High Speed Impact – Test and Simulation

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Summary:

Deformation processes of structures under dynamic loading have been investigated both experimentally and by simulation for many years now. Various rate dependencies in many materials, wave and shock wave phenomena as well as material tests for their quantitative description have been identified. In parallel, mathematical formulations for the observed material behavior and numerical schemes for time dependent approximations of the governing partial differential equations have been developed.

Since both the experimental characterization and the numerical simulation demand for assumptions, e.g. the state and distribution of stress and strain in a specimen or in a discretizing unit, increasing complexity of materials demands for advanced test set-ups and numerical methodologies.

In this paper, a brief discrimination between the regimes of quasi-static, low-dynamic and high-dynamic loading conditions is given. Related experimental means for material characterization as well as components in the numerical model needed to represent the relevant physical aspects are given by some example cases.

Specific emphasis is placed on the characterization of low-impedance materials and on the implementation of a micro-continuum based fabric model into LS-DYNA. An application of the resulting fabric model to ballistic simulations is shown in the final part.

Keywords:

Dynamic material behavior, material testing, low-impedance materials, woven fabrics, impact simulation.

1 Regimes of Dynamic Loading Conditions

In the regime of static and quasi-static loads, the main focus of investigations, be it numerical or experimental, is placed on a state, i.e. the state of equilibrium between acting forces and structural deformation. The load and deformation path leading to that state is of interest only in the case of strong nonlinearities of which type ever.

A different perspective is given under dynamic loading conditions. Here, processes, i.e. the development of deformation and of wave propagation, are in of interest. Basically each load, applied to a structure as slowly as ever possible, is propagated via waves. A major characteristic of dynamic loads is that each individual waves package initiated by the rising load is of significance for the structural reaction. The same high pressure load, applied quasi-statically, that may lead to local elastic-plastic deformations, can be crucial for a structural integrity if applied dynamically. Specifically in the regime of shock wave propagation, each individual wave may cause failure both in the load application zone as in remote positions of the structure.

The keyword shock wave indicates that even the regime of dynamic loading needs to be split into different sub-regimes. Well-known aspects in modeling of low-dynamic processes are strain rate effects. Caused mainly by inertia mechanisms on microscopic or molecular levels, the rate of change in strain influences the mechanical behavior of many materials. This leads to phenomena like strain rate dependent yield stresses, hardening, softening and failure thresholds. Affected areas are processes like automotive crash, deep drawing or low velocity impacts in daily life.

In addition, there is another rate of change that can lead to dramatically changing material behavior. That is the rate of change in pressure amplitudes combined with a non-linear pressure-volume characteristic of the loaded material. It is that combination that leads to the initiation and propagation of shock waves in solids. And whenever arising, shock waves need to be treated since their characteristically short rise times to high pressures, densities and temperatures are non-negligible factors for the resulting material and, thus, structural response. Detailed derivations of non-linear equations of state for shock wave processes are given in [1].

Therefore, both material characterization and numerical modeling need to provide adequate methodologies to describe materials under the respective regimes of dynamic loading conditions.

In the context of this short paper, the experimental example will cover the characterization of low-impedance materials at strain rates around 10^3 [s^{-1}].

The new numerical methodology presented in this paper is related to the influence of micro-structural kinematics of yarns in woven fabrics on their behavior under impact loads.

2 Direct Impact Facility to Characterize Low Impedance Materials

The application of weak foams in automotive seats puts significant importance on their dynamic deformation behavior up to compression states of 80 to 90 percent at high strain rates. A typical facility to characterize materials in strain rate regimes between 100 [s^{-1}] and 5000 [s^{-1}] is the so called Split Hopkinson Pressure Bar (SHPB, Hopkinson [2], Kolsky [3]). However, for extremely low impedance materials like weak foams standard dynamic test set ups as the various Hopkinson Bar configurations are not applicable due to the weak signal to noise ratio resulting from the impedance miss-match and the limited compressions achievable (see Hiermaier [1] for details).

An experimental set-up that attacks both weaknesses of the classical SHPB applied to weak foams was proposed by Meenken [4] via a direct impact facility. As illustrated in Figure 7.9 the specimen is loaded directly by the striker's impact rather than by SPHB-typical wave transmission.

