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Challenges in the Development of Modern Armor Systems

Shock, Detonation and Impact Physics
Ballistic Protection and Armor Materials
Numerical Simulation and Computer-Aided Engineering in Military Technology

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High-Speed Dynamics

Motivation

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High-Speed Dynamics

Motivation

- The threat imposed by terrorist attacks is a major hazard for military installations, vehicles and other items
- An important endeavor of international research and development is to avert danger to life and limb
- Ballistic testing is limited due to costs and permissions for experimental results
- This is why numerical simulations are more frequently applied than experimental tests which are thus being replaced gradually

High-Speed Dynamics

Motivation

Traditional ballistic testing:

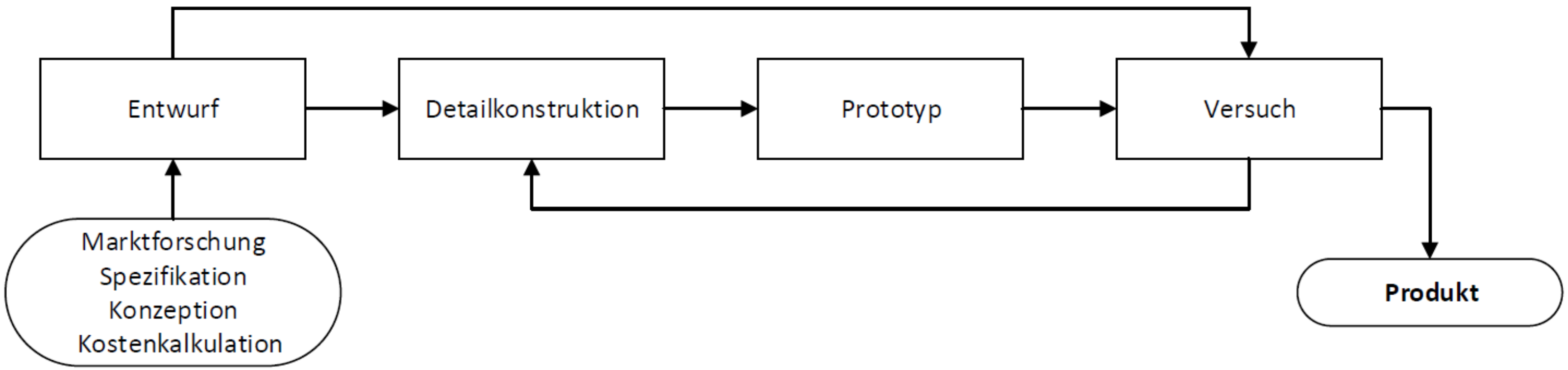
Testing a bulletproof vest in Washington, D.C. (September 1923).

High-Speed Dynamics

Methods of Development

Traditionell

Mehrere Redesignschleifen



- *Krupp*'s Panzer Formula: $$S_b = 0{,}0194 \sqrt[4]{\frac{E^3}{k^5}}$$

  - Approximation of the impact depth of FMJ projectiles on RHA

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High-Speed Dynamics

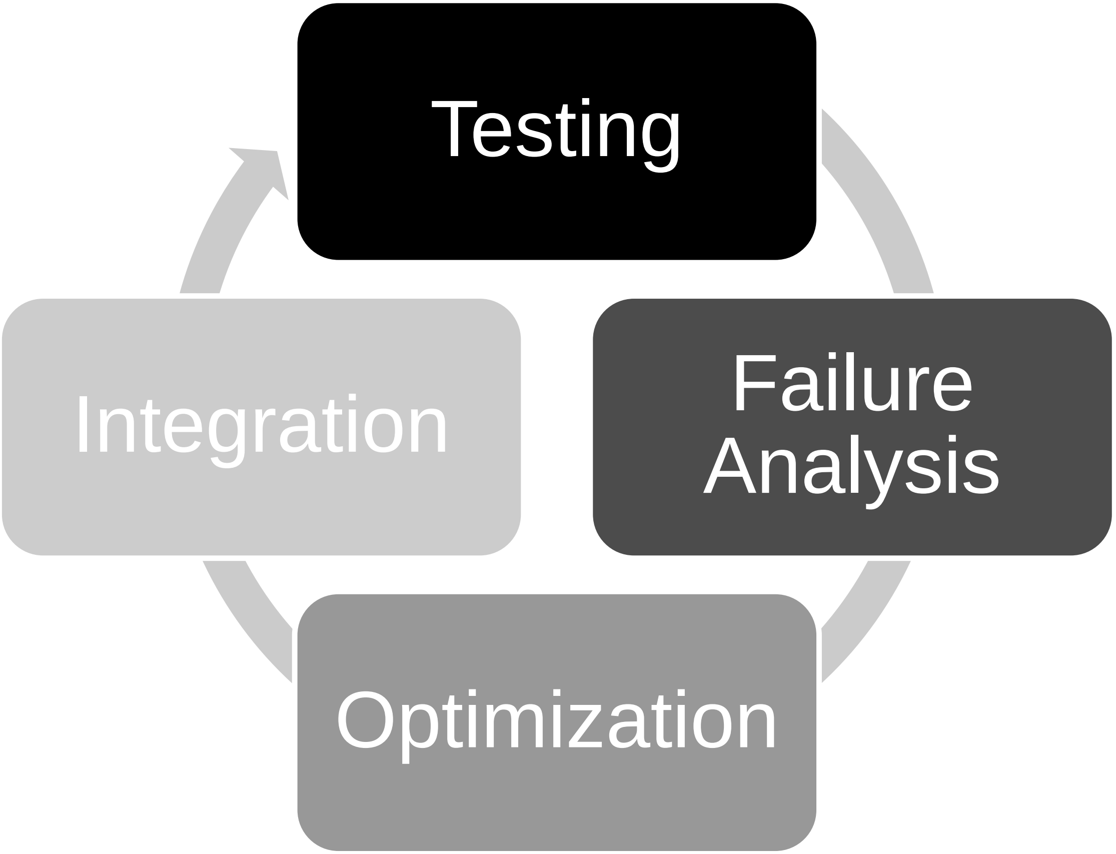
Methods of Development

In order to deal with problems involving the release of a large amount of energy over a very short period of time, e.g. explosions and impacts, there are three approaches:

