NUMERICAL SIMULATIONS OF 3D-DISTANCE FABRICS

VOTRUBEC, VLASTIMIL*

VÚTS, a.s., Department of Virtual and Applied Mechanics, Svárovská 619, Liberec XI – Růžodol I, 460 01 Liberec, Czech Republic

ABSTRACT

This paper presents the results of numerical simulations conducted on inflated panels made from 3D distance fabrics. 3D distance fabrics constitute a subset of 3D woven fabrics. If coated, the structure of the fabric permits the formation of a panel with parallel layers through the process of air inflation. The pressurised air creates a stiff, lightweight and fail-safe structure that can be utilised in a multitude of applications. The mechanical behaviour of these panels can be described analytically by appropriate mathematical theory; however, this approach remains limited to common loading cases. This paper presents computational method for numerical simulations of inflated panels, including determination of the deflections of skins and the distribution of stress. The simulations are based on the results of material property tests and a nonlinear geometric model. The results are then compared with the mathematical theory and experimental data. The results demonstrate the efficacy of this approach and illustrate its advantages. Furthermore, an illustrative example of a specific loading case is presented to demonstrate the versatility of this approach for predicting the behaviour and conducting structural analysis of loaded 3D fabric panels.

KEYWORDS

Simulations; FEM; Distance fabric; 3D fabric.

INTRODUCTION

3D distance fabric is composed of two distinct skins, the upper and lower fabrics, which are simultaneously woven and connected by pile (drop) yarns (Figure 1). The pile yarns serve to lock the two skins together, thereby creating a robust connection. The base fabrics are separated from one another by a distance equal to the length of the pile yarns. This length constitutes a fundamental parameter of the fabric, as it defines its shape and stiffness, and is contingent upon the properties of the weaving machine. This is typically maintained at a constant length, ensuring that the inflated panel exhibits parallel and uniform surfaces. It is likewise feasible to weave distance fabrics with varying lengths of pile yarns; however, the primary advantage of this structure lies in its parallelism of skins. The skins are rendered impermeable through the application of an additional coating material (e.g. PVC, polychloroprene, etc.). The stability and load capacity of inflatable panels depend on their material properties, air pressure, fabric parameters, and shape. During inflation, the air pressure causes biaxial pretensioning of fabric layers and elongation of pile yarns, thereby enabling the panel to achieve the requisite shape and stiffness. 3D distance fabrics, also known as drop-stitched fabrics or space fabrics, offer numerous advantages, including a lightweight structure, portability in a non-inflated state, and a fail-safe mechanism during overload conditions.

The research of 3D fabrics is primarily concerned with woven and knitted fabrics in general where yarns in the third axis are present and the thickness of the fabric is negligible. A survey of 3D woven fabrics can be found in references [1-3]. Earlier research on the mechanics of inflatable fabric structures was limited, with only a few studies conducted on distance fabric panels [4]. Cavallaro [5] described the mechanics of a panel subjected to a four-point bending load, utilising experimental data from material tests to inform his analytical model. Additionally, he conducted an experiment on a bent panel for comparison. Hou [6] employed the finite element method to model knitted spacer fabric. A notable area of development has been the utilisation of these fabrics as reinforced composites [7].

The paper outlines the creation of an appropriate material model and the requisite tests for it (section Material model). It then describes the general rules for building FEM model of the panels and presents the building of a specific FEM model of a panel based on real-world testing (section FEM model). It then presents the results of the simulations and discusses the comparison with the theoretical and experimental results (section Simulation results). Finally, it presents the simulation of an overloaded panel as an

* **Corresponding author:** Votrubec V., e-mail: *vlastimil.votrubec@vuts.cz*

illustrative example of the indispensable role of numerical simulations in the design and analysis of distance fabric panels (section A comparison between the experimental and theoretical results).