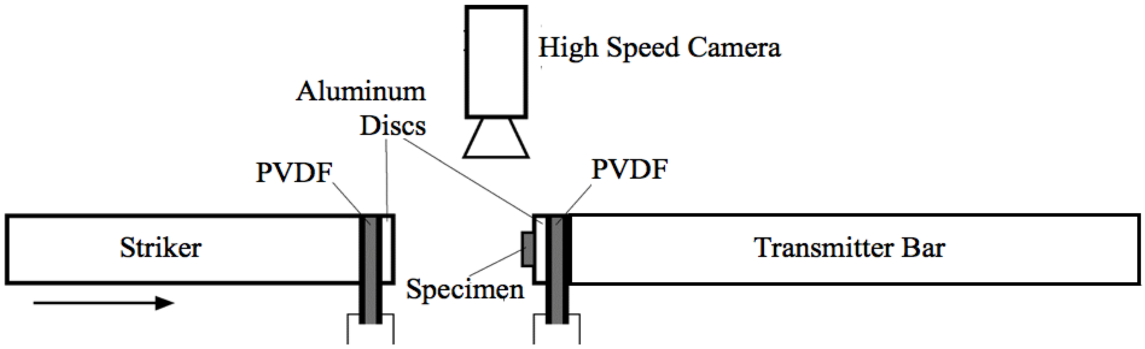


Figure 1: Direct impact facility for the dynamic characterization of low-impedance materials like foams (after Meenken [4]).

Application of a piezoelectric polymer called polyvenylidenfluorid (PVDF) in thin stress gauge foils attached to the interfacial surfaces delivers a clear and smooth signal for the stress measurement. The related compressive strain evolution is derived from optical instrumentation with high speed cameras.

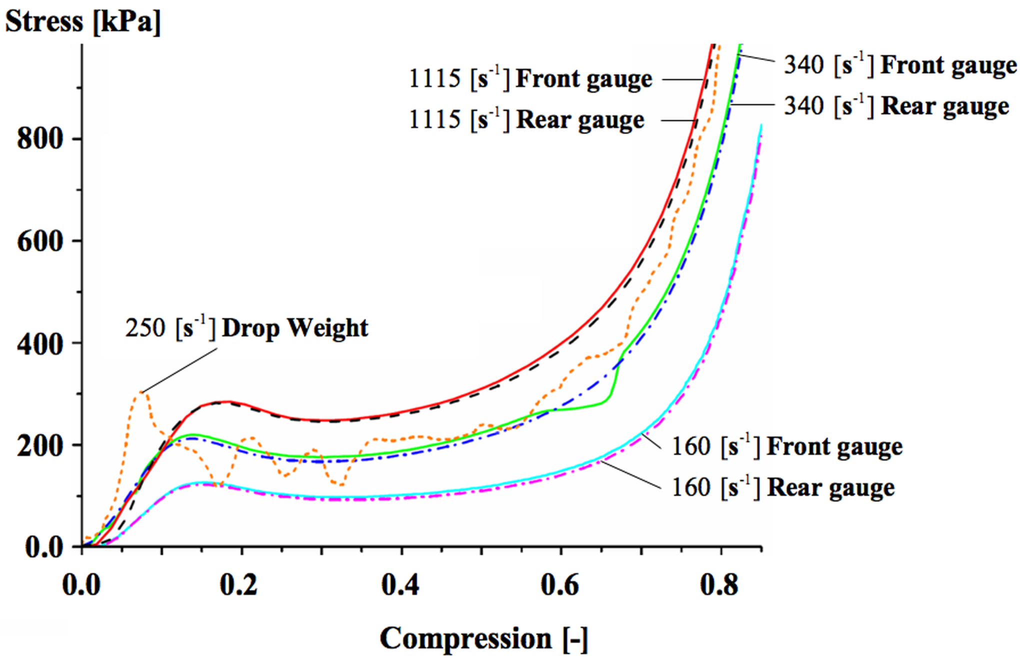


Figure 2: Stress-strain curves measured with the instrumented direct impact facility for Confor-Blue foam at average strain rates of 160 [s−1], 340 [s−1] and 1115 [s−1]. Front (solid lines) and rear gauge (dashed lines) signals are mostly overlapping. For comparison a result from a drop weight tower test at 250 [s−1] is added.

An example application of the direct impact facility to derive stress-strain relations for Confor-Blue foam at average strain rates between 160 and 1115 [s^{-1}] as reported by Meenken is illustrated in Figure 9. Two stress-strain curves were evaluated at each experiment. One by the stress-gauge applied to the striker, the second derived from the stress-gauge mounted at the transmitter bar. Comparison of the two signals allows for an estimate of whether a homogeneous stress distribution is present in the specimen.