- As the problems are highly non-linear and require information regarding material behavior at ultra-high loading rates which is generally not available, most of the work is **experimental** and thus may cause tremendous expenses
- **Analytical** approaches are possible if the geometries involved remain relatively simple and if the loading can be described through boundary conditions, initial conditions or a combination of the two
- **Numerical** solutions are far more extensive in scope and remove any difficulties associated with geometry

High-Speed Dynamics

Methods of Development



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High-Speed Dynamics

Methods of Development

- In order to have a sufficient data base for the simulation, some actual testing must be done prior to the simulation
- Each shot is being recorded with a high-speed-camera and then analyzed in detail
- The fragments of the projectile must be caught and analyzed in the following

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High-Speed Dynamics

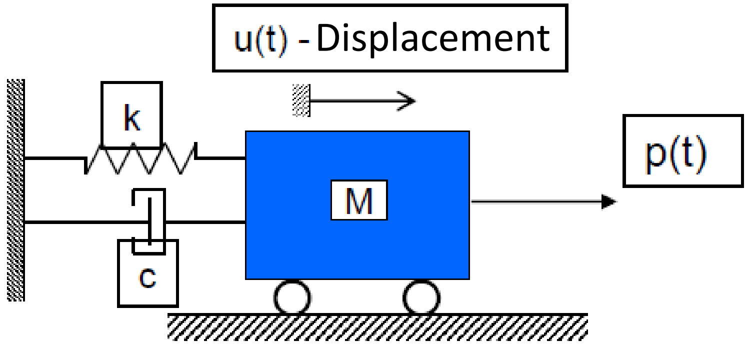
Methods of Development

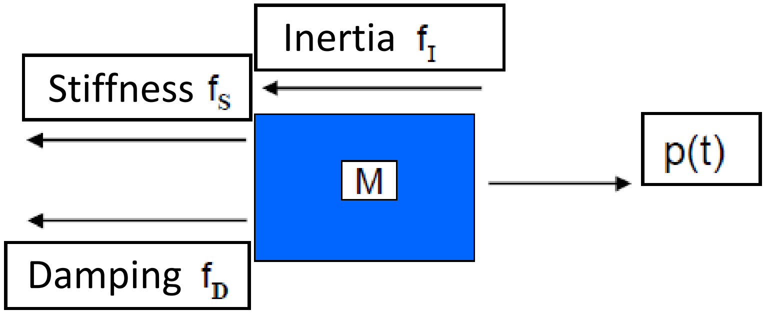
High-Speed Dynamics

Methods of Development

Main principle: Solving the equation of motion

$$M \cdot \ddot{u}(t) + C \cdot \dot{u}(t) + K \cdot u(t) = p(t)$$





Inertia: $f_I = M \cdot \ddot{u}(t)$

Damping: $f_D = C \cdot \dot{u}(t)$

Stiffness: $f_S = K \cdot u(t)$

Equilibrium: $f_I + f_D + f_S = \mathrm{p(t)}$

High-Speed Dynamics

Methods of Development

The equation of motion is a function of time

The discretization of the time is required

Two options:

Implicit or explicit integration of time

High-Speed Dynamics

Methods of Development

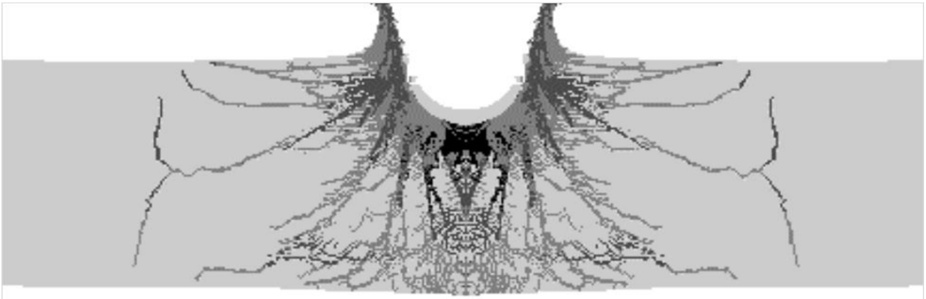
Method	Velocity of impact (m/s)	Velocity of deformation (1/s)	Type of impact
Implicit		$< 10^{-5}$	static / crawl
	< 50	$10^{-5} - 10^{-1}$	elastic
	50 – 1000	$10^{-1} - 10^{1}$	elastic-plastic
	1000 – 3000	$10^{1} - 10^{6}$	plastic
	3000 – 12000	$10^{6} - 10^{8}$	hydro-dynamic
Explicit	> 12000	$> 10^{8}$	vaporization

High-Speed Dynamics

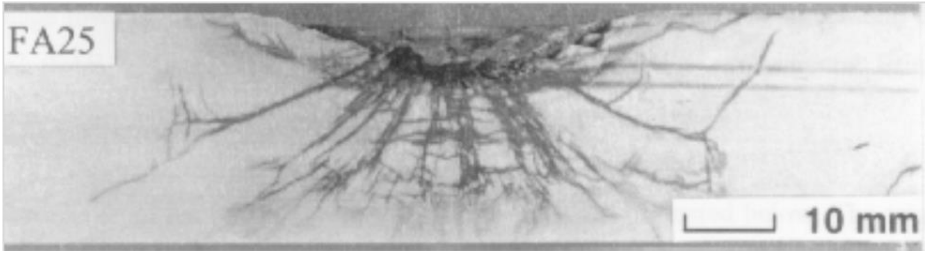
Methods of Development

- Challenge:

