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Parametrized regression model and experimental validation for an effective spacer fabric compression

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ABSTRACT

Warp-knitted spacer fabrics are featured by a 3d integral structure consisting of two warp-knitted fabric layers, which are kept on distance by vertical threads. This structure enables the realization of several functions like mechanical cushioning, permeability for air and moisture, and thermal insulation. Due to these functions, spacer fabrics can be used as moisture and thermal-regulating functional components in various sewing products, whereby compression stability is essential for the functionalities mentioned above. These can also be influenced locally by stitching. A numerical tool is preferred to compute the mechanical properties in an accurate way, taking into account the varying sewing parameters. This study's objective is to extend the macroscopic material law for spacer fabrics through numerical analysis of experimental data. For this purpose, 3d samples stitched at varying intervals were tested by a compression test. A regression analysis was applied to predict the compressive stress for each structure. The research steps included representing and approximating the coefficients and potencies for the experimental curves as explicit functions of the distance between the stitch lines. An effective contact model for spacer fabrics with stitches was developed, which is to be expressed in the form of seam distance in terms of the effective compression of the spacer fabrics. Thus, in the future, it will be much easier to predict the effective properties for selected semi-analytically applications with such materials.

Keywords
3D warp knitted spacer fabrics,
sewing parameters,
compression properties,
numerical modeling,
regression analysis

1 Introduction

Spacer fabrics represent an innovative class of textiles that, due to their unique three-dimensional structure—comprising two fabric layers connected by spacer yarns—offer a wide range of applications [1]. Thanks to their integral 3D design, spacer fabrics can absorb mechanical energy under compression. Their compressive resilience, breathability, and low weight make them a promising material for diverse applications where both comfort and protection are essential [2]. In particular, they show potential as cushioning components in the development of personal protective equipment [3, 4, 5], medical orthoses and pads [2, 3, 4, 6, 7], and seating cushions [5, 8], where they may replace conventional materials such as polyurethane or rubber foams. As composite materials [9], they are used in the aerospace [6, 10, 11] and automotive industries [12, 13]. In construction, they offer potential as lightweight panels with ventilating effects [14, 15], as well as in textile-based thermoelectric generators [16]. Moreover, they hold promise as filter components in water treatment applications [17, 18].

The 3D dimensional stability, especially of the spacer layer, is essential for functional performance under load, such as pressure relief or ventilation in the assembled state. Numerous experimental studies have investigated the compression behavior of warp- and weft-knitted spacer fabrics. Liu et al. [7] and Chen et al. [3] demonstrated that structural parameters such as monofilament diameter, connection length, and mesh density significantly affect compressive stiffness and fabric thickness. Particularly, warp-knitted spacer fabrics with smaller monofilament diameters and longer connecting distances show enhanced vibration damping potential.

The studies by Liu & Hu [19] and Yu et al. [8] emphasize the high variability of compression properties through targeted structural modifications. For example, the integration of elastic yarns allows the stiffness and resilience to be adjusted without significant losses in air permeability or weight.

Additionally, studies such as that of Schwager et al. [20] highlight the necessity for standardized testing methods to achieve reproducible and comparable compression results. The development of corresponding standards (e.g., DIN 60022-1) forms a vital foundation for future comparative studies.

By systematically selecting materials, optimizing the complex 3D textile topology, and refining the manufacturing process, the properties of spacer fabrics can be tailored for specific applications. Typically, such optimization follows a classical trial-and-error design process. However, the use of simulation tools has proven highly effective, reducing the need for extensive physical experiments and thus saving both time and materials. First systematic simulations of warp-knitted spacer fabrics were conducted analytically by Kyosev [21], [22], [23], [24], [25] and Helbig [26]. Subsequent work has focused on both experimental and simplified finite element model (FEM) investigations.

The finite element method (FEM) is increasingly used to model the complex mechanical deformations of spacer fabrics under compressive loads. For 3D textile structures with nonlinear material behavior, experimental characterization alone is often insufficient. Studies such as Hou et al. [27] and Liu & Hu [28] demonstrated that combining µCT data with structural mechanical models allows for a realistic representation of compression behavior. Local effects such as buckling, torsion, and contact forces between monofilaments play a central role.

Datta et al. [4] developed a FEM model capable of simulating not only flat but also cylindrically curved fabric surfaces—a crucial advancement for realistic load scenarios, particularly in anatomical contexts.

Further model developments, such as those described by Zhang et al. [29], show that geometric variations within spacer monofilaments—e.g., in length, curvature, or torsion—significantly influence the global compressive behavior. These insights allow for targeted optimization of spacer fabric design using digital twins.

Currently available commercial software tools, such as TexMath [30] and TexMind Warp Knitting Editor [31], provide valuable support for the simulation-based design of fabric structures, spacer thicknesses, and yarn material selection to meet specific development objectives.

Several studies have pursued a combined simulation-experiment approach (e.g., Yu et al. [10] and Velosa et al. [32]) to investigate the compressive behavior of multilayer warp-knitted spacer fabric composites.

The FEM simulations, e.g., Yu et al. [6], reliably reproduce the nonlinear compressive deformation curves and provide insight into local stress states, such as at buckling points or contact zones between monofilaments.

The work of Orlik et al. [33] contributes a novel asymptotic multiscale approach that enables efficient analysis of complex, heterogeneous textile structures and systematically captures the influence of microscopic stress distributions on macroscopic compressive strength.

Orlik's and Pietsch's teams [34, 35] conducted extensive physical and numerical experiments and developed a mathematical multiscale model to compute key structural mechanical properties of spacer fabrics. This accelerates the costly design process via simulation and facilitates future spacer fabric development.

The numerical methods used are based on dimension reduction and homogenization and have been iteratively validated and refined through experimental comparison. Simulations at the yarn level have successfully predicted permeability, relaxation, and compressive elasticity of warp-knitted spacer fabrics.