MATERIAL MODEL

A comprehensive understanding of the material data is essential for the successful development of a model. In order to serve as a point of reference, real coated 3D distance fabric was selected for the purposes of experimental and simulation validation. The fabric is composed of a primary fabric woven on a weaving machine DIFA produced by VÚTS, a.s. All yarns (warp, weft and pile) are made of polyester (PES) with a fineness of 55 tex. The outer surfaces of the fabric skins were coated with polychloroprene on a nylon fabric substrate. The coating does not typically impact the mechanical properties of the material; however, it does ensure airtightness. Figure 2 illustrates the structure of the fabric and its basic textile properties, as produced by the Taiwan Textile Research Institute.

Textile materials, including yarns and fabrics, typically exhibit nonlinear tensile properties. However, the deviation from linearity is typically minor, with a constant young modulus. Fabrics are composed of two types of yarns: warp and weft. These are woven with varying densities, and warp and weft yarns may also differ in material and fineness. Consequently, fabrics are orthotropic materials, exhibiting nonlinear properties in both the warp and weft directions.

The tensile curves of the fabric were measured on a universal testing machine (Instron) in accordance with the standard ISO 13934-1, which outlines a procedure for determining the maximum force and elongation at maximum force using a strip method. Furthermore, the specimens were modified to a dog-bone shape, thereby ensuring that rupture occurred in the centre of the specimen, rather than in the jaws (Figure 3 on the left). The specimens were marked with white dots on the coated surface in order to facilitate the measurement of strain with an optical extensometer. The pile yarns were measured in accordance with the standard ISO 2062 on the same testing machine with pneumatic textile jaws (Figure 3 on the right). For the purpose of measuring strain, small balls with a through hole were placed and glued on the yarns. A tensile test was conducted on fabric skins and pile yarns using a universal testing machine.

The tensile curves are presented in Figure 4. It is evident that there is a notable distinction between the warp and weft tensile properties, as well as a nonlinear character. However, the divergence from the linear course is not substantial, and for the purposes of simulations, it can be approximated by a line. Notably, in the initial portion of the tensile curve, the variance is minimal. In the textile industry, it is customary to relate the tensile properties, strength of the fabric, and young modulus to the unit width of a fabric. Similarly, this approach is also employed in this case.

It should be noted, however, that FEM software requires the input of a material model in stress/strain quantities. Therefore, both tensile curves of fabric and pile yarns are recalculated in order to obtain the stress-strain dependence, despite the fact that the absolute values lack practical significance.

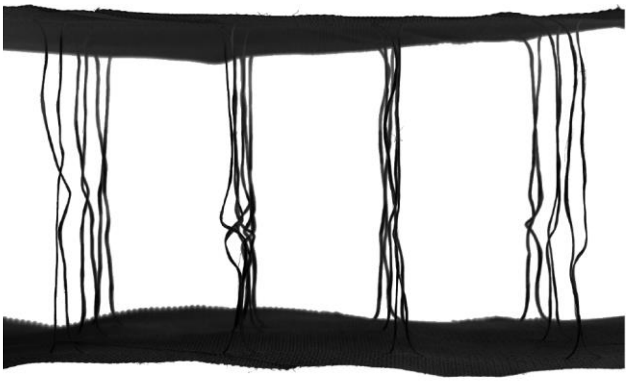

Figure 1. An example of 3D distance fabric.

Figure 2. The 3D distance fabric made by Taiwan Textile Research Institute. Total warp pile is 64 650 with different density after warp (150 ends/10 cm) and weft (4.31 ends/ 10 cm). The length of pile yarns is 180 mm.