– The materials of the test objects are normally unknown – they have to be created and optimized for the calculation, so that the material behavior in the simulation can be conveyed in an exact manner



Simulation



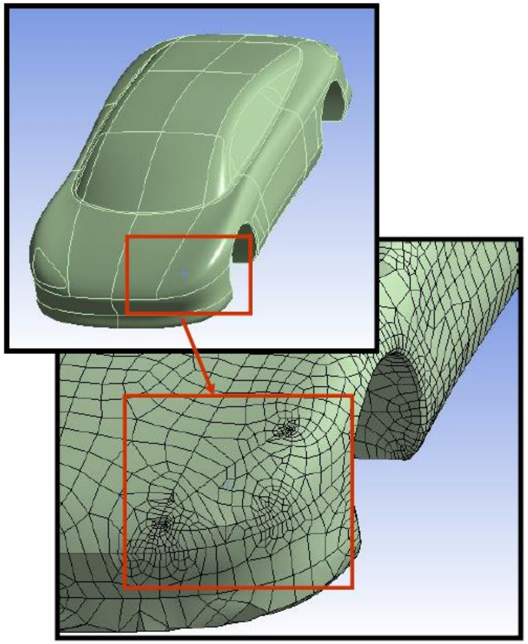
Experiment

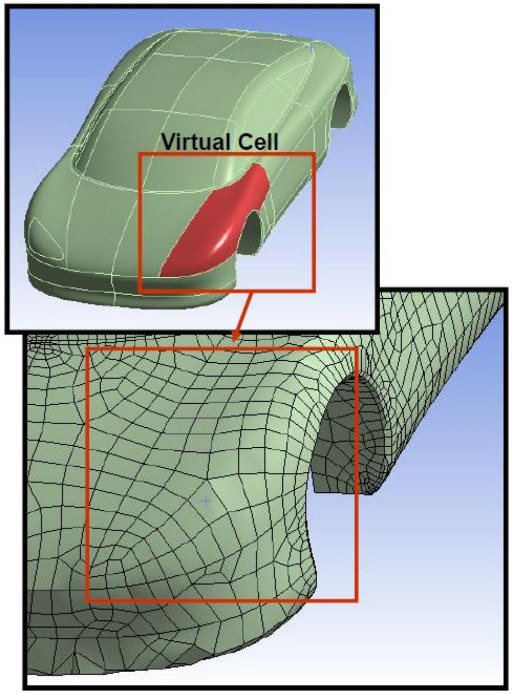
High-Speed Dynamics

Methods of Development

- Challenge:
  - The mesh used in CAD model has to be as detailed as possible, as particularised as necessary

Virtuelle Topologie

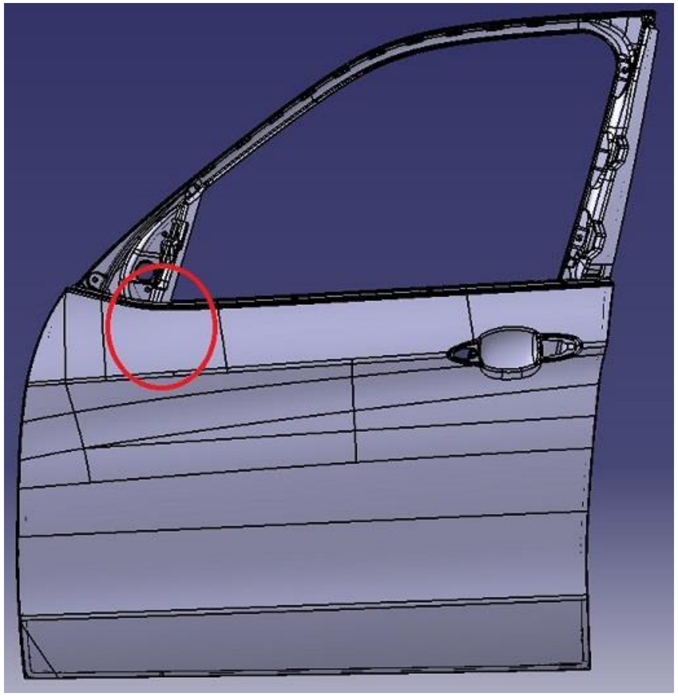


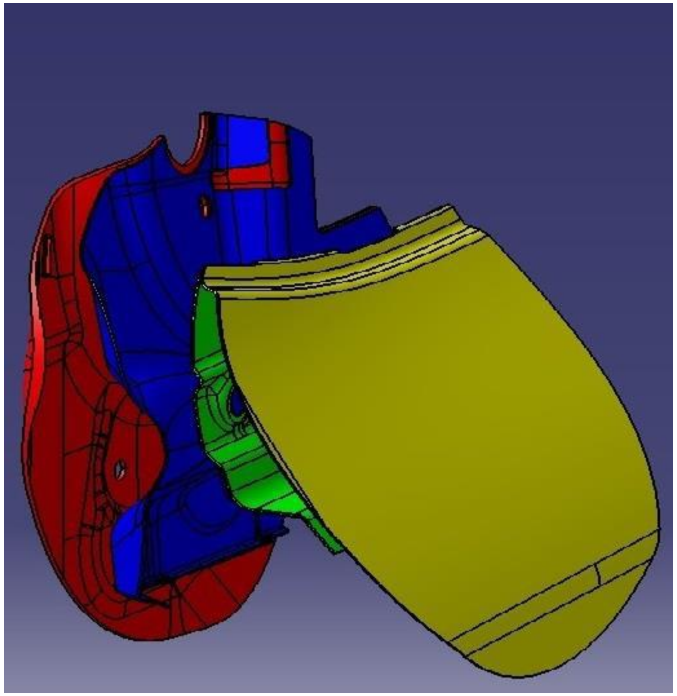


High-Speed Dynamics

Methods of Development

- Challenge:
  – Regarding significant places, the models must be refined and the elements must be minimized