3 Material characterization and modeling of woven fabrics

High stiffness and high strength at very light weight are combined within one material by so-called high-performance fibers, e.g., aramid and polyethylene with high molecular weight. Besides their exceptional mass-specific strength, most of these polymer fibers exhibit a very good chemical and thermal resistance.

Textiles made of these fiber materials are primarily used for the manufacturing of personal protective garment and the development of lightweight ballistic armor. Other fields of application can be found within the traffic and transportation sector. Airbag systems, parachutes and safety nets and fences are only few examples

Material properties of textile membranes are strongly influenced by the underlying two-dimensional fiber architecture. Besides the experimental challenges for the characterization of textile materials, e.g. special testing equipment and sophisticated gripping mechanisms, the modeling of the material deformation behavior is a challenging undertaking.

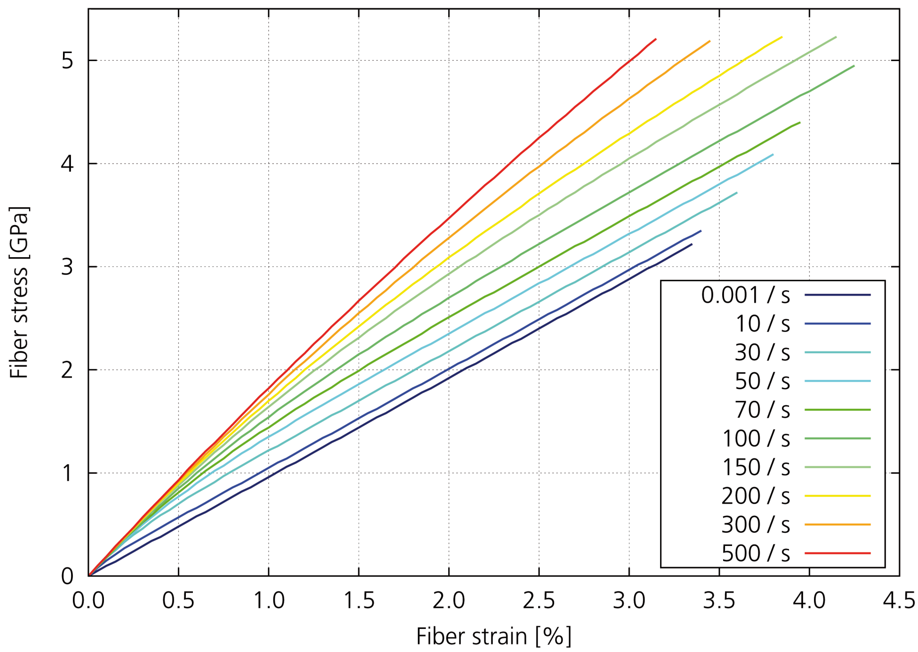


Figure 3: Modeled strain-rate dependence of aramid fibers.

For the evaluation of textile structures under high-speed loading conditions like impact or blast, it is important to take into account the setup of the fiber architecture, its construction parameters and the inherit material non-linearities, i.e., fiber viscoelasticity, plasticity or frictional effects. Unfortunately, woven fabric material models of commercially available finite-element codes are – in most cases – able to capture the specific properties of woven structures only indirectly, i.e., phenomenologically. The effects of characteristic yarn interaction mechanisms like

- crimp interchange
- yarn slippage
- yarn trellising
- yarn locking

are modeled by fitting generalized material models to non-linear experimental curves, without being able to take into account the source of the non-linearities. The aim of the development of an efficient and reliable material model at Fraunhofer EMI, therefore, was to capture the relevant yarn interactions at mesoscopic scale by applying a representative volume technique and by deriving the continuum stresses directly from the deformed representative volume cell at mesoscopic scale.

By the integration of a kinematic model at yarn level within the framework of a continuum mechanical material model, finite-element models of complex three-dimensional shapes can still easily be generated using commercial modeling tools. Moreover, since the deformation of the textile structure is evaluated at all integration points, the deformation of the woven fabric at the mesoscopic scale can be tracked and, thus, efficient and reliable simulation results can be achieved. Numerical studies on parameter variations are easily available and can be used to optimize the response of fabric structures for given loading conditions.