Current research focuses on Orlik and Pietsch [36, 37] lies in predicting and controlling the compressive properties of 3D textiles with localized constriction due to seam insertion. Particularly when used as cushioning and damping materials, understanding the compressive stiffness after sewing is of great interest. Work [38] has shown that seams within the fabric structure significantly influence the variation of mechanical properties. The intended curvature of the fabric between seams and the required compressive stiffness must be ensured through local reinforcement. Numerical simulations of a flat punch indentation into a spacer fabric were performed on the yarn level as in [34, 35], incorporating frictional contact between yarns. A dynamic contact search algorithm was implemented in TexMath [30], showing good agreement with experimental results [36].

However, the primary interest of this study, embedded in the ongoing research of Orlik and Pietsch [36, 37], is the parametrization of the stitch line distance to optimize seam design. In this paper, we present a simple regression analysis, a method widely used in modern scientific research to analyze experimental data. This method estimates mathematical relationships between process-affecting parameters and their outcomes. Various equation types, including linear, nonlinear, and differential equations, may be used. The regression model shows the average change in the response variable (y) as a function of the factor variable (x). Choosing an appropriate model allows for highly reliable process prediction and parameter optimization.

From this perspective, the main objective of this study is to develop and validate a numerical model that accurately predicts the compression behavior of 3D-knitted spacer fabrics based on how their structural parameters, such as stitch line distance and compressive strain, affect their mechanical response. By combining experimental testing with regression analysis, the study aims to provide a reliable tool for engineers to better understand and optimize the application-specific performance of spacer fabrics.

2 Materials

2.1 Spacer fabrics

The warp-knitted spacer fabrics consist of two horizontal warp-knitted layers interconnected by thin monofil threads, forming a 3D structure, as can be seen from Fig. 1. In most cases, these textiles are made of synthetic material, usually polyester. While mainly flat or textured filament fibers are used for the upper surfaces, monofilaments are predominantly used in the spacer yarn zone to achieve a permanently elastic knitted construction of a certain thickness. Other types of yarn are also used as spacer yarns if, in addition to the mechanical properties, requirements for improved thermo-physiological properties (e.g., moisture dissipation) are to be met.

German company Essedea GmbH & Co. KG provided the physical sample for the experimental test. The parameters of the 3D warp knitted-structure are:

Monofil yarn	PES 900 S
Mesh yarn	PES multi-filament yarn

The distance d between the layers 20 mm
The radius r of the monofils 0.2 mm

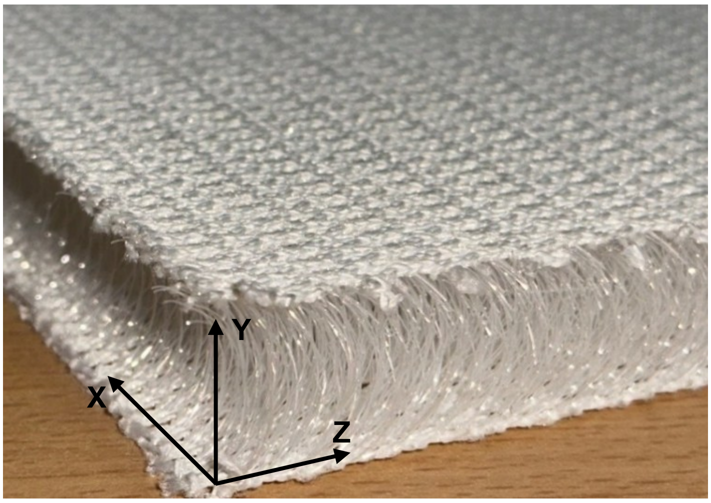


Fig. 1 3d warp-knitted spacer fabric.

2.2 Stitched 3d samples

A Dürkopp Adler Delta Machine "M-Type" sewing machine with needle transport function and the following adjustable parameters was utilized to produce the 3D seams. The sewing stitch type was a Double lock stitch according to the DIN 61400/ISO 4915. To determine the local influence of stitching parameters on the compression force, the samples were manufactured with varying **stitch** line placements on the fabric, while keeping the sewing machine parameters constant, which were set as follows:

- Tension needle thread 50 %
- Foot stroke 9.00 mm
- Sewing foot pressure 1st position
- Stitch length 4.00 mm.

The external shape and parameters of the obtained samples are shown in Table 1 below.

Table 1 Stitched experimental samples [36]

Testing material sample	Samples with different seam distances (cross-section view)	Stitch line distance, mm	Thickness*, mm
		No stitch	20
		12	8
		24	15
		43	20

* The table includes the maximum thickness value measured at the highest position of the material width according to the DIN EN ISO 5084 (1996-10) requirements.

To verify the results obtained, another sample of the material with seams spaced at 33 mm was manufactured as a continuation of the main experimental part.

3 Experimental methods and data

3.1 Determination of the compressive-elastic properties

Compressive-elastic behavior is a central functional element of all warp-knitted spacer materials. In our experiments, a universal material testing machine (Zwicki Z 2.5 kN) is used to determine the relevant properties, enabling direct measurements following the DIN EN ISO 3386-1 standard. To determine the compressive stress-deformation properties according to DIN EN ISO 3386-1, a material thickness of at least 10 mm is required, which, in our case, is met by the spacer fabric. The rectangular test stamp has a test area of 11 x 11 cm. During the test procedure, a speed of 100 mm/min was applied. This velocity value is commonly used in tensile testing of materials like fabrics, where it represents the rate at which the specimen is stretched or compressed. The primary comparison value is the pressure that leads to a 70 percent deformation of the test specimen. Further comparison values can be determined using the compressive force-deformation curve. The hysteresis, which results in a diagram of the compressive-elastic behavior, describes the compression deformation in the upper branch and recovery during unloading in the lower branch (Fig. 2).