High-Speed Dynamics

Research and Development

- Research and development focus on the following areas:
  - Protection and safety of people, vehicles and infrastructures
  - Selection of materials and optimization of armor systems
  - Analysis of weapons and ammunition
  - Usage and effect of explosives
  - Civil and military defense systems
  - Protection technologies in aerospace applications
  - Vulnerability of buildings and infrastructures

High-Speed Dynamics

Range of Services

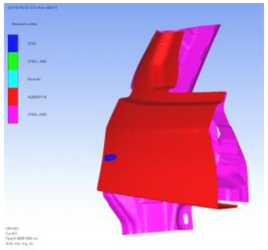
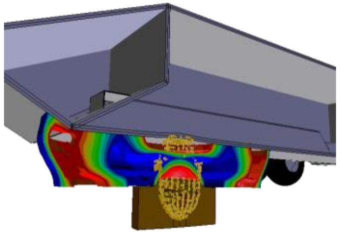
- **Experiments** can be performed to analyze and evaluate ballistic processes precisely (both blast and impact)
- To capture high-speed dynamics, a wide range of methods is available which enables the **measurement and visualization** of processes
- For example, **high-speed cameras** and high-intensity pulsed light sources are used
- Material properties are tested under highly dynamic conditions and suitable descriptions for the **simulation** can be defined

High-Speed Dynamics

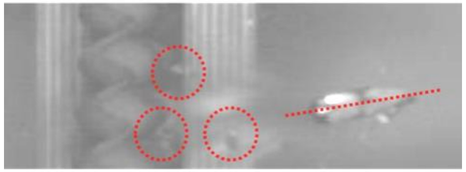
Main Areas

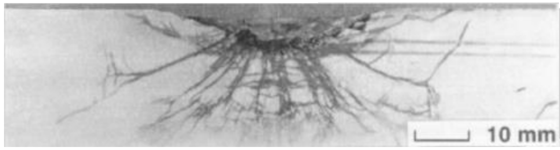
- Ballistic protection and safety systems
- Material analyses and optimization
- Simulation and computer-aided development
- Energetic systems and effectors
- Detonation effects
- Wound ballistic analyses

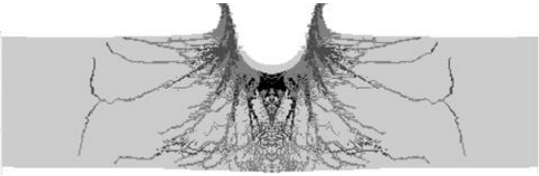








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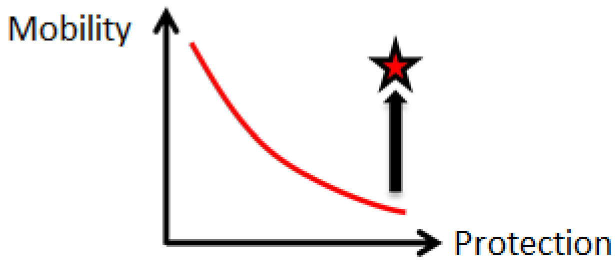
Application Example: Fiber-Reinforced Composites

Fiber-Reinforced Composites

Lightweight Ballistic Protection

- **Problem**: Weight



- **Idea**: Lightweight armor design with fiber-reinforced composites

- **Problem**: Experimental testing
  - Structural restrictions
  - Analytical disadvantages
  - Economic aspects
  - Time expenditure
  - Dangers and risks

- **Idea**: Numerical simulations

➢ **Goal**: Numerical simulations of ballistic impacts on fiber-reinforced composites