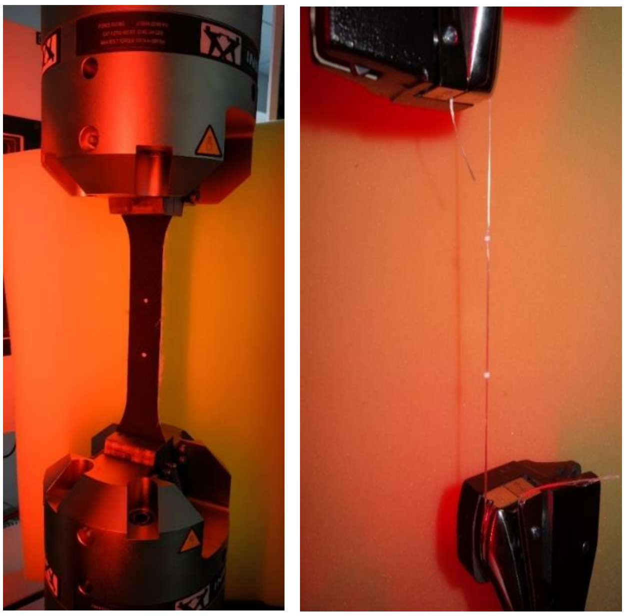

Figure 3. Tensile test of fabric skin and pile yarns using a universal testing machine.

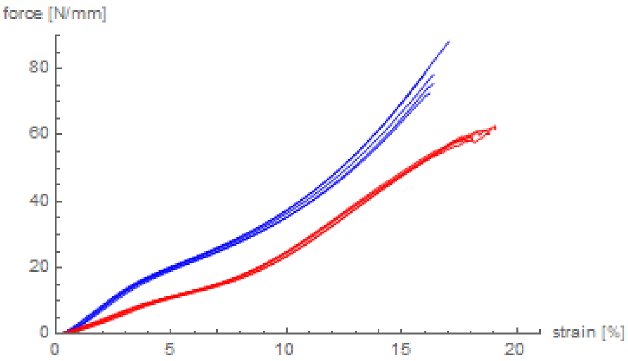

Figure 4. The tensile curves of the fabric skin for both the warp and weft directions. The units are related to the 1 mm width of the fabric.

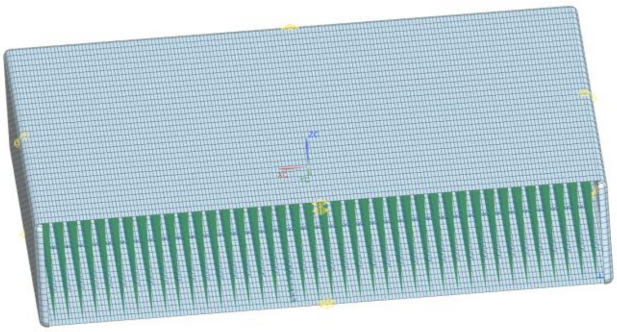

Figure 5. A section of the simulation model of the 3D distance panel. The mesh on the skins is created in such a way that four elements are placed after warp, which ensures an accurate representation of skin deflection. The green lines represent pile yarns, while the blue crosses represent suppressed displacements.

The combination of a nonlinear tensile curves and an orthotropic material presents a significant challenge for modelling. The nonlinear solver in the Siemens NX software is designed to work with isotropic nonlinear materials or orthotropic linear materials. However, it has been observed that using linear and orthotropic materials results in a smaller error. The calculated Young modulus of fabric is 428 MPa for the warp and 299 MPa for the weft.

FEM MODEL

The FEM model was built in a manner analogous to that of the tested panel. The dimensions of the panel used for experiments are identical to those of the modelled panel, namely 94 x 94 mm in area, 180 mm in thickness and subjected to a loading pressure of 100 kPa. The tested panel differs in that the edges were affixed by adhering the ends of the fabric and clamping them together with steel bars. The common application of a glued belt necessitates the replication of this panel in the same manner.

It is essential to prepare the geometry of the fabric panel in an inflated state. There is no relevant reason for simulating the panel in its undeveloped state, as this would entail significant difficulties. The model's geometry corresponds to the state, wherein the pile yarns are extended but the axial force is still zero, and the fabric skin between the binding points is not deflected. The side belt of the panel is affixed to the upper and lower skins, and thus is modelled and simulated. However, the model lacks a glue layer, the fabrics (and meshes) are connected directly. This is a reasonable simplification, as the stress distribution is analysed with precision and the computation is considerably more straightforward. Furthermore, potential sources of computational errors in corners are eliminated.

