Improved Numerical Investigations of a Projectile Impact on a Textile Structure

Authors:

Gunther Blankenhorn [1], Karl Schweizerhof [1/2]
Hermann Finckh [3]
[1] Institut für Mechanik, Universität Karlsruhe, Germany
[2] also Dynamore GmbH, Stuttgart, Germany
[3] Institut für Textil- und Verfahrenstechnik Denkendorf, Germany

Correspondence:

Karl Schweizerhof
Institut für Mechanik
Universität Karlsruhe
D-76131 Karlsruhe
Germany

Tel: +49 (0)721 608 2070
Fax: +49 (0)021 608 7990
e-mail: Karl.Schweizerhof@ifm.uni-karlsruhe.de
www: http.//www.ifm.uni-karlsruhe.de

Keywords:
Impact, fabric, weave, finite element modelling

ABSTRACT

Past perceptions to the processes of the penetration mechanisms of projectiles acting on textile structures [1] are often based on continuum models [2] or simplified models [3] and admit only limited conclusions concerning the real behavior of protective clothing made from several layers of fabric. Only a few investigations are known up to now with models based on single yarns as a major component for discretization [4].

Thus, for the prediction of the protective effect of several layers of high-strength fibers in a textile, a structural approach is chosen by a separate modelling of each fiber by a shell or continuum based element. The single modelled fibers interact over a contact formulation with the adjacent fibers in the same way the fibers in the different layers do. This allows to model the in-plane motion and deformation of each fiber separately, as well as the failure of fibers thereby avoiding artificial localization effects to a great extent. With the so-called explicit finite element code LS-DYNA [8] different possibilities of the discretization of the fiber bundles are investigated. Also the description of the fiber material by available material models is varied modifying the load deformation relation and the damage evolution.

The goals of the current project [10] are first to achieve a geometrically consistent model of the layered structure and second to better understand the phenomenological process of the impact of ballistic projectiles on such textiles. Finally, the particular effect of different layer setups can be studied.

INTRODUCTION

Up-to-date bullet proof vests are consisting of several layers of fabrics made of high performance fibers like Kevlar® (Du Pont), Twaron® (Tijin) and Zylon® (Toyobo). These vests have a specific weight up to 2000 g/m². Many so called “trial-and-error” tests have to be performed to improve the weight of this vests. So far, only few attempts are known to predict the behavior of new constructions, like new fiber materials or different fiber materials for different layers, by way of exploring the mechanical phenomena. Numerical simulations by a finite element program could be a useful tool to detect this phenomena and they would allow the developers to optimize their products.
To perform a numerical simulation, some research into fiber and fabric geometry and their possibilities to approximate them through finite elements is necessary. Also, the material behavior of the fibers exposed by high velocity loading must be measured to choose a suitable material model.

The objective of this paper is the description of the fabric geometry, the discretization by shell and solid elements and first investigations of the model behavior in the analysis.

Weave geometry and fiber properties

Fabric and fiber geometry
Following the approach to discretize the weave through a collection of single yarns, the shape of the cross section and the curve through the center of gravity of the cross sections must be acquired. To get this information of an unloaded weave, two specimen of a Kevlar® weave were embedded in epoxy resin. One of them was ro-

tated by 90° to the other one to obtain the cross section geometry of both yarn type's in a fabric, the fill yarn and the warp yarn. The epoxy resin specimen was cut off in a plane perpendicular to the two fiber types and pictures were taken with the help of an optical light microscope. Several pictures are taken from different planes perpendicular to the fiber cross section, one of them shown in Figure 1. It becomes obvious that the shapes of the cross sections of the two yarn types are different, but each shape does not vary much along the corresponding length axis. By this perception the curve geometry of the fiber length axis of one of the yarns can be defined through the upper or lower shape of the cross section of the other yarn. With the approximation of the lenticular shape of the fiber cross section by two circle segments, a mathematical description of the weave geometry is possible. This description is then used to generate the geometry, followed by the discretization by either shell elements or solid elements.

