Stress relaxation of three-dimensional warp-knitted fabrics in compression

S Vassiliadis\(^1\), D Matsouka\(^1\), L Rešetárová\(^2\), L Bouin\(^3\) and A Marmarali\(^4\)

\(^1\)University of West Attica, Department of Electrical and Electronics Engineers, Egaleo, Greece
\(^2\)Technical University of Liberec, Liberec, Czech Republic
\(^3\)ENSAIT, Roubaix, France
\(^4\)Ege University, Bornova/Izmir, Turkey

ptosky@gmail.com

Abstract. Spacer fabrics are a versatile textile construction that can be modified and adapted for a wide range of uses. While the behaviour of spacer fabrics in compression has been extensively studied, their time dependant properties such as creep and stress relaxation have not been investigated equally well. In this research project warp-knit spacer fabrics underwent consecutive compression cycles and the resulting stress degradation over time curves were analysed in order to develop a mathematical and mechanical model of the material behaviour. Based on this analysis it was found that the complexity of spacer structure results in the creep behaviour being connected to the creep bending of interconnecting yarns.

1. Introduction

The typical fabric structures (woven or knitted) in textiles can be considered essentially two-dimensional surfaces as the thickness of the fabric structure is negligible compared with the length and the width of the fabric piece. Nevertheless, there exist textile structures where the thickness is significant, and that thickness is the added value characteristic of the structure. These 3D knitted, or woven fabrics or spacer fabrics as they are also called, are utilized in applications where there is requirement for added “padding” or thickness and they tend to replace materials like polyurethane foam which has historically been used for such applications. These applications include automotive interiors, personal protective equipment, medical textiles, and construction. Combining satisfactory behavior in compression with advanced mechanical properties, breathability and air permeability 3D with acoustic properties spacer fabrics have been extensively studied [1–6]. 3D knitted spacer fabrics are three-dimensional knitted fabrics consisting of two layers of outer fabric that are connected by a layer of, usually, monofilament, synthetic fibres (Figure 1).

Figure 1. Side view of a 3D spacer fabric.
While the behavior of 3D warp-knitted spacer fabric in compression has been investigated and modeled so that the typical compression stress strain curve has been determined (Figure 2) [7–11], the mechanical behavior of the fabrics regarding time dependent deformations has not been yet investigated. The different areas on the typical compression graph have to do with the rearrangement of the interconnecting monofilaments during the compression among themselves and with the outer layers. The compression in the densification stage (stage III) shows a rapid increase of the force due to the swift densification of the entire fabric.

![Typical compression stress-strain curve](image)

**Figure 2.** Typical compression stress strain curve of 3D spacer fabric where the three distinct areas are visible.

By comparison the time dependent properties of materials (creep/ stress relaxation) present a very different behavior. Specifically stress relaxation is defined as the observed decrease in stress in response to the same amount of strain generated in the structure. This is primarily due to keeping the structure in a strained condition for some finite interval of time and hence causing some amount of plastic strain. The inverse phenomenon is called creep, which is defined as constant state of stress with an increasing amount of strain. The graphic illustration of stress relaxation can be seen in Figure 3.

![Stress relaxation](image)

**Figure 3.** Stress relaxation a) Applied strain, b) induced stress as function of time.
2. Materials-methods
In this research project two samples of 3D warp knit fabrics (Table 1) with different weights where subjected to a compression deformation cycle of 1mm. The deformation was maintained for 4 mins. This interval was chosen since from preliminary tests it was observed that the phenomenon of stress degradation for these samples was moving towards equilibrium within this time. During compression the load that developed on the specimens was recorded (Figure 4).

| Sample   | Composition      | Weight (g/m²) |
|----------|------------------|---------------|
| 51100120 | 100% Polyester   | 900           |
| 50100130 | 100% Polyester   | 1120          |

The load results were plotted over time and the resulting graphs were analysed with regards to the behaviour of the material. Firstly, stress relaxation phenomena were investigated in accordance with the exponential laws described in the literature. For all samples there was little agreement between the results and the behaviour described in the literature. Then the case of the creep in bending of viscoelastic beams, was investigated. This approach was applied to the behaviour of the interconnecting monofilaments during the deformation cycles and good agreement was achieved between the model and the experimental results.