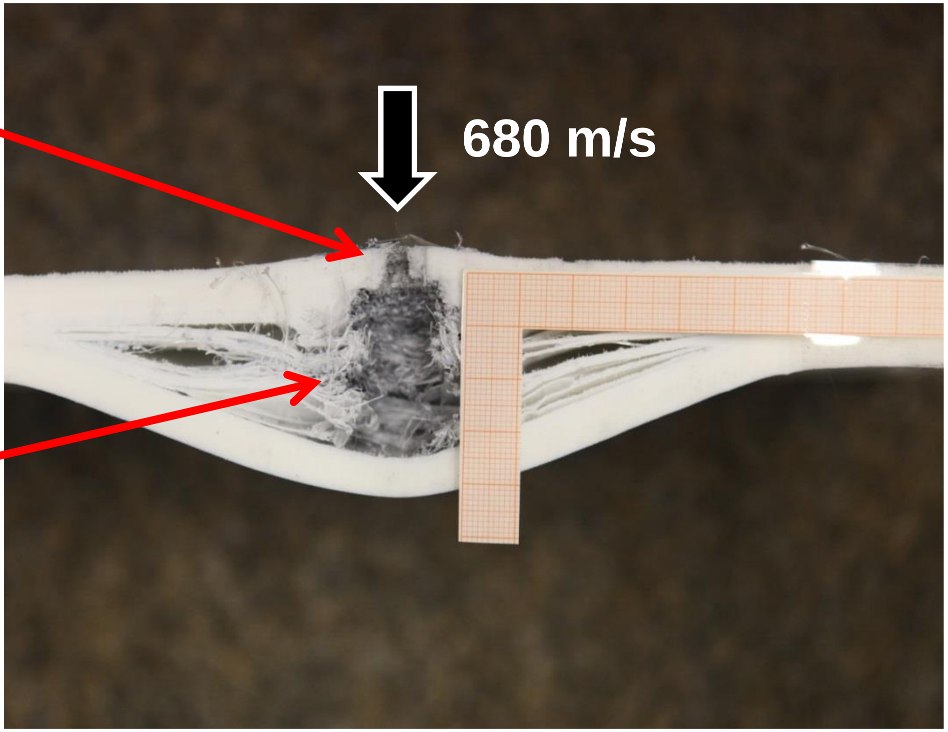
Fiber-Reinforced Composites

Lightweight Ballistic Protection

FAILURE MECHANISMS DUE TO IMPACT

Shear failure

- Elastic fiber extension
- Delamination
- Tensile failure



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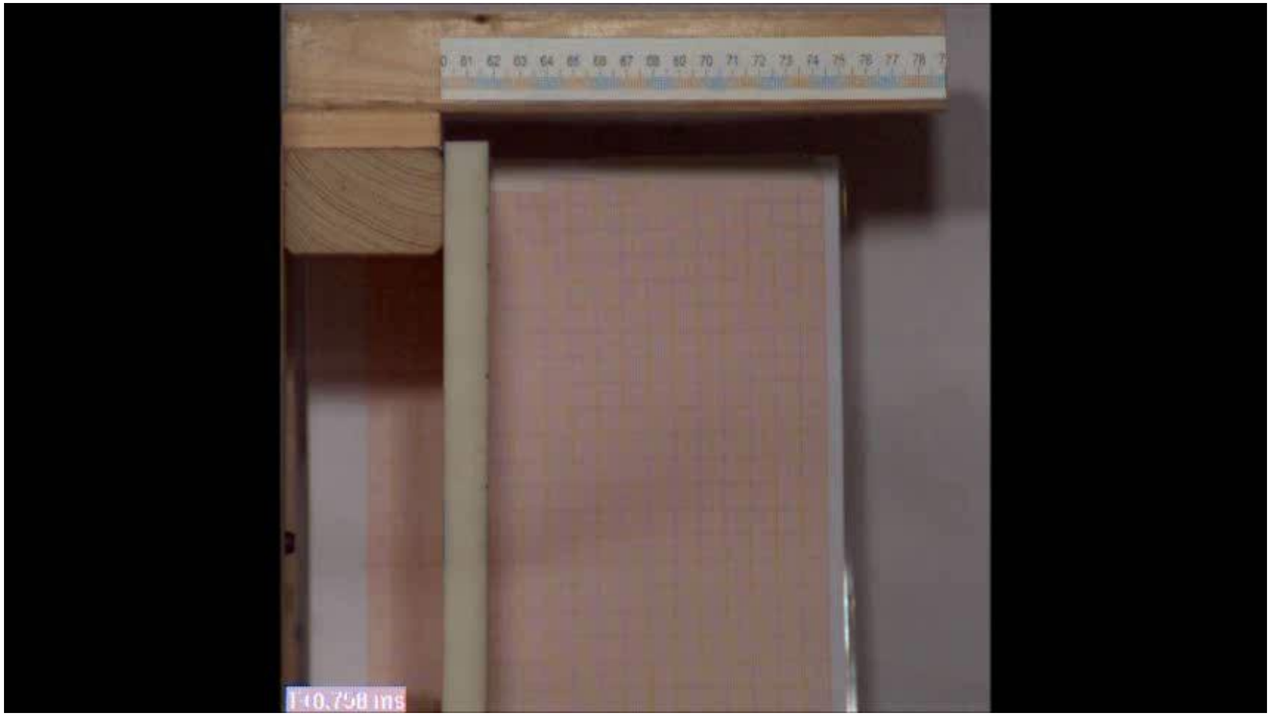
Fiber-Reinforced Composites