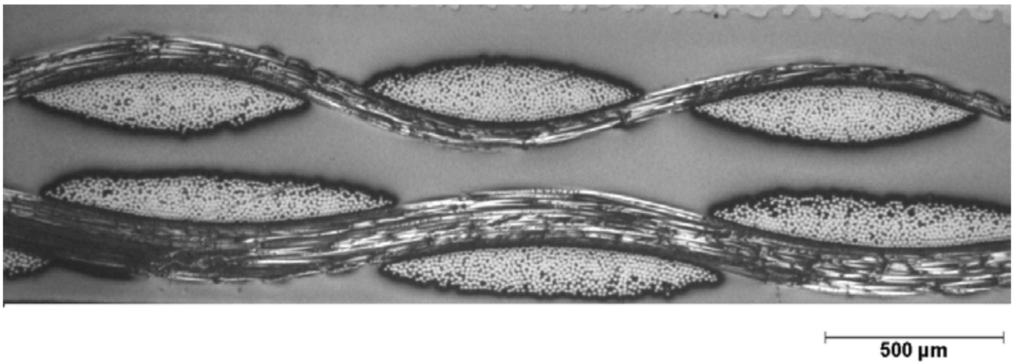

Figure 1: Optical light microscopy picture of a Kevlar® weave

Material properties of high performance fibers under high-speed loading
Petterson, Stewart, Odell and Maheux [6] reported that Hookean behavior of nylon yarns is not valid for high rates of straining. A first approximation of the strain rate behavior of this kind of materials is a viscoelastic - viscoplastic material behavior, were the strain rate depends on the loading velocity. Since a yarn consists of many single filaments and for the rupture of the whole yarn the rupture of every single filament is necessary, damage processes must be taken into account. The filaments of a high performance fiber are strictly oriented in fiber length direction. This implies a transversal isotropic behavior.

All these phenomena should be considered in the formulation of the constitutive equations, which are needed for a correct finite element simulation. However, at the time of writing this article preparations for detailed experimental material studies are still under way.

Geometry discretization of the weave

Previous approaches
In the past, many different approaches for numerical investigations of the impact of projectiles on textile structures were made. One typical model is reported in Shim, Tan and Tay [3], using a network of viscoelastic fiber elements. These fiber elements are pin-joint connected at crossover points at so called nodes, and on each node the

mass of half the fibers connected to them is assigned. One of the disadvantages of this model is the absence of friction between two yarns crossing each other.

Current approaches
A state-of-the-art model is suggested by Barauskas and Vilkauskas [4] using shell theory to discretize the single fiber. The cross-section of a single fiber is approximated by several adjacent shell elements with different thicknesses.
As an alternative Tabiei and Ivanov [2] developed a material model for membrane type shell elements, using a micro-mechanical and a homogenization technique for simulation of the ballistic impact on textile structures.

Discretization with shell elements
The geometrical model generation is based on the pictures taken from a light-optical microscope. The lenticular shape of the fiber cross-section is approximated through two circle segments (see left figure in Figure 2). Connected to this cross-section geometry the axis of a perpendicular fiber in it’s length direction is a curvilinear line of several alternating circle segments. Based on these assumptions a geometrical model can be generated directly by a mathematical description.

Discretization with solid elements
This follows the geometric assumptions made for the shell elements as described above. The first advantage of the discretization by solid elements is a smoother surface for the cross section because the boundary geometry can be approximated by a polygon (see Figure 2). The other advantage of the solid element model is the chance of capturing the damage process within a single fiber in the cross section. Shell elements with different thickness show a jump at the element boundaries. A smooth surface will pose a major improvement for the reproduction of the frictional process. The disadvantage of the solid element model is the computational cost as a consequence of the rather large number of elements needed for this kind of generation.