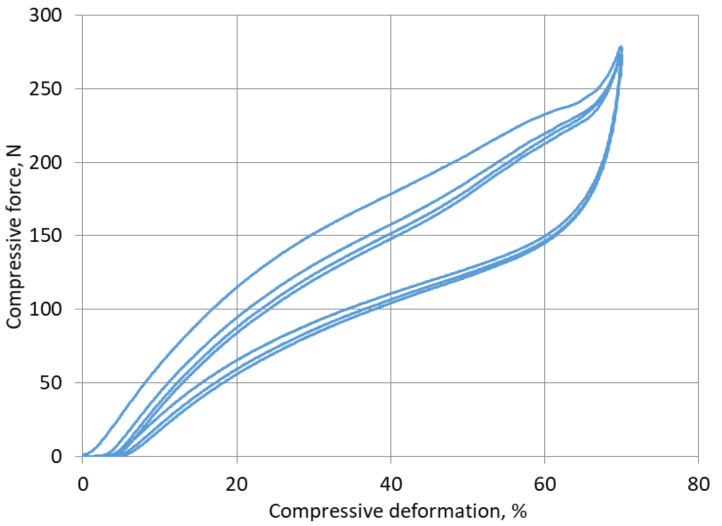


Fig. 2: Compressive force-deformation curve of the 3D warp knitted fabric (thickness 20 mm)

According to preliminary tests, the thickness of a spacer fabric is made up of approx. 2 mm thickness of the outer surfaces and the remaining 18 mm thickness, which is formed by free spacer monofil threads between the outer surfaces. The work done by the compressive load can essentially only be absorbed by these spacer threads, as is typical for textile materials, through viscoelastic deformation, so that the deformation path actually available is approx. 18 mm. In order to deform the 3D knitted fabric to 70 % of the original thickness, a distance of 12.6 mm is covered. Consequently, the remaining deformable thickness is about 5 mm. Fig. 3 illustrates the deformation of the spacer threads under the load.

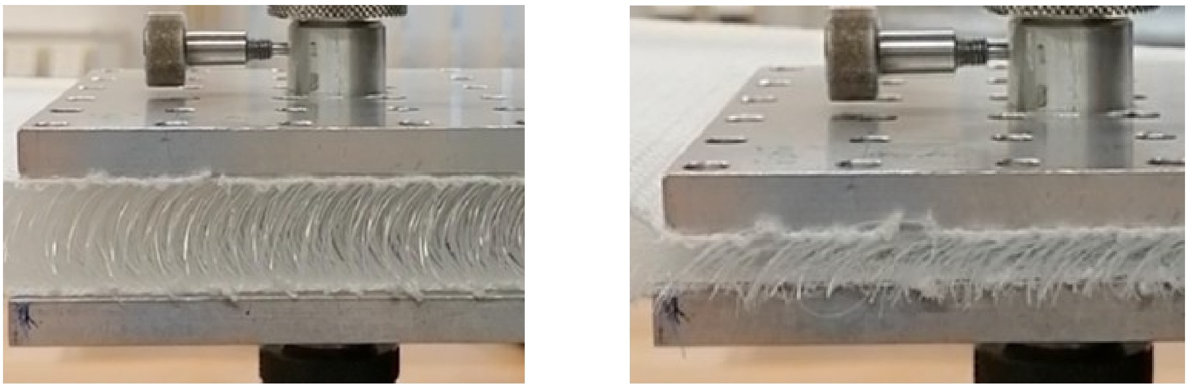


Fig. 3: Deformation test: left: uncompressed/ undeformed spacer fabric; right: deformed spacer thread under compression load

3.2 Regression analysis

The detailed simulations require modeling competence, a software to create a structure on the yarn level setting all the contacts and a numerically expensive contact search. However, if one is only interested in the compression for elastic deformation area, it can be done faster and more efficiently, using statistical methods.

More than a few statistical approaches are now available to researchers to investigate multiple outcomes or informants. With multiple informants, researchers can jointly model the associations between the informant and outcome using a modeling approach available in standard software packages in different statistical software.

In our research, we employed the Microsoft Excel Data Analysis Toolpak to perform regression analysis which models the relationship between a dependent variable, the compressive force in our case, and one independent variable, compressive deformation, using a linear function.

The linear regression equation always has an error term because, in real life, predictors are never perfectly precise. However, some programs, including Excel, do the error term calculation behind the scenes. So, in Excel, we do linear regression using the Least Squares method and seek coefficients a and b such that: $y = bx + a$.

However, as our research aimed to investigate the compression behavior of 3D warp knitted fabrics in a three-dimensional context that considers multiple influencing factors, we required a more complex modeling approach. Multiparameter regression modeling enables us to obtain additional insights into the complex behavior of 3D knitted fabrics under compression, which is essential for the development of advanced textile materials. In this case, the two input parameters are the distance between stitch lines (x1) and relative compression deformation (x2). The output parameter is the compression force (y). The order of the polynomial model is kept as low as possible. The two-variable first- and second-degrees polynomial models were applied to describe the compression behavior of multi-spaced fabric, impacted by the stitching.

Previously used Microsoft Excel statistical analysis tool is limited to linear regression models, which cannot capture the interactions between multiple variables. To address this limitation, we utilized the StatMod software, which is conditionally free and provides the required capabilities for more complex regression analysis, specifically multiparameter regression modeling. The use of the Stat Mod software for the calculation of the regression coefficients, determination of their significance, and confirmation of the adequacy of the obtained model is justified by its ability to handle complex regression models and provide accurate results. The conditionally free software is a suitable choice for this research, as it provides the necessary capabilities for multivariate regression analysis and allows for the simulation of the system with greater accuracy.