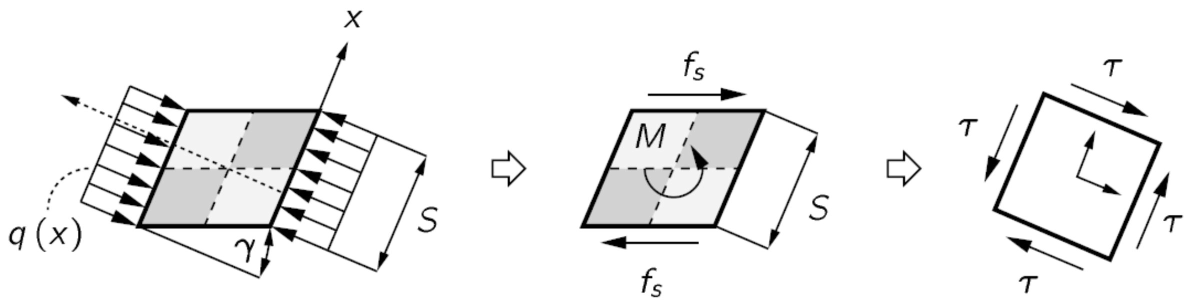


Figure 4: Derivation of a shear-locking moment.

Taking into account the influence of various weave styles was of particular importance during the model-development process since the shear behavior of woven fabrics is strongly influenced by the yarn interlacing type. The shear stiffness of woven fabrics can be derived from lateral compaction forces occurring at large shear angles between adjacent yarns (see Figure 4). If one focuses on the smallest repetitive unit of a certain interlacing type, a specific load distribution of these compaction forces can be obtained. Based on this distribution, a weave-type specific moment of shear resistance is deduced for any given weave style.

The woven fabric material model that has been developed at Fraunhofer EMI unites latest research efforts within the field of woven fabric modeling and has been implemented as user-defined material subroutine for shell elements within the explicit finite-element code LS-DYNA. The three-dimensional woven fabric structure is captured by the superposition of two individually orientated and transversally isotropic layers that represent the warp-yarn and the weft-yarn system, respectively (see Figure 17). All components of the final stress tensor are derived from the integrated kinematic model and are based on simple non-linear constitutive equations.

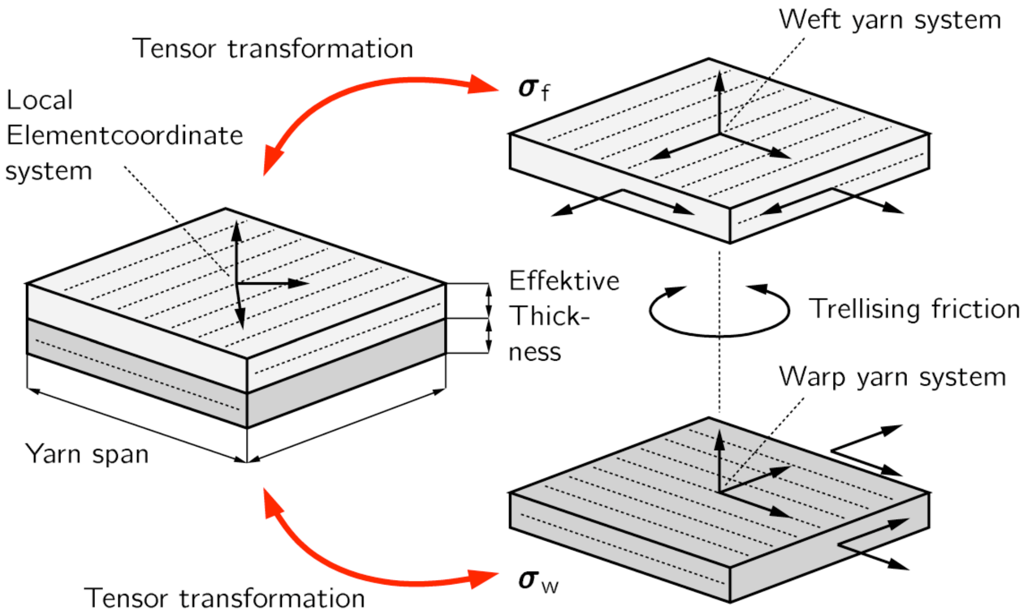
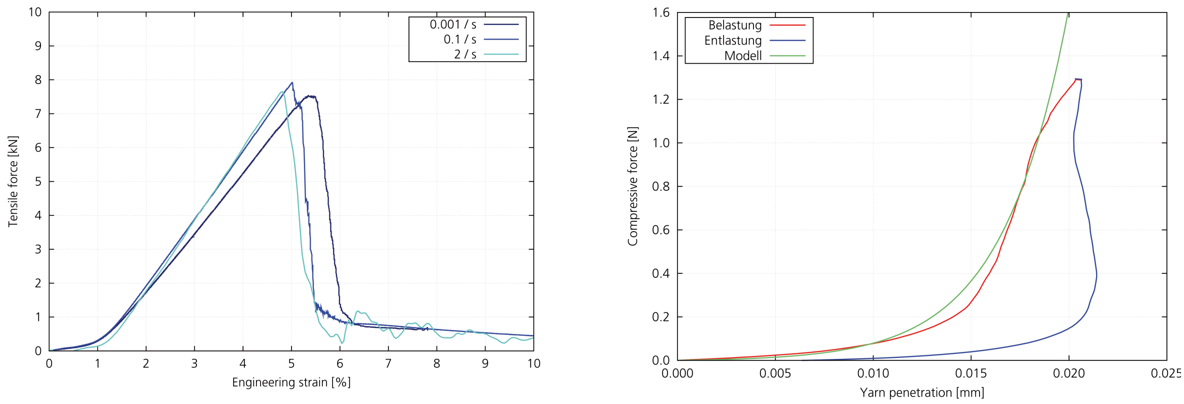