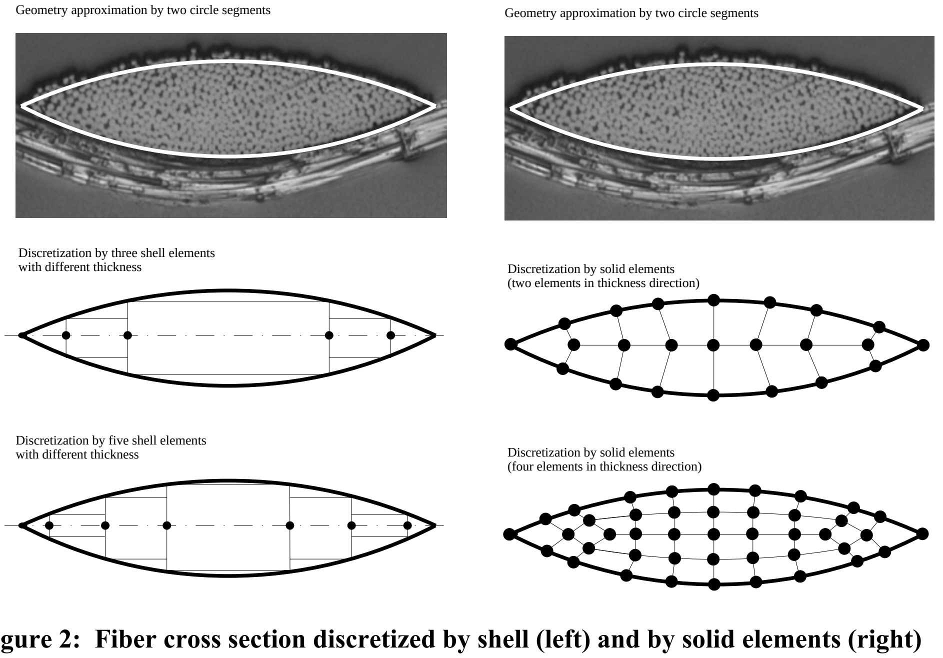

Figure 2: Fiber cross section discretized by shell (left) and by solid elements (right)

Material models

LS-DYNA [8] offers many constitutive models for simulating various materials. To find the right one for both, the shell elements and the solid elements, the observed mechanical phenomena at high speed loading of the fibres as described above must be taken into account. A material model such as MAT 104 [9] which can represent the viscoplastic material behaviour could be used. The damage process must be characterized and an option for element erosion is needed. Current efforts are directed to get experimental data of the fibre behaviour under high strain rates, like they are observed for ballistic impacts. These experimental data are needed to identify the parameters used in the different constitutive equations.

Example Simulation

In a first test simulation a single layer of Kevlar® is impacted by a MFK projectile at a velocity of 100 m/sec. The geometry of this fabric is acquired as described above and the fibres are discretized by two solid elements in thickness direction and five elements in width direction (Figure 3). Because of missing material data for high speed loading, the static ones are used in this analysis. No conclusions about the quantitative deflection of the weave can be drawn due to the absence of some important material parameters, but the general modelling can be verified. The deflection figure of the fabric in the shape of an pyramid (Figure 4 and Figure 5) is in agreement with high speed photography investigations done by Cunniff [1].