Lightweight Ballistic Protection

EXPERIMENT

- .44 Rem. Mag. FMJ (about 440 m/s) vs. 16.2 mm fiber-reinforced composite

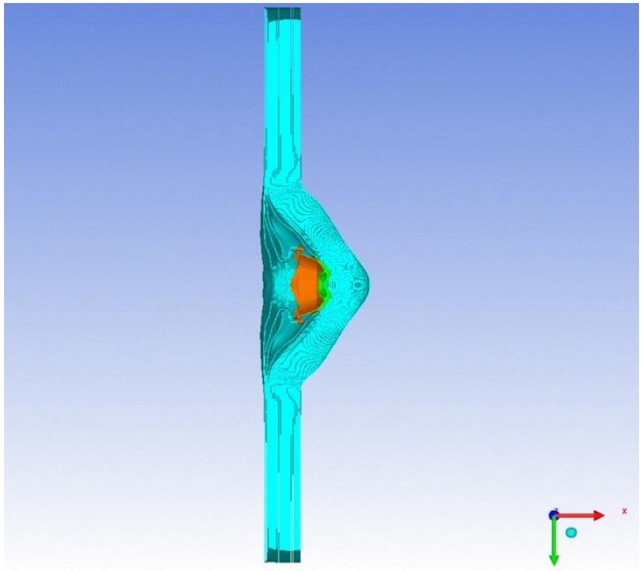


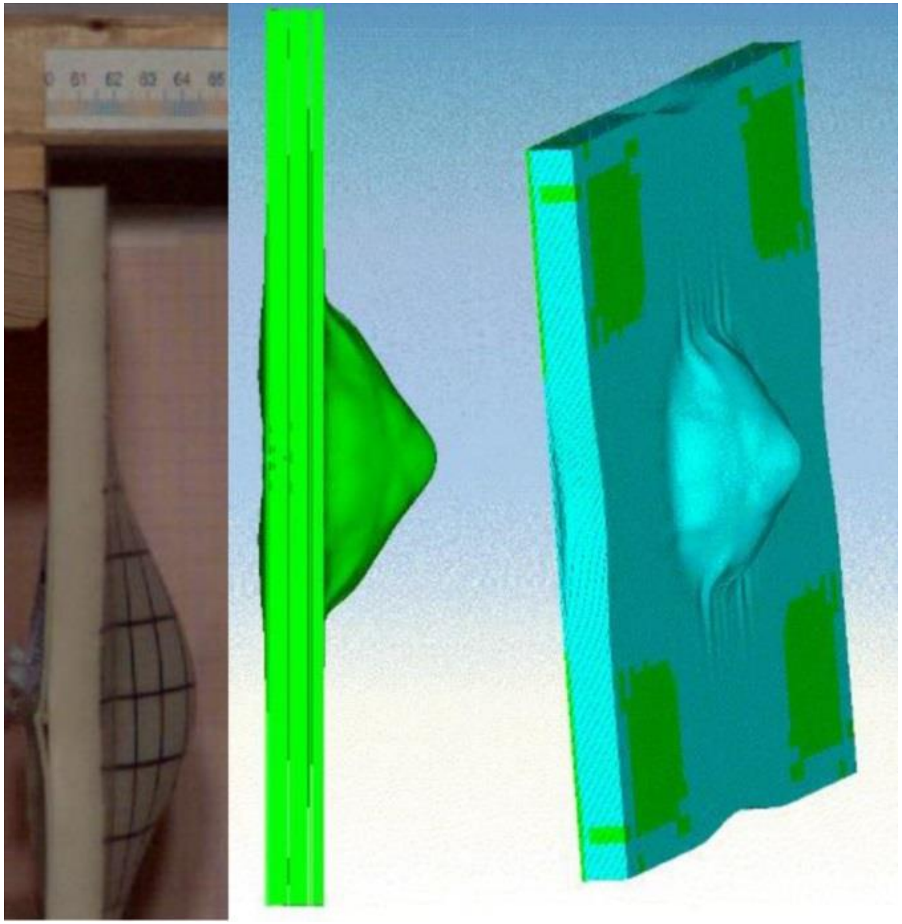
Fiber-Reinforced Composites

Lightweight Ballistic Protection

Simulation

- ✓ Bulging depth
- ✓ Bulging diameter
- ✓ Delamination



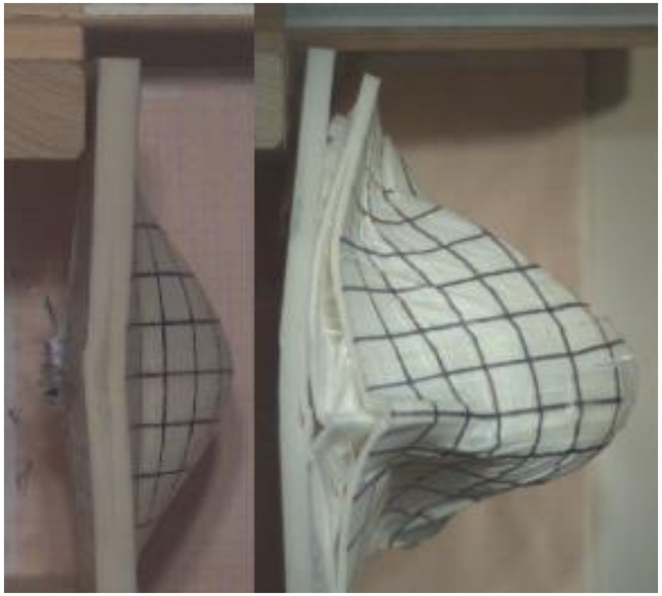


Fiber-Reinforced Composites

Lightweight Ballistic Protection

Optimization

- Caliber: 7.62×39 mm (Kalashnikov)
- Impact energy: approx. 2000 J
- Target: 16.2 mm fiber-reinforced composite
- Temperature: 110 °C



	Optimized plate (left)	Commercial plate (right)
Impact velocity	820 m/s	819 m/s
Perforation	No	Yes
Residual velocity	0 m/s	N/A
Bulging diameter	144 mm	-
Bulging depth	42 mm	-

