**
	B	Std. Error	Beta		
(Constant)	273.628	85.092	-	3.216	0.005
D1	–40.037	12.815	–0.191	–3.124	0.006
D2	49.167	36.769	0.227	1.337	0.029
Δl (mm)	22.166	2.663	1.228	8.323	0.000

c) $\alpha_0 + \alpha_2 = 273.628 + 49.167 = 322.795$ represents the average value estimated for the variation of the penetration force depending on the group of G3 fabrics and deformation arrow;
d) $\beta_1 = 22.166$ shows the variation of the penetration force for the fabrics from 5 layers of Kevlar in the conditions in which the deformation arrow increases.
Interpreting value Sig < 0.05 from table 5, it can be concluded that between the variation of the penetration force there are significant differences depending on the groups of fabrics studied and the deformation arrow (alternative hypothesis H1 is accepted).
Verification of the ANCOVA model involves a series of econometric modelling steps, such as: testing hypotheses on errors; homoscedasticity; normality; error autocorrelation and collinearity testing of independent variables.
a) Testing hypotheses on errors, $M(\varepsilon) = 0$ (zero error average)
H_0: $M(\varepsilon) = 0$; H_1: $M(\varepsilon) \neq 0$
The Student t test for errors (Unstandardized Residual), presented in table 6, is applied, from which it is observed that the value Sig. = 1 ($p > 0.05$), so the null hypothesis H_0 is accepted, whereby the average of the errors is 0.
b) Homoscedasticity, $V(\varepsilon_i) = \sigma^2$ (error variant is equal to dispersion)
H_0: the correlation coefficient is insignificantly different from 0 (null hypothesis of the Student's t test)
H_1: the correlation coefficient is significantly different from 0 (the null hypothesis of the Student's t test is rejected).
A nonparametric correlation test is applied between the estimated errors and the dependent variable, the Spearman correlation coefficient and the Student test are calculated for this coefficient, according to table 7. Because the values of Sig. of Student's t test for correlations: Penetration force T (N) – estimated errors (0.084), D1 – estimated errors (0.242), D2 – estimated errors (0.443), deformation arrow – estimated errors (0.352) are greater than 0.05, the null hypothesis of the Student test is rejected, so the model is homoscedastic.
c) Normalcy of errors, $\varepsilon_i \sim N(0, \sigma^2)$
The testing of the normality of the error distribution is done with the non-parametric Kolmogorov-Smirnov test or by the graphical procedure in the form of a histogram. As can be seen from table 8, the value Sig = 0.970 is higher than the critical value $p = 0.05$, so the normality hypothesis H0 is accepted. From the error distribution, presented in figure 5 it is observed that the values are not normally distributed, they do not follow the distribution law described by the Gauss Laplace curve.
d) Error autocorrelation testing, cov (εi, εi)
H0: $\rho = 0$ (errors are not autocorrelated); H1: $\rho \neq 0$ (errors are autocorrelated)
The verification is done with the Durbin Watson test, according to table 9.

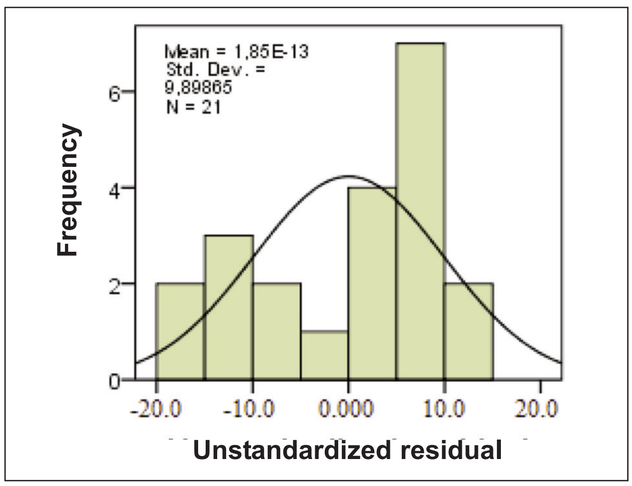


Fig. 5. Errors distribution

Table 6

STUDENT T TEST						
One-Sample Test	**Test Value = 0**					
	t	**df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
Unstandardized Residual	0.000	20	1.000	0.000	–1.8991	1.8991