3.3 Paired t-Test

A paired t-test was employed to evaluate the statistical agreement between the theoretical model and experimental data. This method is appropriate when comparing two related samples, such as measurements obtained under two conditions (e.g., predicted vs. observed values for the same sample points). The paired t-test assesses whether the mean difference between paired observations is statistically significantly different from zero. It assumes that:

- the data are interval or ratio scaled,
- the pairs are independent and randomly selected,
- the differences between pairs are approximately normally distributed.

The resulting t-statistic is compared against the critical t-value from the Student's t-distribution with $n-1$ degrees of freedom. A $p\text{-value} < 0.05$ (for a 95 % confidence level) indicates a statistically significant difference between the two datasets [39].

This method was implemented using Microsoft Excel's Data Analysis Toolpak, selecting the Paired Two Sample for Means test.

4 Results

4.1 Development of a numerical model for predicting the compression behavior of 3d-knitted spacer fabrics

After testing the compression properties of knitted fabrics according to the “loading-unloading” scheme, the data was statistically analyzed using the add-on application in Excel. The results were presented graphically in the form of hysteresis curves that describe the elastic properties of fabric samples, poor and with different types of stitch line locations (stitch line distance 12 mm, 24 mm, 43 mm). Since our study aims to analyze the compressive loading process separately, the graph in Fig. 4 shows only the part of the curve corresponding to the loading under the experimental conditions.

An analysis of the resulting curves allows us to identify three characteristic areas. The first area corresponds to a curve segment close to the horizontal (0 – 10 % deformation). At this experiment stage, deformation occurs with a minimal growth of the applied load. For the second area, a moderate linear increment of the compressive modulus (E) is typical (10 - 50 % of the deformation). The third area is characterized by a faster rise of the E-modulus (50 – 70 % of the deformation).

When interpreting these results, the following should be understood and considered. The 3D elements of spacer fabrics are incorporated into the structure in a pre-shaped, Z-direction curved position as a result of being anchored in 2D planes during the knitting process (Fig. 1). Since the load-bearing 3D elements are curved, they are predominantly subjected to bending under compressive loading.

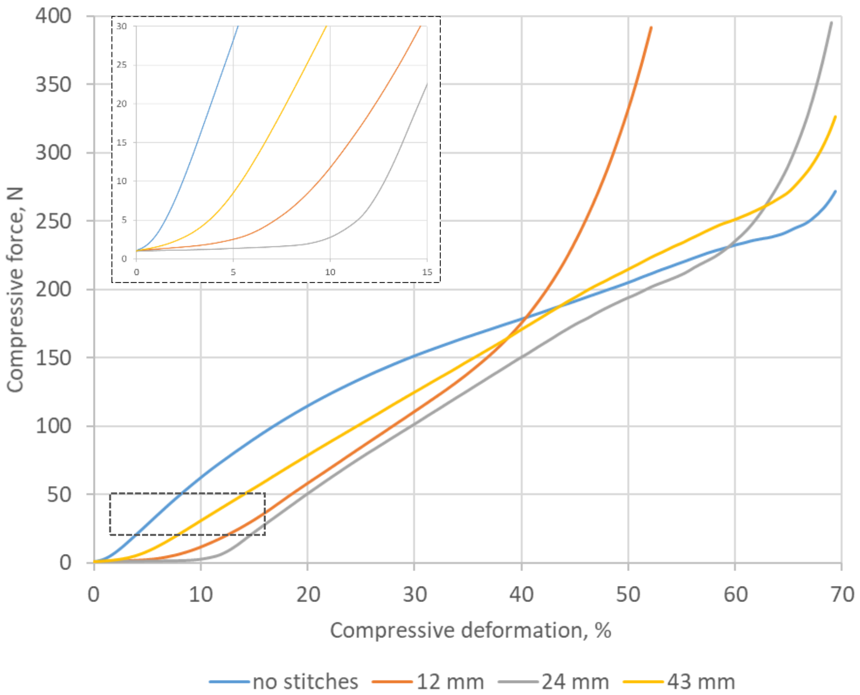


Fig. 4: Compressive properties of 3d warp knitted fabric samples without and with different stitch line distances

In the first stage of deformation, the configuration of the 3D threads changes due to buckling at the anchor points. Therefore, the resistance caused by bending is initially low. In samples with stitching, the first graphic area (Fig. 4) is slightly longer compared to the poor sample because the initial deflection of the monofilaments in the preformed state is bigger.

In the second compressive deformation stage, the 3D structure expands the horizontal deflection of the monofilaments in the Z and X directions. Therefore, in the main deformation range between 10% and 60%, a quasi-elastic compression occurs, which is nonlinear in nature and cannot be fully described by Hooke's law (1), but tends toward a linear geometric behavior. The blue and orange curves, representing the “no stitches” and “12 mm” configurations, respectively, show a greater deviation from linearity due to their different initial pre-deformation states compared to the 24 mm and 43 mm stitched materials. In our research, we follow the hypothesis that the range between 10 % and 60 % can be considered approximately linear for simulation purposes, as we aim to begin our modeling with the simplest possible approach.

$$\sigma = E \cdot \varepsilon \tag{1}$$

At a higher stress level matching the third deformation stage, the experimental curve begins to rise rapidly due to changes in the 3D structure behavior. The bending strain is complemented by the shear strain between the 2D planes in the Z direction (Fig. 1), resulting in a significant increase in the compressive stress-strain value for the final thickness reduction.

A regression analysis approach was used to evaluate the relationship between the seam parameters and the compressive strength of 3D-knitted materials analytically. Based on the results of the foregoing discussion, it was assumed that linear equations can adequately predict the compressive loading process in the predominant deformation area. The Least sq\.s method was applied to find the equation coefficients. The main results are presented in Table 2. Since the constant terms in the three linear equations have negative values, while the load can only take positive values, we limited the range of X values to a specific interval (Table 2). Data extrapolation beyond this interval is not possible.