Figure 5: Derivation of a shear-locking moment.

Besides basic microscopic investigations in order to reveal weave-specific geometrical parameters, special experimental investigations have been performed to analyze the response of various aramid woven fabrics under different loading conditions. Representative results of different experimental setups are shown in force-displacement curves (see Figure 6) for a simple plain woven fabric that is widely used for ballistic impact applications.

Uniaxial tension (warp) Compression



Uniaxial tension (weft) Biaxial tension

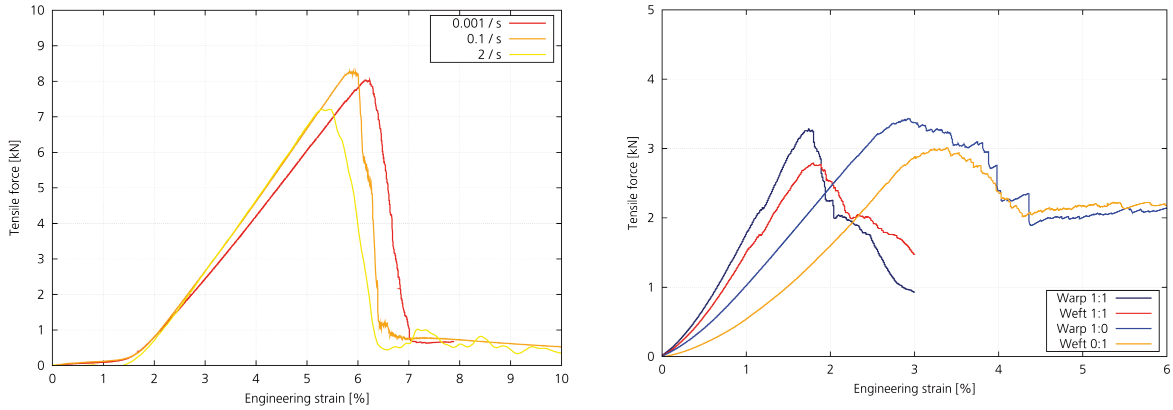


Figure 6: Force-deflection curves of experimental investigations for various deformation modes.

The primary application domain of the developed material model is the analysis of ballistic impact of small projectiles and fragments whereas other application scenarios are conceivable without restriction. Ballistic vests have to reduce the kinetic energy of striking projectiles in such a way that it is not possible to completely penetrate the vest. In general, the kinetic energy of the projectile is dominantly converted to strain energy of the fiber material and therefore needs to be spread to a wide area of fabric material. The most common vests are the so-called soft vests that are made from many layers of woven or laminated fibers.

To verify the developed material model, 20 layers of plain woven fabric made of aramid fibers with dimensions 200 x 200 millimeters have been analyzed numerically under ballistic impact conditions. The fabric package is loaded by a 357-Magnum-projectile at 390 meters per second and a 7.62-NATO-projectile at 790 meters per second. Both projectiles are of roughly the same mass.