A further significant issue pertains to the question of bending stiffness. The actual bending stiffness of a fabric can be considered to fall between the values of a membrane, which exhibits no bending stiffness, and a solid sheet, which demonstrates full bending stiffness and is dependent on the thickness of the fabric. The modelling of fabric as an aerial body can be achieved through the use of shell elements. These elements permit the setting of arbitrary bending stiffness, although this is limited to a linear solver. Consequently, the bending stiffness cannot be adjusted. The behaviour of coated fabric is further complicated by the fact that the coating is situated on only one side of the fabric. This results in a dependence of the bending stiffness on the direction of bending loading, as the coated side of the fabric exhibits a greater bending stiffness than the uncoated side.

Pile yarns are represented as one-dimensional continuous rod (CROD) elements. The aforementioned elements are responsible for connecting the upper and lower skins, which have been prepared in accordance with the specified nodes, in a regular pattern. Non-linear material is assigned to these elements, thereby allowing for compression without stiffness. The young modulus of the tensile part of the curve is calculated from the measured tensile curve, while the young modulus of the compression part of the curve is set to be almost zero (zero is not a viable option). The inflation of the panel results in significant displacement of the side belt, causing the edgings of the skins to move towards the centre plane of symmetry. Here, the pile yarns undergo a reduction in length with no resistance, while in the middle of the panel, the pile yarns experience an increase in length.

The boundary conditions include the pressure loading on the inner walls and the suppressed displacements at specific nodes. The pressure value was set to 100 kPa, which is typical for common applications. All lower binding points (nodes for pile yarns) were disabled to enable vertical movement, thereby simulating the free inflation of the panel. To suppress displacement of the panel in both horizontal axes, one line of lower nodes in each direction was disabled to move.

SIMULATION RESULTS

The simulation results, namely the fabric deflections (Figures 6 and 7), are in accordance with the observed experimental outcomes. The greatest deflection is observed in the panel sides, which lack the fixation provided by pile yarns in the upper and lower skins. However, from the perspective of mechanics and real-world applications, the displacement of the fabric in the vertical direction (z-axis) is of greater significance. It is expected that the elongation of the pile yarns (measured in distance) will correspond to the results obtained from the experimental and analytical studies. A closer examination of the fabric surface reveals a series of undulations, indicative of a pronounced deflection of the fabric between pile yarns following the warp direction. Conversely, the deflection of the fabric between pile yarns after weft is nearly negligible. The discrepancy can be attributed to the notable disparity in the density of the pile yarns following the warp and weft processes. The height of the "wave" (the distance between the binding point and the peak value) is another crucial parameter in panel mechanics. It is also employed for the validation of simulations, with a value of 0.8 mm for a 100 kPa pressure within the panel.

The values of strain and displacement demonstrate that the stresses are minimal, falling below the ultimate strength of the fabric and pile yarns. The concentration of stress is observed to be located around the mesh connections in corners where the simulation consistently produces slight distortions in the results. Another location of concentration of stress is in binding points, where the material exhibits non-standard behaviour. Nevertheless, the stress is consistently below the ultimate strength.

A COMPARISON BETWEEN THE EXPERIMENTAL AND THEORETICAL RESULTS

The deflection of skin u between binding points after warp is described by the following relation:

$$u(x) = \frac{D}{H}\frac{1}{k}\left(\frac{e^{k(D-x)}+e^{k\,x}}{e^{k\,D}-1} - \frac{e^{k\,D}+1}{e^{k\,D}-1}\right) - \frac{(D-x)^2}{H} + \frac{D}{H}(D-x)$$

where *D* represents the distance between the binding points after warp, *H* denotes the length of the pile yarns, and *k* incorporates the bending stiffness. This equation integrates the theories of thin plates and membrane theory. If the bending stiffness is disregarded (first bracket), the deflection shape transforms into a parabolic function. The maximum deflection occurs at the midpoint of the arc, where *x = D/2*.

The objective of the experiment was to measure the height of the profile (deflection of the skin) by means of a laser scanner and to compare the experimental data with theoretical predictions and then the simulation results (Figure 8). The vertical distance from the scanner was recorded for an increasing level of pressure. The test was concluded at the level of 120 kPa of air pressure inside the panel. Both the experimental and theoretical aspects were described in detail in paper [8], and thus no further details are provided here.