Table 2 Regression coefficient, t-values, and significance level of linear regression model

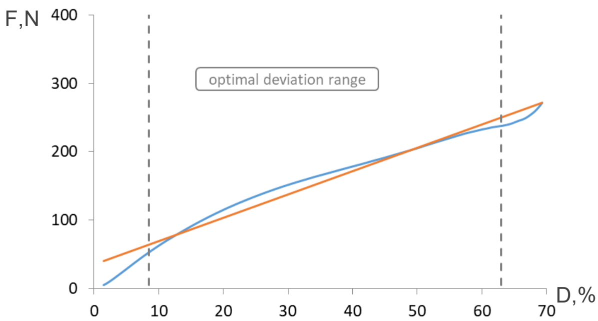
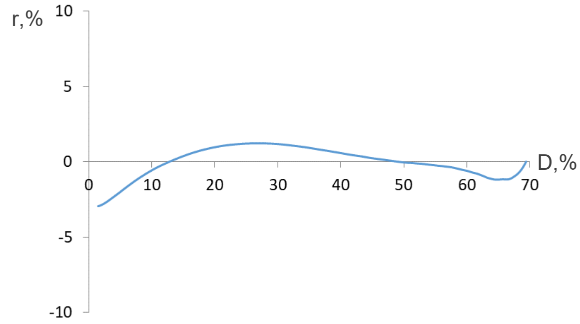
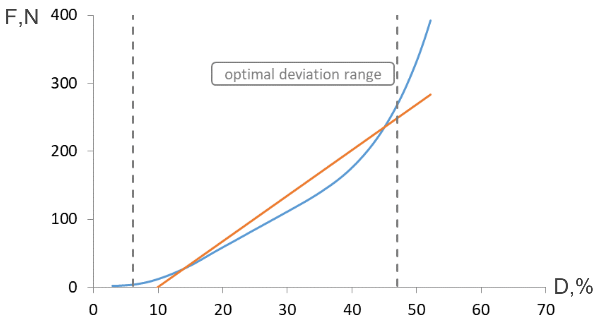
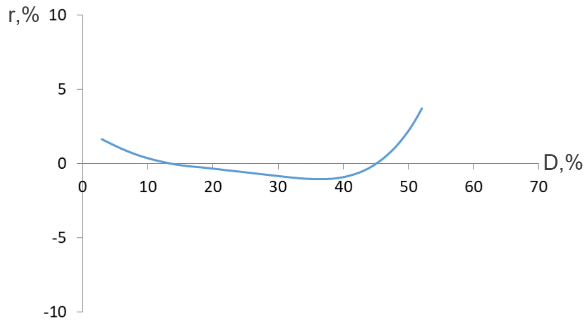
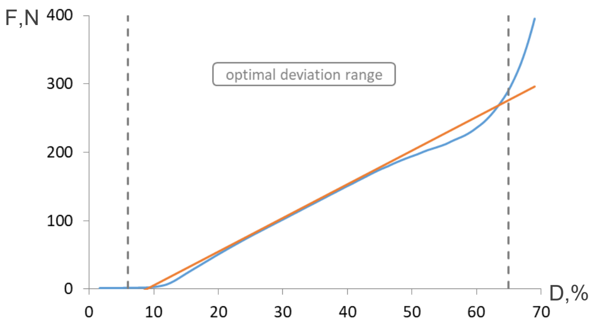
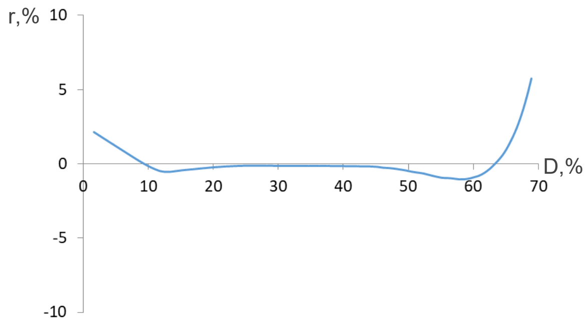
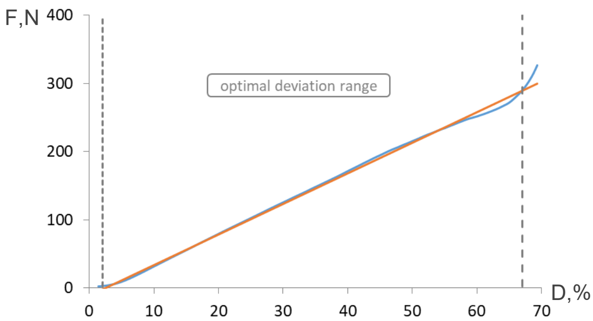
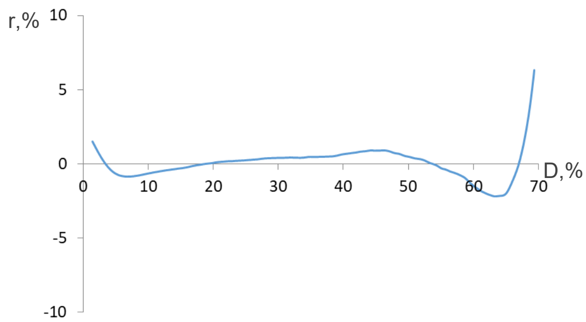
No stitches	$f(x) = 35.31 + 3.41 \cdot x, x \in [0; 70)$ (2)			
Coefficient	*Standard error*	*t-statistic*	*P-value*	Correlation coefficient, R^2
35.312	0.837	42.176	0.676E-210	0.985
3.406	0.021	164.850	0	
Seam distance 12 mm	$f(x) = -67.44 + 6.73 \cdot x.\ x \in [10; 50)$ (3)			
Coefficient	*Standard error*	*t-statistic*	*P-value*	Correlation coefficient, R^2
-67.442	3.621	-18.626	3.054E-52	0.957
6.733	0.117	57.733	0.317E-165	
Seam distance 24 mm	$f(x) = -43.53 + 4.93 \cdot x.\ x \in [8.8; 70)$ (4)			
Coefficient	*Standard error*	*t-statistic*	*P-value*	Correlation coefficient, R^2
-43.531	1.283	-33.924	2.431E-155	0.984
4.928	0.032	154.899	0	
Seam distance 43 mm	$f(x) = -11.12 + 4.49 \cdot x,\ x \in [2.5; 70)$ (5)			
Coefficient	*Standard error*	*t-statistic*	*P-value*	Correlation coefficient, R^2
-11.127	0.302	-36.879	1.068E-178	0.999
4.486	0.008	602.109	0	