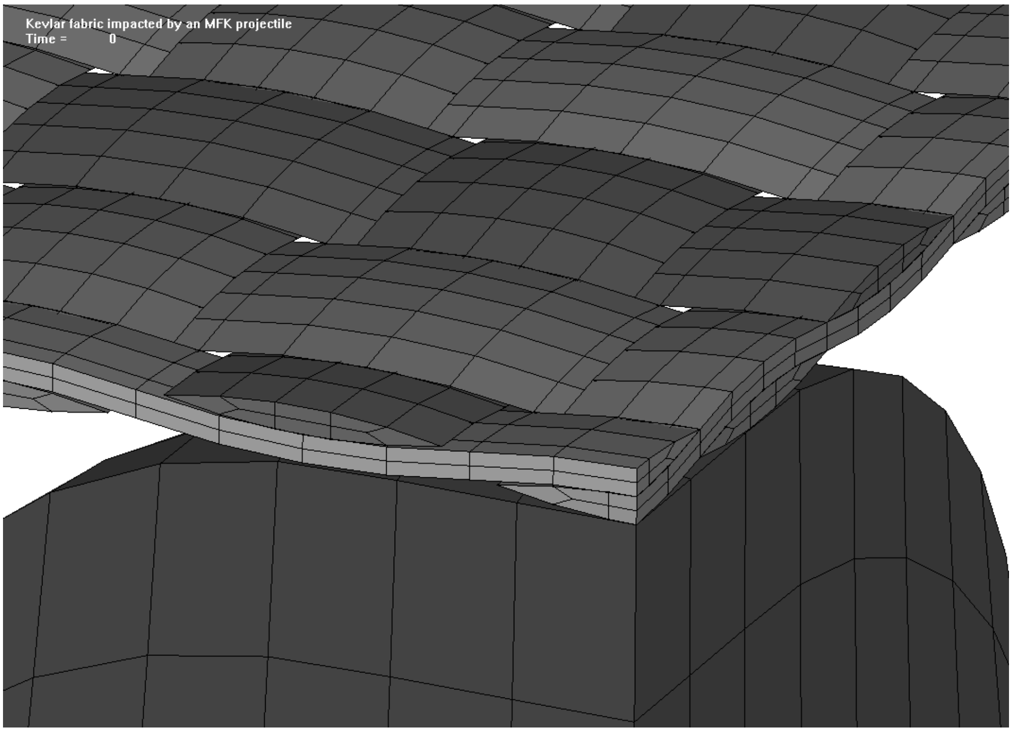

Figure 3: Discretization of the fabric and projectile; symmetry conditions assumed

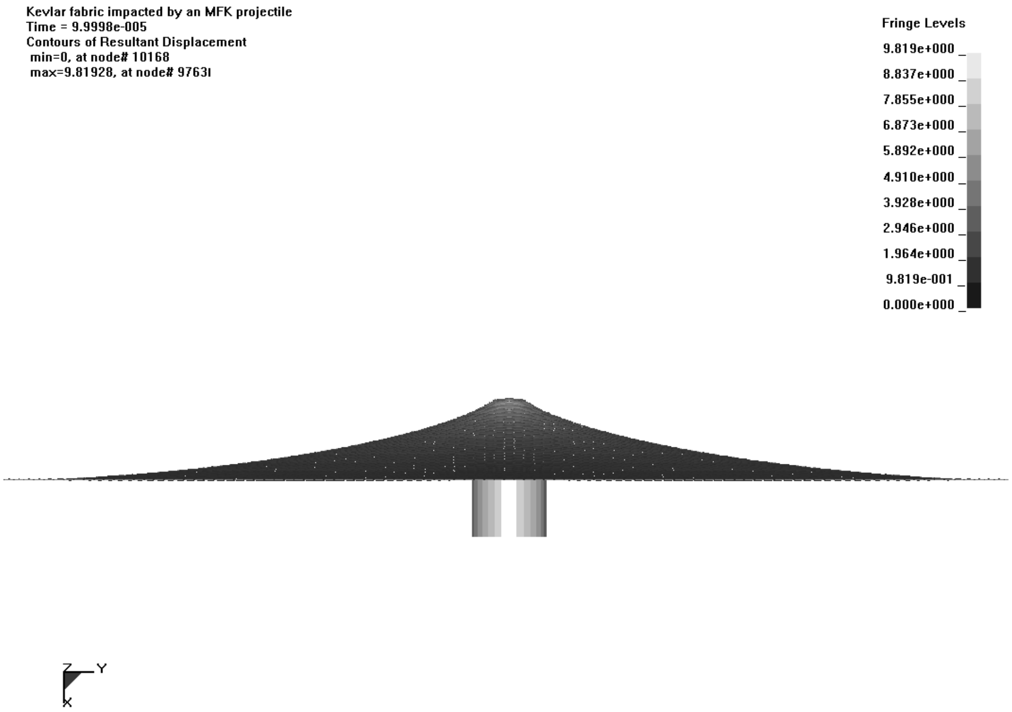

Figure 4: Impact of a MFK projectile on a single layer Kevlar® fabric (lateral view)