As expected, the projectile of the small gun can be stopped by the fabric panels (see Figure 7) whereas the sharper projectile of the rifle easily penetrates the fabric armor at its considerable higher velocity (see Figure 8).

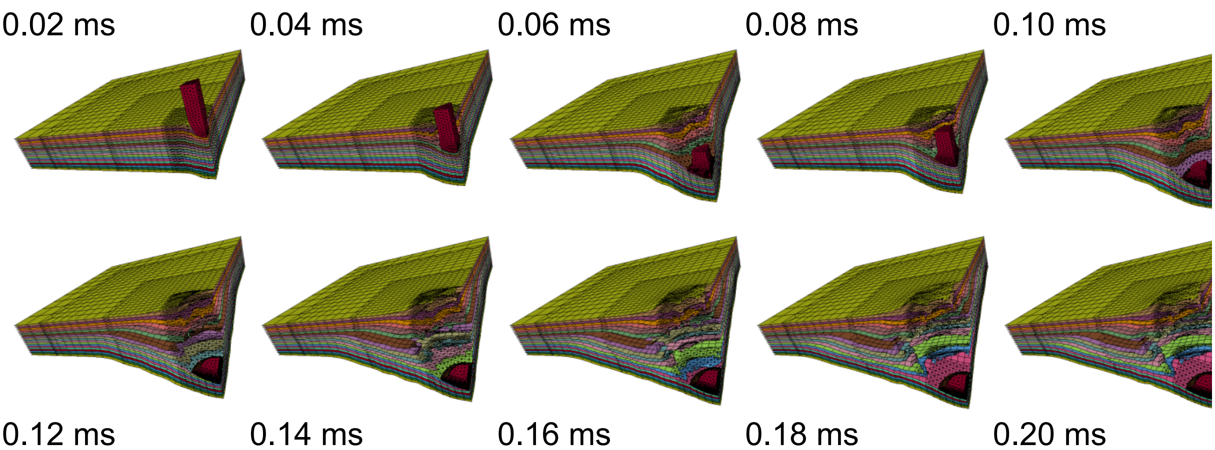


Figure 7: Deformation of 20 layers of aramid woven fabric under impact of a 357-Magnum-projectile.

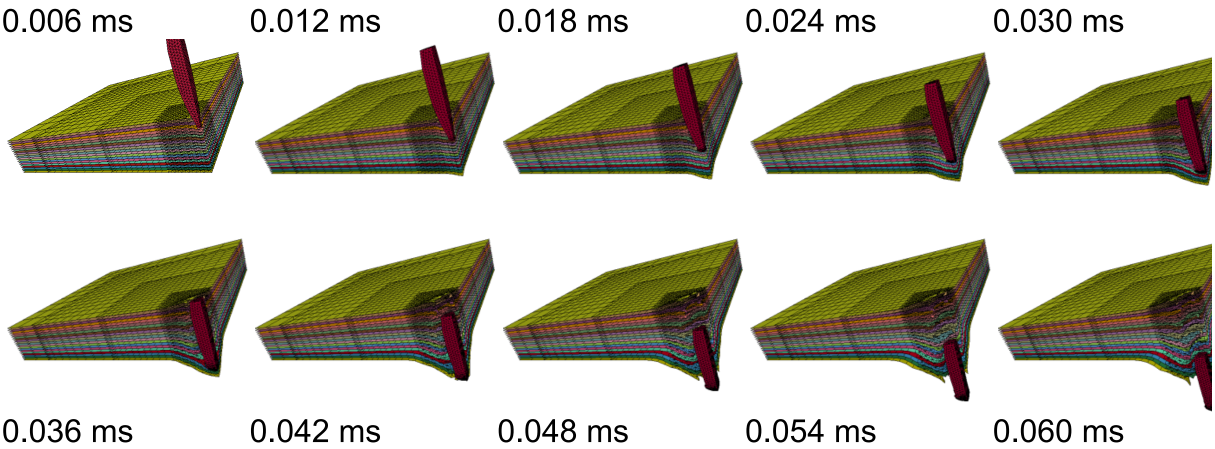


Figure 8: Deformation of 20 layers of aramid woven fabric under impact of a 7.62-NATO-projectile.

The evaluation of the simulation enables an insight into the deformation of the representative volume cell at each material integration point. In Figures 9 and 10, colored plots of selected history variables of the fabric layer at the backside of the fabric package are presented. One can clearly observe regions with varying yarn undulations due to initial asymmetries (Figure 9) and regions of high warp-yarn stresses and low weft-yarn stresses (Figure 10).