The data presented in Table 2 indicate that the studied processes can be described with high reliability using linear functions. The value of the correlation coefficients R^2 at a confidence level of 0.95 in all cases exceeds 0.9. The t-statistics of all regression coefficients are higher than t_{crit} = 1.96 by their absolute value, so we reject the null hypotheses of the insignificance of the regression coefficients and conclude that, in our case, all regression coefficients, including the constant, are statistically significant. The coefficients have the expected, logically justified signs. The interpretation of the constant terms is logical and makes sense.

Graphical analysis of the data obtained as a result of regression analysis is presented in Table 3. According to the experimental setup, the deformation level was limited to 70 %, in line with the guidelines set by the DIN EN ISO 3386-1 standard, which specify the range of deformation to be tested for the materials used.

These standards help ensure consistency and reproducibility across tests involving fabric compression, outlining the acceptable strain limits for each material type. However, for the sample with a 12 mm seam distance, the workflow was interrupted at the 50 % deformation limit. This was due to the fact that the maximum deformation level was achieved earlier than expected, because of the strong pre-deformation of the sample due to parallel seems placed almost close to each other. Therefore, the graph for the 12 mm sample is limited to 50 % deformation level, while the other sample have a 70 % deformation limit, in accordance with the observed behavior of the fabric samples under compressive stress.

Table 3 Analysis of the theoretical and experimental curve fitting

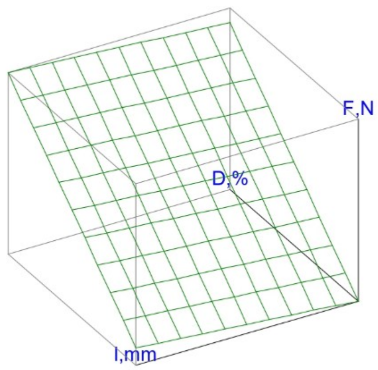
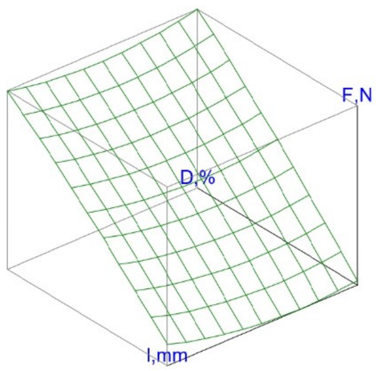
	Stress-strain diagram	**Residual (*r*,%) plot**
No stitches		
Seam distance 12 mm		
Seam distance 24 mm		
Seam distance 43 mm		

Analyzing the obtained images, we note high data agreement in the elastic deformation range of 10 – 50 %, while the deviations increase significantly in other areas. That is, it is worth choosing higher-level functions for the mathematical prediction of the compression process in these deformation areas.

There is a directly proportional relationship between the seam distance and the gradient of the graph relative to the x-axis: as the distance increases, the gradient increases, i.e., the value of the compressive elastic modulus grows. This pattern can be traced by analyzing the angular regression coefficients in equations (3-5). This can be explained by the fact that a decrease in the distance between the seams increases the pre-deflection of the 3D fabric. Therefore, the elasticity of such material is reduced.

In the next step, a model will be developed to determine the relationship between the seam parameters and the deformation properties of spacer fabrics under compressive stress. To do this, we use a multivariate experimental design approach where the input parameters are the distance between stitch lines and the relative compression strain, and the output parameter is the compression force. Since the conditions of the experiment allow recording the input and output values at all experiment points, using a simple full factorial design is recommended as this allows for greater simulation accuracy. The calculation of the regression coefficients, the determination of their significance, and confirmation of the adequacy of the obtained model were carried out using the conditionally free Stat Mod software. In the functional equations in Table 4, the independent variables are the distance between the stitch lines in the material samples (x1) and the relative compressive strain (x2), and the dependent variable is the compressive force.

Table 4: Results of two-factor regression analysis of the deformation of the 3D-knitted fabric with different seam distances under the compressive loading

<table>
<tr><td>Linear equation</td><td colspan="3">$\mathbf{f(x) = -53.32 + 0.897 \cdot x_1 - 0.003 \cdot x_1 \cdot x_2 + 4.67 \cdot x_2}$ (6)</td></tr>
<tr><td>Coefficient</td><td>t-statistic</td><td>Correlation coefficient, R^2</td><td rowspan="5">
</td></tr>
<tr><td>-53.320</td><td>-</td><td rowspan="4">0.989</td></tr>
<tr><td>0.897</td><td>22.775</td></tr>
<tr><td>-0.003</td><td>2.323</td></tr>
<tr><td>4.666</td><td>108.784</td></tr>
<tr><td>Polynomial equation</td><td colspan="3">$\mathbf{f(x) = -22.62 - 3.17 \cdot x_1 + 0.08 \cdot x_1^2 - 0.02 \cdot x_1 \cdot x_2 + 5.95 \cdot x_2 - 0.01 \cdot x_2^2}$ (7)</td></tr>
<tr><td>Coefficient</td><td>t-statistic</td><td>Correlation coefficient, R^2</td><td rowspan="7">
</td></tr>
<tr><td>-22.616</td><td>-</td><td rowspan="6">0.999</td></tr>
<tr><td>-3.168</td><td>77.770</td></tr>
<tr><td>0.075</td><td>107.667</td></tr>
<tr><td>-0.017</td><td>42.843</td></tr>
<tr><td>5.946</td><td>247.396</td></tr>
<tr><td>-0.011</td><td>39.173</td></tr>
</table>

As can be seen from the results, both models obtained describe the studied process with a high degree of accuracy. All coefficients with a constant included are statistically significant at the 5 % significance level. Guided by the rule that the choice of model should be from simple to more complex, provided the model meets all other requirements, the authors recommend using a linear relationship (6) to predict the compression process of 3D-knitted materials.