The data presented in Figure 9 comprises measured data, calculated data derived from aforementioned equation, and data obtained from the simulation. The data demonstrate a high degree of correlation. The displacements calculated from the FEM simulations exhibit discrepancies from the experimental data, particularly in the mid-arc region where the curve intersects with the theoretical curve, which does not account for bending stiffness. Closer to the margins

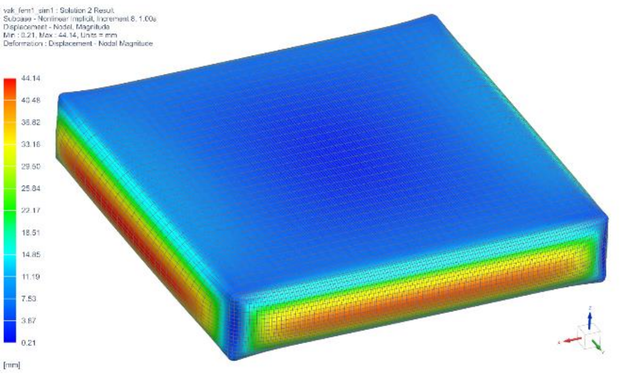

Figure 6. Displacements of pressure loaded fabric panel.

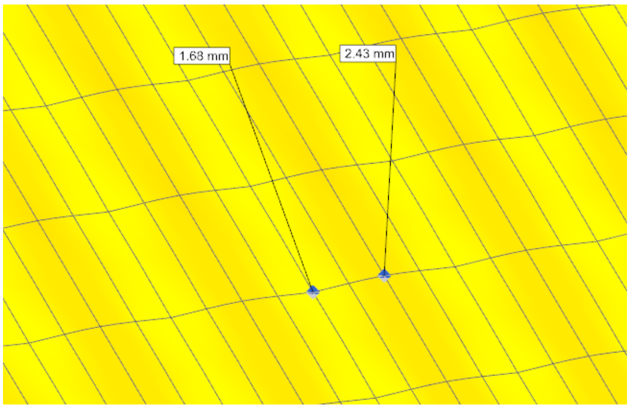

Figure 7. A detail of the displacements of the vertical axis of the bent fabric skin between the pile yarns.

Figure 8. The 3D distance fabric panel during the safety test. In the center there are visible deflections of the skin between binding points that were measured by a laser scanner.

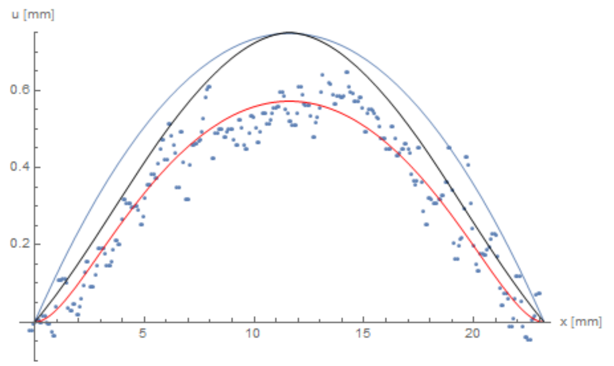

Figure 9. A comparison of the measured deflection of the fabric skin, loaded by 100 kPa (blue dots). The theoretical curve, derived from the equation, is shown in red. The interpolated simulation data is represented in black and a theoretical curve, which neglects the bending stiffness, is illustrated in blue.