Table 7

SPEARMAN TEST FOR HOMOSCEDASTICITY HYPOTHESIS VERIFICATION						
Spearman's rho		**Penetration force, T (N)**	**D1**	**D2**	**Deformation arrow**	**Residual for penetration force**
Penetration force, T (N)	Correlation Coefficient	1.000	0.065	–0.817	0.945	0.312
	Sig. (1-tailed)	0.000	0.390	0.000	0.000	0.084
	N	21	21	21	21	21
D1	Correlation Coefficient	0.065	1.000	–0.555	0.138	–0.162
	Sig. (1-tailed)	0.390	-	0.005	0.276	0.242
	N	21	21	21	21	21
D2	Correlation Coefficient	–0.817	-0.555	1.000	–0.818	–0.033
	Sig. (1-tailed)	0.000	0.005	-	0.000	0.443
	N	21	21	21	21	21
Deformation arrow	Correlation Coefficient	0.945	0.138	–0.818	1.000	0.088
	Sig. (1-tailed)	0.000	0.276	0.000	-	0.352
	N	21	21	21	21	21
Residual for penetration force	Correlation Coefficient	0.312	–0.162	–0.033	0.088	1.000
	Sig. (1-tailed)	0.084	0.242	0.443	0.352	-
	N	21	21	21	21	21

Table 8

KOLMOGOROV-SMIRNOV TEST		
One-Sample Kolmogorov-Smirnov Test		**Standardized Residual for T (N)**
N		21
Normal Parameters	Mean	0.0000
	Std.Dev	0.92195
Most Extreme Differences	Absolute	0.107
	Positive	0.074
	Negative	–0.107
Kolmogorov-Smirnov Z		0.491
Asymp. Sig. (2-tailed)		0.970

The value of the Durbin-Watson test DW = 2.091 is compared with the calculated value of the test (dl, du).

According to the literature, it is found that the value obtained is in the range (du, 4 – du), which leads to the acceptance of the null hypothesis (errors are not autocorrelated).

e) Testing the collinearity of independent variables

In practice, the identification of the collinearity of independent variables is done by different methods. Using the SPSS package, collinearity can be detected based on two indicators: Tolerance and VIF (Variance Inflation Factor), presented in table 10. In practice, it is considered that a VIF value > 10 indicates the presence of collinearity. If the tolerance indicator, TOL = 1 there is no collinearity, and if TOL = 0 we are in the extreme situation of perfect collinearity.

It is observed from table 10, that the VIF indicator has a high value between 4.410 and 25.797, which indicates

Table 9

DURBIN WATSON TEST FOR ERROR AUTOCORRELATION TESTING					
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**Durbin-Watson**
1	0.993[a]	0.986	0.983	13.57997	2.091

Note: [a] Test distribution is Normal.

Table 10

TESTING THE COLLINEARITY OF INDEPENDENT VARIABLES COEFFICIENTS								
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**	**Collinearity Statistics**	
		B	**Std. Error**	**Beta**			**Tolerance**	**VIF**
1	(Constant)	273.628	85.092		3.216	0.005		
	D1	–40.037	12.815	–0.191	–3.124	0.006	0.227	4.410
	D2	49.167	36.769	0.227	1.337	0.199	0.029	34.212
	Deformation arrow	22.166	2.663	1.228	8.323	0.000	0.039	25.797

that there is collinearity between the dummy variables D1, D2 and the quantitative independent deformation arrow variable, Δl (mm), used in the model.

CONCLUSIONS

The paper highlights the existence of significant differences between the variation of the penetration force in the function of the deformation arrow.

By analysing the presented data, it can be remarked that the use of G1 layers structure ensures the product a medium elongation, determined by a force and a pressure of low values, while the use of Kevlar layers combined with metallic gauze (G2 and G3 layers structure) generates similar results with the first one, but with significantly higher values in terms of puncture strength and pressure.

The ANCOVA model allows us to evaluate the homogeneity of a statistical population by separating and testing the effects caused by the factors considered. Through Tests of Between-Subjects Effects, it is observed that the effect of the nominal independent variable "Fabric group" is significant, $F(2.17) = 410{,}790$, $Sig. = 0.000$, $p < 0.05$ and also the effect of the covariate "deformation arrow" is significant, $F(1.17) = 2.676$, $Sig. = 0.020$, $p < 0.05$. Interpreting the value of $Sig < .05$, it can be concluded that between the variation of the penetration force there are significant differences depending on the groups of fabrics studied (null hypothesis H0 is rejected). The properties of the estimators of the regression model parameters were verified through specific tests and allowed the construction of the ANCOVA model with a nominal independent variable and a quantitative independent variable. The ANCOVA model shows that the variation of the penetration force is significantly influenced of the nominal independent variable "fabric group", $F(2.17) = 410{,}790$, $Sig. = 0.000$, $p < 0.05$, as well as by the effect of the covariate „deformation arrow", $F(1.17) = 2.676$, $Sig. = 0.020$, $p < 0.05$.

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