Application Example:
Safety Glass

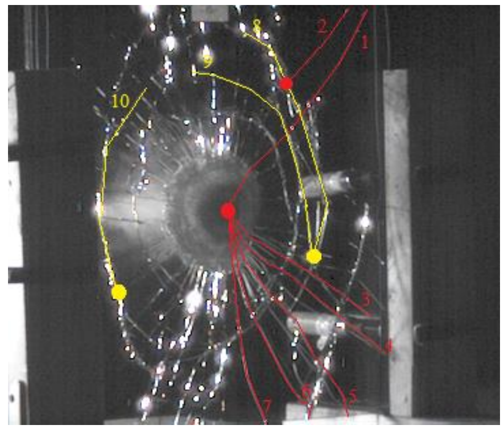
Safety Glass

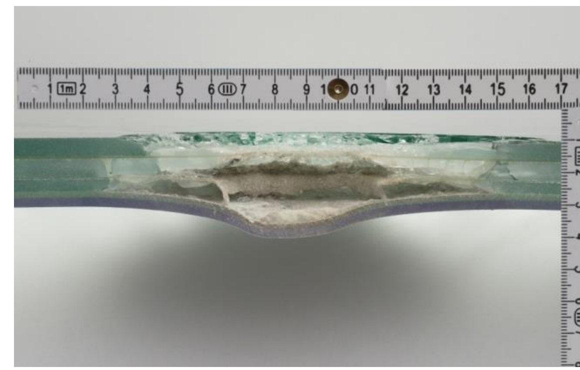
Motivation

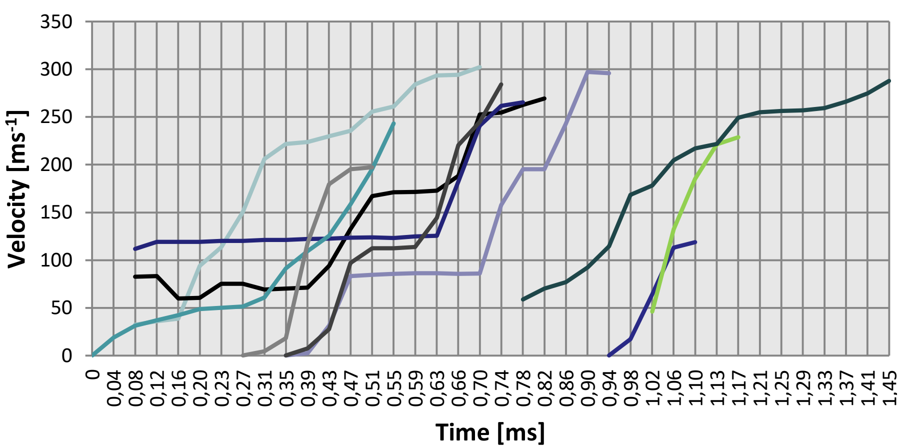
Safety Glass

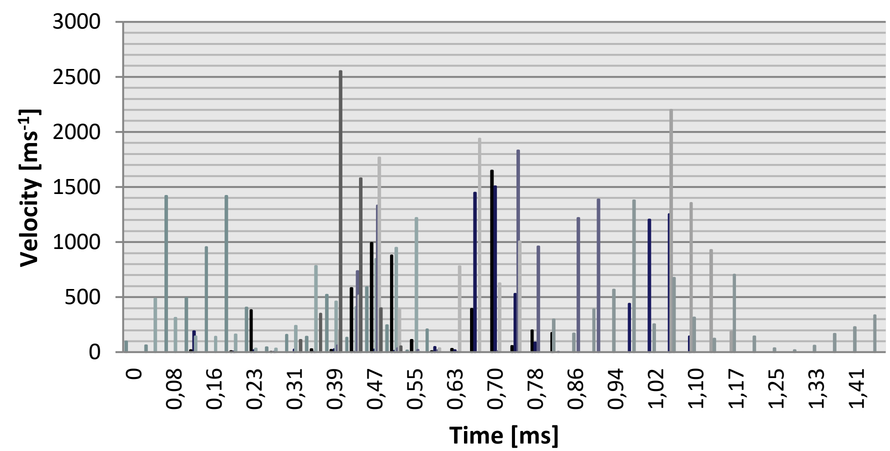
Optimization

Video Analysis







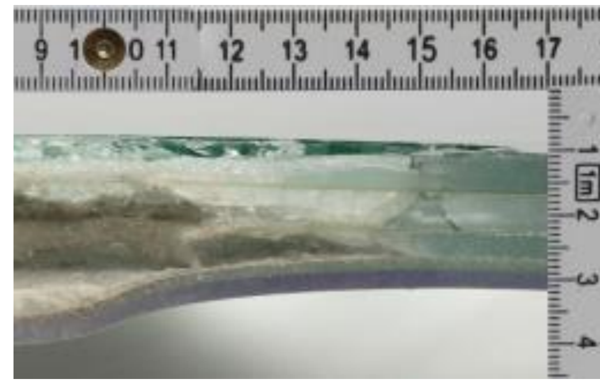


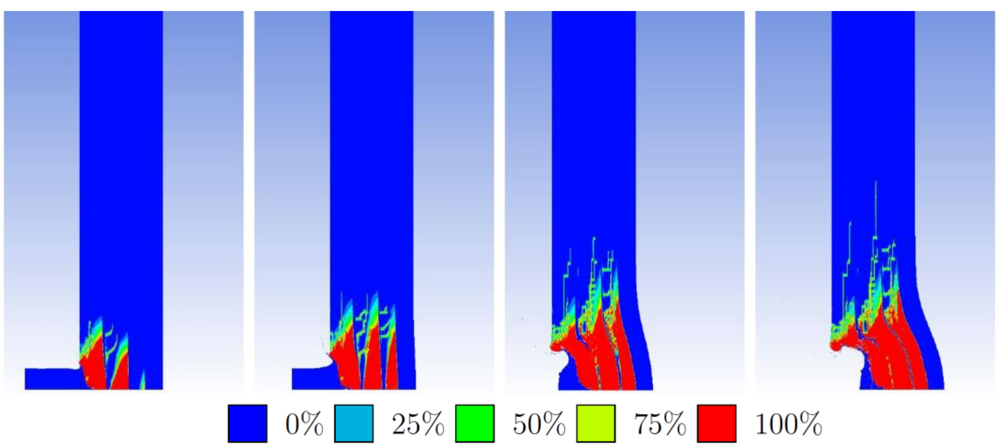
Safety Glass

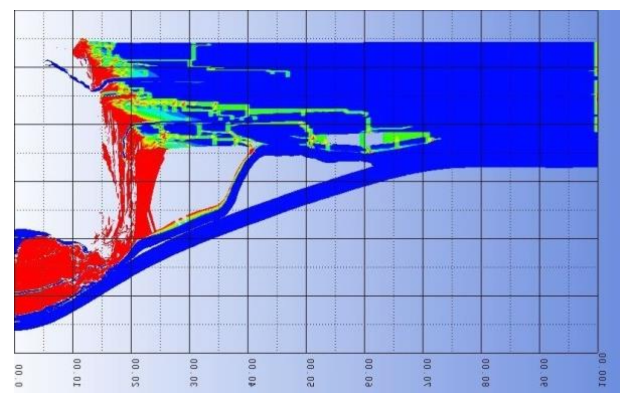
Optimization

SIMULATION RESULTS

- Simulation model adapted to real experiments
  - Material parameters
  - Solver methods
- Precise representation of crack propagation
- General simulation model for laminated safety glass