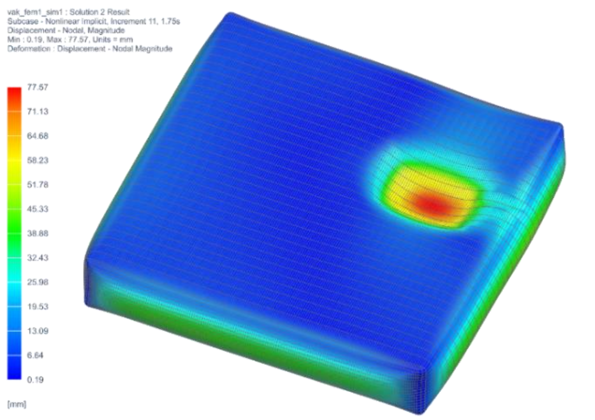

Figure 10. A case study of an overloaded fabric panel. Large displacements occur in the place of loading.

of the arc the simulation curve is getting nearer to the experimental data. However, due to the inherent limitations of the FEM model, as previously discussed, the agreement between the simulation and experimental data is still fine. When considering the absolute values of displacement along the arc, it is evident that the exact value is not a crucial parameter for practical applications. Instead, it serves primarily to validate the mathematical theory and ensure the accuracy of the simulations.

A CASE STUDY OF AN OVERLOADED PANEL

The advantages of this methodology are readily apparent when considering the example of the overloaded fabric panel. The panel is typically loaded by its working pressure, as illustrated in the preceding example. Additionally, it is subjected to a force 15 kN acting on an area of approximately 120 x 150 mm. This force causes significant deflection of the upper skin, with a maximum value of 78 mm. The depression almost reaches approximately half of the panel thickness, which is clearly unacceptable in practical terms. The maximum values of stress and strain are considerably higher than the typical range, yet they remain within the third of the tensile curve, indicating that the structure remains safe. Nevertheless, a discernible decline in stability is evident, attributable to the considerable displacements. The fabric between the depression and the panel edge exhibits slight warping, which presents numerical challenge. A larger load would result in computational collapse, which is not viable state for the panel. While the expansion of the panel can be well described analytically using the elongation of pile yarns, the external compression of the panel must be computed numerically. As with loading of panel sides, combined loading or complicated boundary conditions require the use of a numerical simulation via the finite element method is irreplaceable.

CONCLUSIONS

In many cases, numerical simulations are an invaluable tool for the analysis and design of air inflated 3D distance fabric structures. These simulations are based on precise material testing and the nonlinear computation of appropriate FEM software. The correlation between the outcomes of these simulations and the mathematical theory, as well as the results of physical experimentation, is highly satisfactory, thereby substantiating the efficacy of this approach. The benefits of simulation are most evident in the context of structures subjected to challenging boundary conditions, as illustrated by the example of an overloaded panel.

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REFERENCES

1. Badawi S.S.: Development of weaving machine and 3D woven spacer fabric structures for light-weight composite materials. Ph.D. Thesis, Technical university in Dresden, Dresden, Germany, 2007.
2. Chen X.: Advances in 3D Textiles. Woodhead Publishing, 2015.
3. Gokarneshan N., Alagirusamy R.: Weaving of 3D fabrics: A critical appreciation of developments. Textile Progress, 41(1), 2009, pp. 1-58. https://doi.org/10.1080/00405160902804239
4. Falls J., Waters J.K.: Bending test of inflatable dropstitch panel. Proceedings of the 11th International Conference on Fast Sea Transportation, Hawai, USA, 2011.
5. Cavallaro P.V., Hart C.J., Sadegh A.M.: Mechanics of air-inflated drop-stitched fabric panels subject to bending loads. Proceedings of ASME International Mechanical Engineering Congress and Exposition, ASME, 2013. https://doi.org/10.1115/IMECE2013-63839
6. Hou X., Hu H., Silberschmidt V.V.: A study of computational mechanics of 3D spacer fabric: Factors affecting its copmression deformation. Journal of Material Science, 47, 2012, pp. 3989-3999. https://doi.org/10.1007/s10853-012-6252-2
7. Chen X., Taylor L.W., Tsai L.J.: An overview on fabrication of three-dimensional woven textile preforms for composites. Textile Research Journal, 81, 2011, pp. 932-944. https://doi.org/10.1177/0040517510392471
8. Votrubec V., Žák J.: Mechanics of air-inflated 3D distance fabric. Applied and Computational Mechanics, 15(1), 2021, pp. 85 – 96. https://doi.org/10.24132/acm.2021.650