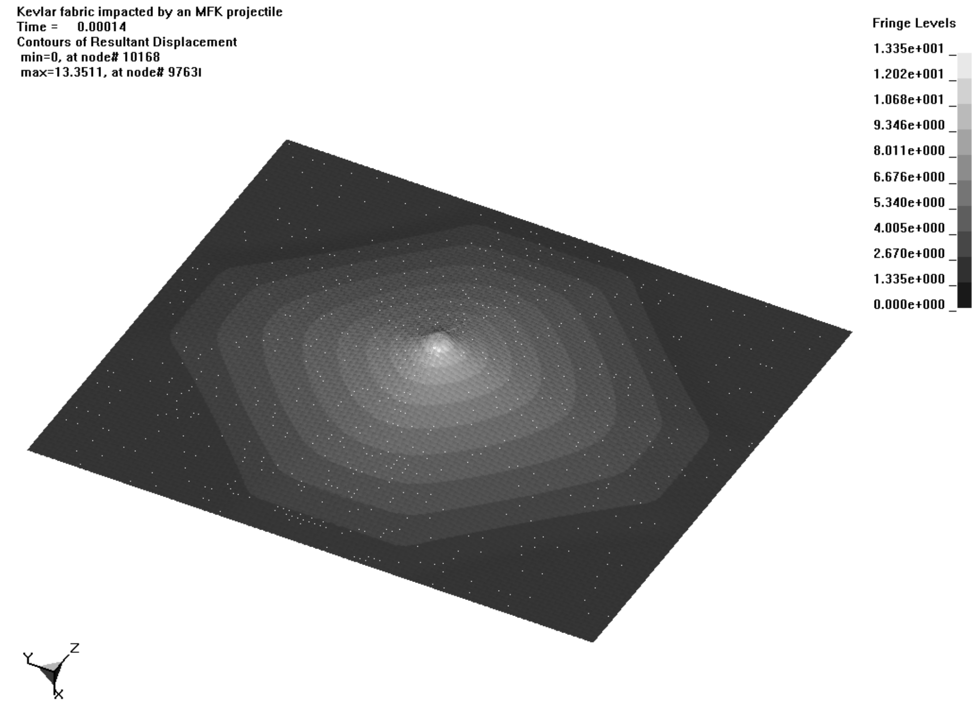

Figure 5: Impact of a MFK projectile on a single layer Kevlar® fabric (isometric view)

The models for multi-layer textiles with shell elements have been finished and have been analyzed with elastic material and element erosion to simulate the interlayer behavior (Figure 6).