3. Results and Discussion
From the literature the relationship between the applied strain and the induced stress can generally be described following Maxwell’s model as follows, (Equation 1) [12].

\[
\sigma = \sigma_0 e^{-Kt}
\]  

where \( K \) is a constant representing the rate of spontaneous stress relaxation and \( \sigma \) and \( \sigma_0 \) are the stresses at times \( t \) and 0.

As can be seen by Equation 1, the relationship between time and stress is exponential in nature. When attempting to model the results of the experiments following the exponential relationship between the stress results (Figure 4) and time, there was little agreement between the results and the fitting curves produced.

In order to model the behaviour of the 3D spacer fabrics extensive review of the behaviour of viscoelastic materials under the application of stress/strain, was carried out. During this research the
laws describing the creep in bending behaviour of elastoviscoplastic beams [13] were located and fitting curves were produced based on this type of behaviour.

This approach showed good agreement with the behaviour of the 3D samples. In Figure 5 the results for sample 51100120 can be seen together with values obtained using the model that was produced. The curves follow a tendency of a logarithmic function, indicating the dominance of the secondary creep characterized by a stationary deformation rate as described in the work by Hadid et al. [13]. The behavior of the materials can be broadly described by Equation 2.

\[ \sigma = -A \ln \sigma_0 + B \]  

(2)

Where parameters A and B are connected to the structure of the 3D fabric and the composition of the interconnecting monofilaments.

4. Conclusions
Based on the analysis of the stress degradation curves produced by the compression of the spacer fabric specimens it was shown that the time dependant properties of the fabrics are connected to the creep bending of the interconnecting yarns. This observation underscores the complexity of 3D warp knit fabrics and the need for further investigation of time dependant properties of these materials.

References
[1] Yip J and Ng S-P Study of three-dimensional spacer fabrics: 2009 Molding properties for intimate apparel application J. Mater. Process. Technol. 209(1) 58–62
[2] Armakan DM and Roye A 2009 A study on the compression behavior of spacer fabrics designed for concrete applications Fibers Polym. 10(1) 116–23.
[3] Vassiliadis S, Kallivretaki A, Psilla N, Provatidis C, Mecit D and Roye A 2009 Numerical modelling of the compressional behaviour of warp-knitted spacer fabrics Fibres and Textiles in Eastern Europe 76(5) 56–61.
[4] Umbach KH 2000 Physiological comfort on car seats Kettenwirk-Praxis 34(1) E9–E13+34-40.
[5] Rajan TP, Souza LD, Ramakrishnan G and Zakria GM 2016 Comfort properties of functional warp-knitted polyester spacer fabrics for shoe insole applications. J. Ind. Text. 45(6)1239–51.
[6] Arumugam V, Mishra R, Militky J and Novak J 2015 Thermo-acoustic behaviour of 3D knitted spacer fabrics Fibers Polym 16(11) 2467–76.
[7] Mokhtari F, Vaghefi PM, Shamshirsaz M and Latifi M 2013 Analysis of compressibility behavior in warp knitted spacer fabrics: experiments and van wyk theory J. Eng. Fibers and Fabrics 8(3):6.
[8] Hou X, Hu H and Silberschmidt VV 2012 A study of computational mechanics of 3D spacer fabric: factors affecting its compression deformation J. Mater. Sc. 47(9) 3989–99.
[9] Li M 2015 Effect of structural parameters on compression performance of warp-knitted spacer fabric *Journal of Fiber Bioengineering and Informatics* 30(2) 267–76.

[10] Liu Y and Hu H 2016 Compressive mechanics of warp-knitted spacer fabrics. Part I: a constitutive model *Tex. Res. J.* 86(1) 3–12.

[11] Mecit D and Roye A 2009 Investigation of a testing method for compression behavior of spacer fabrics designed for concrete applications *Tex. Res. J.* 79(10) 867–75.

[12] Vorotnikov GS and Rovinskii BM 1966 Stress relaxation, creep, and uniaxial strain: General and special features *J. Appl. Mech. Tech. Phys* 7(6) 13-7.

[13] Hadid, M., Saadallah, Y., Debilou, A. et al. The creep of an elastoviscoplastic beam under a bending loading *Mech Time-Depend Mater* 18: 573-87.