4.2 Validation of the numerical model with experimental results

The purpose of comparing theoretical calculations with experimental data is to validate the accuracy and reliability of the theoretical model. By comparing the results of the theoretical calculations with actual experimental data, we can determine if the model accurately represents the real-world phenomenon. There are several potential sources of discrepancies between theoretical calculations and experimental data. These can include experimental errors, limitations of the theoretical model, and unaccounted for variables in the experimental setup.

In order to validate the calculated numerical models, an additional test was carried out to determine the compressive stress-deformation properties for a sample of a knitted fabric with a seam distance of 33 mm. The selected seam distance is within the range of the factor analysis. The theoretical values for a given example were calculated by substituting the relevant data into the linear equation (6) in Table 4. The theoretical and experimentally obtained data were compared using the "Paired Two Sample for Means" option in the Excel Data Analysis Toolpak. A paired t-test was conducted to determine whether a statistically significant difference exists between the means of the theoretical and experimental datasets. The results are presented in Table 5.

Table 5: Paired Two-Sample for Means Test results for the predicted models

Parameter	Value for initial equation (6)	Value for adjusted equation (9)
Observations	651	651
Pearson Correlation	0.999	0.999
Hypothesized Mean Difference	0	0
Degrees of Freedom (df)	650	650
t Stat	4.622	-2.458E-13
P(T<=t) one-tail	2.291E-06	0.5
t Critical one-tail	1.647	1.647
P(T<=t) two-tail	4.582E-06	1
t Critical two-tail	1.964	1.964

The Pearson correlation coefficient was found to be 0.999, indicating an exceptionally strong linear relationship between the theoretical predictions and the experimental measurements. This demonstrates that the model accurately reflects the trend of the experimental data. However, the initial t-statistic exceeded the critical t-value, and the corresponding p-value was 4.582E-06 (or 0.00046 %), well below the 0.05 threshold. This allowed us to reject the null hypothesis and conclude that a statistically significant difference exists between the theoretical and experimental mean values. While the model closely followed the trend of the data, this result indicated it might not perfectly predict the actual values and may require refinement. The large sample size (n = 651) likely contributed to this significance, as even small discrepancies can appear meaningful in large datasets. Importantly, this does not suggest that the model is inadequate — it may simply exhibit a slight, consistent bias (e.g., consistently over- or underestimating the values).

To improve accuracy, a linear regression correction was applied to the initial model. In this adjustment, the theoretical values were treated as the independent variable (X) and the experimental values as the dependent variable (Y). After determining the regression coefficients, *a* and *b*, we applied an inverse transformation using the following approach:

$$Adjusted\ model = \frac{Theoretical - b}{a} \quad (8)$$

The resulting regression equation is as following:

$$f(x) = -32.38 + 0.799 \cdot x_1 - 0.003 \cdot x_1 \cdot x_2 + 4.16 \cdot x_2 \qquad (9)$$

Following the model refinement, the t-test was repeated (see Table 5). The revised results showed a perfect match with statistical requirements. The Pearson correlation coefficient remained at 0.9986, reaffirming the model's strong alignment with the experimental trends. The updated t-test yielded a p-value of 1.0, indicating that the difference in mean values was statistically insignificant. The t-statistic was essentially zero, confirming that the residuals were negligible, which is precisely the outcome desired for a successful validation. The refined model exhibits no observable bias and provides a highly accurate representation of the experimental behavior.

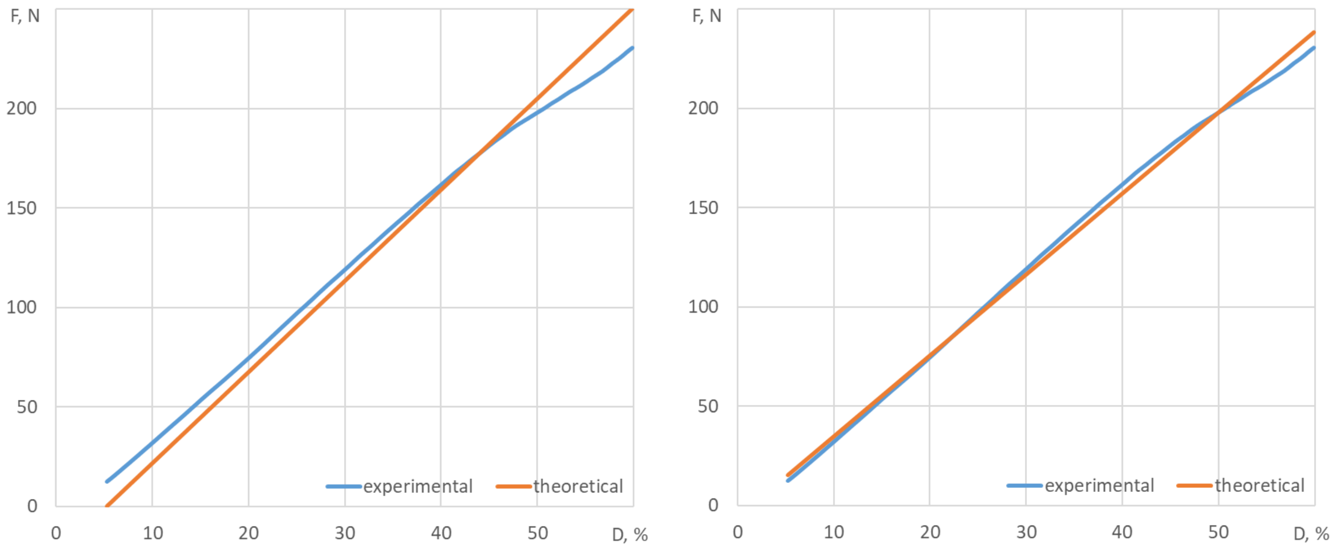


Fig. 5: Discrepancies between theoretical and experimental results for the test sample with the 33 mm seam distance before the improvement (left) and after the model improvement (right)