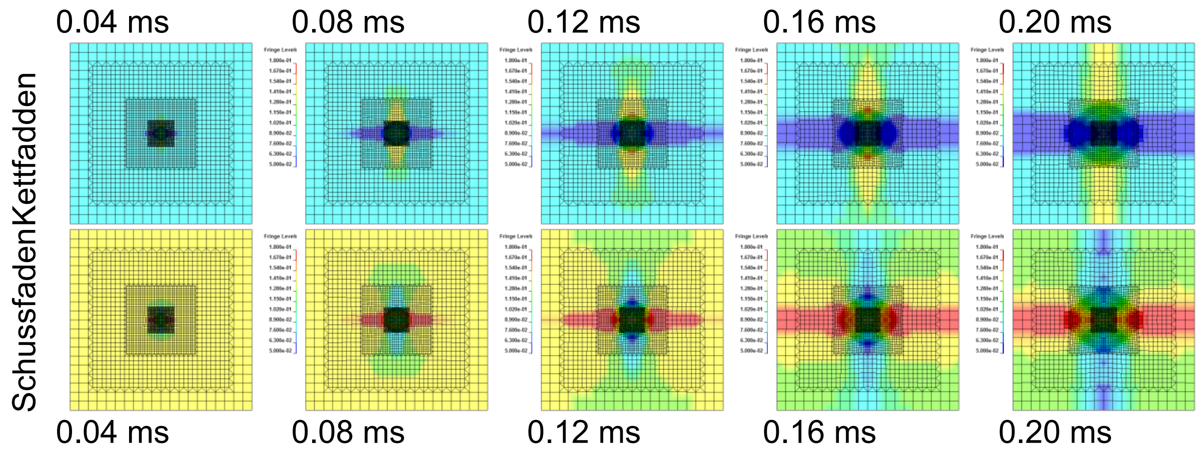


Figure 9: Fadenwelligkeiten der Kett- und Schussfäden.

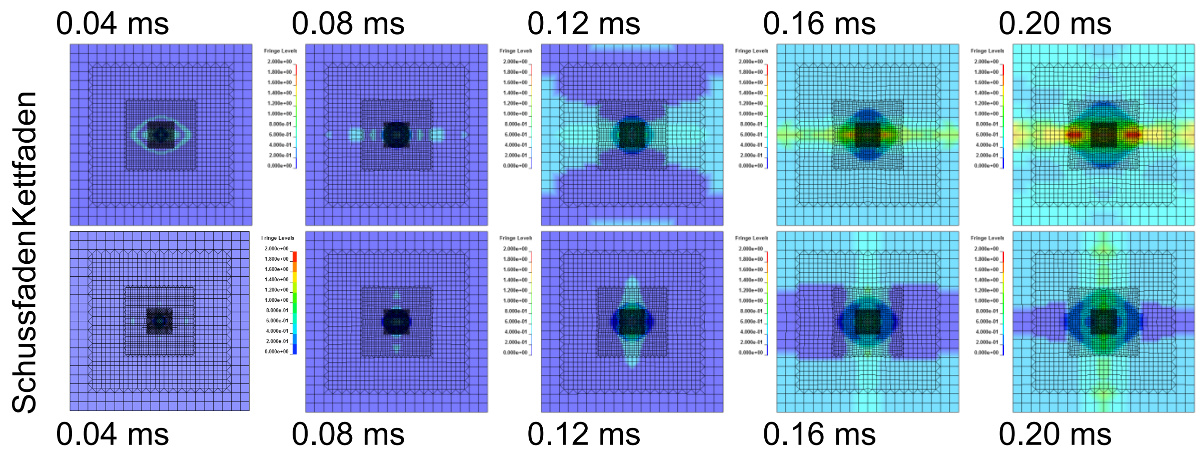


Figure 10: Fiber stresses in warp and weft yarns.

The material model for woven fabrics developed at the Ernst-Mach-Institut enables efficient and accurate calculations of woven textile structures at high-speed loading conditions. The subtle integration of the weave-specific mesostructure within the framework of a continuum material model bypasses the problem of very small elements, consecutively small time steps and, thus, avoids long simulation runs. At the same time, typical yarn interaction modes are directly captured at mesoscopic scale and can be modeled with physical means.

References

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