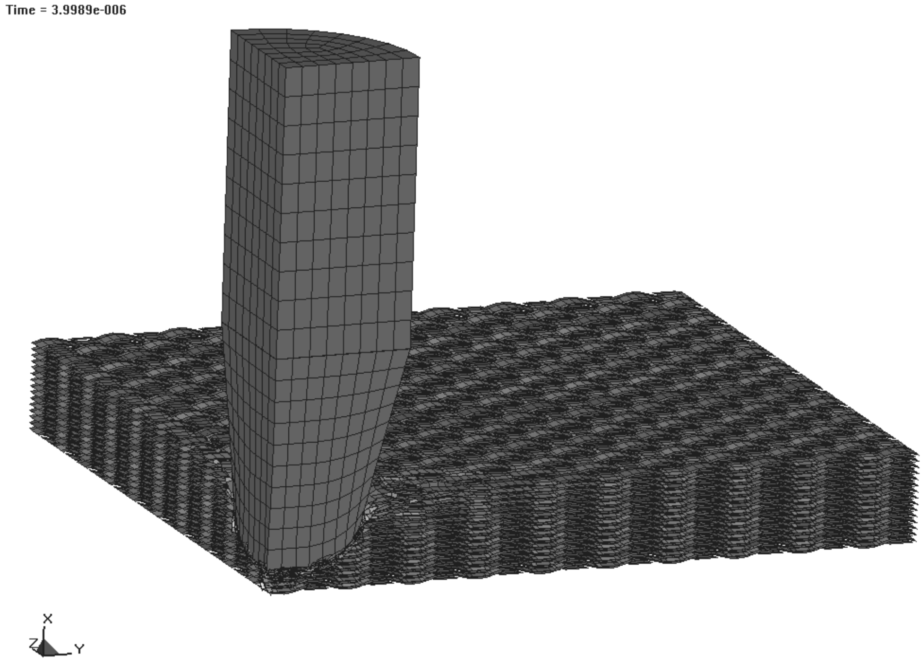

Figure 6: 15 layer fabric, discretized by shell elements, impacted by a MFK projectile

Outlook

Currently, work is under way to obtain material data for the fibers at high speed loading. After this, the parameters of the constitutive equations can be identified and simulation results can be compared with experiments.
A second focus is on the definition of the boundary conditions at the unloaded end of the fabric, which have a major influence due to the reflection of the stress wave.
The final goal of this investigation is the simulation of a multi-layer textile lying on a clay block, as it is prescribed in the German standards [7].

Acknowledgements

The project of the authors is currently supported by the *Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V.* This support is gratefully acknowledged.

References

[1] Cunniff, P.M., An analysis of system effects in woven fabrics under ballistic impact, Textile Research Journal, 1992, 62(9), p. 495-509

[2] Tabiei, A., Ivanov, I., Computational micro-mechanical model of flexible woven fabric for finite element impact simulation, International Journal for Numerical Methods in Engineering, 2002, 53(6), p. 1259-1276

[3] Shim, V. P. W., Tan, V. E. C., Tay, T. E., Modelling deformation and damage characteristics of woven fabric under small projectile impact, International Journal of Impact Engineering, 1995, 16(4), p. 585-606

[4] Rimantas Barauskas, Andrius Vilkauskas, Finite Element Analysis of Ballistic Properties of a Multilayer Textile Package in LSDYNA, Proceedings of the Nordic LS-DYNA Users' Conference 2002

[5] Anthony F. Wilde, David K. Roylance, Joseph M. Rogers, Photographic Investigation of High-Speed Missile Impact upon Nylon Fabric, Textile Research Journal, December 1973, p. 753-761

[6] Petterson, D.R., Stewart, G.M., Odell, F.A., Maheux, R.C., Dynamic Distribution of Stain in Textile Materials Under High-Speed Impact, Textile Research Journal, Vol. 30, No. 6, June 1960, p. 411-431

[7] DIN EN ISO 14876-2, Schutzkleidung Körperschutz, Teil 2, Widerstandsfähigkeit gegen Projektile, Anforderungen und Prüfverfahren, Deutsche Norm, Entwurf, März 2000

[8] LS-DYNA, Livermore Software Technology Corporation (LSTC), 7374 Las Positas Road, Livermore, CA, USA 94551

[9] LS-DYNA Keyword User’s Manual Volume II, March 2001, Livermore Software Technology Corporation (LSTC), 7374 Las Positas Road, Livermore, CA, USA 94551

[10] Entwicklung leichter durchstichfester Schutzkleidung mit Hilfe der rechnergestützten Simulation, AIF-FV-Nr. 12813 N/2, Förderung durch die Arbeitsgemeinschaft industrieller Forschungsvereinigungen