For further analysis of the developed models, we plot the deviation of the theoretical result from the experimental data for the testing sample with the seam distance of 33 mm (Fig. 5). As can be seen from Figure 5, the discrepancy between the theoretical and experimental values significantly reduced after the model was refined. The increase in the deviation at high loads area is explained by the fact that this region describes the part of the experiment forming a boundary for the linear compression behavior. An interesting finding is that the description of geometrically nonlinear compression using the method based on the linearized equation (9) allows us to achieve sufficiently high accuracy over an interval of forces that exceed those traditionally accepted for linear methods of the theory of viscoelastic materials.

The refined theoretical model for compressive stress-deformation of knitted fabric with 33 mm seam spacing has been successfully validated. It shows excellent agreement with the experimental data in both trend and magnitude. The model can be confidently used for predictive and analytical purposes within the studied parameter range.

The proposed method of predicting the compression process of 3D-knitted fabrics with equally located stitch lines numerically is simple enough in application, which allows its use for engineering applications, for example, at the stage of designing finished items with a prescribed compression value or compression deformation. By varying the distance between the stitched seams, the compressive behavior of the 3D spacer knits can be systematically influenced in a predictable manner.

4.3 Limitation of the Proposed Method

Even though the regression analysis method we used in this research offers a fairly simple and fast way to predict the compression behavior of 3D-knitted spacer fabrics, several limitations should still be taken into account, especially when considering how much we can rely on the results for other types of fabrics or different conditions.

First of all, it’s important to understand that the regression models we developed are purely empirical. Basically, they’re built from the specific dataset we collected for this particular type of fabric, with its own set of structural parameters and tested under quite controlled lab conditions. So, the prediction abilities of this model are pretty much limited to the range of parameters we’ve tested — like the stitch distances and deformation levels we’ve worked with. If someone tries to apply the same model to fabrics with different yarns, densities or other testing parameters, the results probably won’t be accurate since such cases weren’t covered in our experiments.

Also, we should mention that our models mainly cover the elastic deformation area. That means they don’t fully catch more complex behaviors like plastic deformations, material damages, or progressive failures which could show up under bigger loads or long-term compressive forces.

Another point is that regression models generally assume the relations between the variables stay the same over time. However, in practice, textile materials change as they age or get used. Properties like stiffness can decrease, and this isn’t reflected in a static regression model. To make the model reliable for long-term use, it would actually need to be updated from time to time or replaced with a more advanced time-dependent model.

Our findings hold promising potential for scaling to other materials within similar categories, such as upholstery fabrics, mattresses, or foamed elastomers, where the structural behavior under stitching and compression is comparable. Since these spacer materials share common deformation characteristics, particularly in the way stitching influences compression response, the parameters we used — like stitch line distance and compression strain — remain relevant and applicable. While materials with fundamentally different structures, would still require separate experiments and model adjustments, our approach provides a solid foundation that can be effectively extended to a broader group of flexible, compressible materials.

5 Conclusion

The developed numerical model predicts the compression behavior of 3D knitted spacer fabrics by establishing empirical relationships between seam placement and material deformation characteristics. Using regression analysis methods, we obtained linear and polynomial functions that relate seam distance (x_1) and relative compression deformation (x_2) to the resulting compression force. The regression coefficients determined by the full factorial experiment demonstrated high statistical significance and accuracy, with correlation coefficients exceeding 0.98 for all models.

The utilized linear model, in particular, proved to be effective in predicting the compression behavior in the main strain use-related range (10-50 % strain), where the material exhibits predominantly elastic properties. Here, Hooke's law applies, and the stress-strain response can be accurately described by linear equations derived from experimental data. The polynomial model, although more complex, gives slightly better accuracy, especially when taking into account minor nonlinear effects at higher strain levels.

To verify the reliability of the numerical model, the theoretical predictions were compared with additional experimental data obtained on a knitwear sample with a seam spacing of 33 mm, a value that is within the range of parameters under study. As a result of the t-Test analysis, the initial linear equation has been refined using inverse transformation. The refined model exhibits no observable bias and provides a highly accurate representation of the experimental behavior, with a Pearson correlation coefficient remaining at 0.9986, and a p-value of 1.0.

In general, the strong agreement between numerical predictions and experimental observations confirms the adequacy of the developed model for practical applications. This proves that the model can reliably predict the compression response of 3D knitted fabrics and can be confidently used in the design and optimization of textile structures requiring specific compression characteristics. Using the established relationship, we can predict how the compression properties of three-dimensional materials would change depending on the number of seams and their location. This fact, together with the relative simplicity of the method, gives reason to believe that the approximate analytical solution obtained is applicable in practice, for example, at the design stages of finished products with a given value of compression or compression strain.

Author Contributions

Conceptualization, J.O.; methodology, J.O. and K.P., validation, N.S., K.P. and J.O.; formal analysis, N.S.; investigation, N.S., K.P. and J.O.; resources, K.P.; writing - original draft preparation, N.S.; writing - review and editing, N.S., K.P.; visualization, N.S.; supervision, J.O. and K.P.; project administration, K.P, and J.O.; funding acquisition, J.O. and K.P.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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