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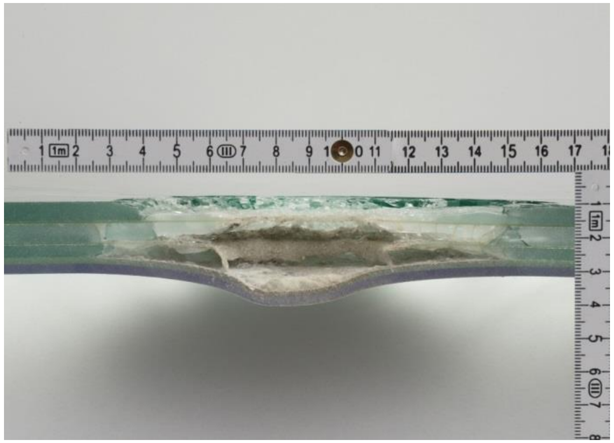
Safety Glass

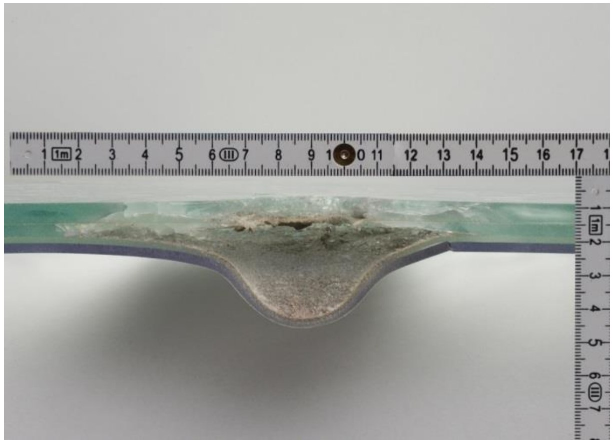
Optimization

OPTIMIZATION

- Ideal arrangement of the individual layers

Glass [mm]	Configuration [mm]	Result	Residual velocity
20	4 + 4 + 4 + 4 + 4	fails	approx. 50 ms^{-1}
	8 + 8 + 4	withstands	-
	8 + 6 + 6	withstands	-
	8 + 4 + 4 + 4	withstands	-





- Reduction of total thickness
  - Safety glass of protection level 6 by approx. 13%
  - Safety glass of protection level 4 by approx. 24%
- Virtual optimization approaches tested and proven in experimental settings

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Application Example: Wound Ballistics

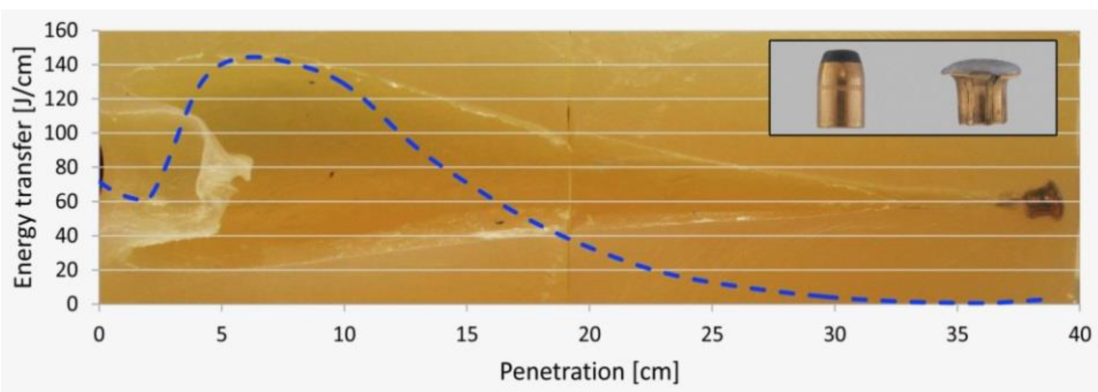
Wound Ballistics

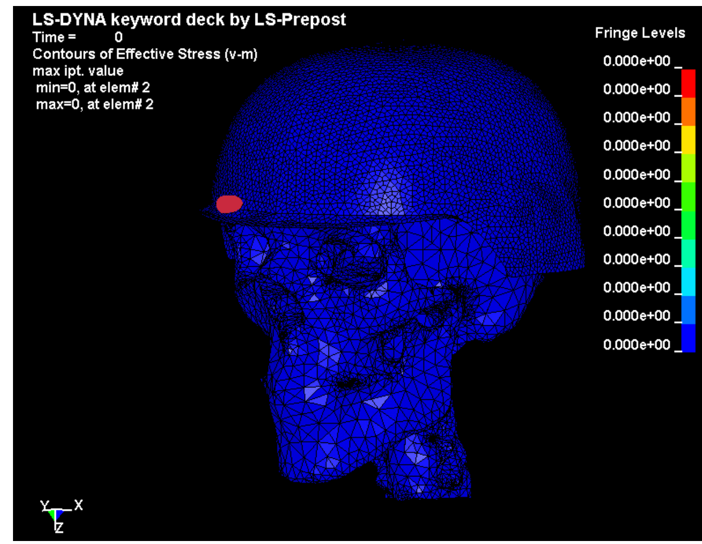
Analysis and Consulting

- The field of wound ballistics largely comprises the study of physiology and medical effects of projectile weapons on humans or animals
- Wound ballistics is an interdisciplinary field with connections to medicine, forensics, physics and military research
- For wound ballistics, the examination of the temporary wound canal plays a particularly important role
- The phenomena can be simulated in experimental studies and analyzed simulatively
- This research area is supported by our medical experts

Wound Ballistics

Analysis and Consulting





Application Example: Trajectory Prediction

Trajectory Prediction

Encampment Protection

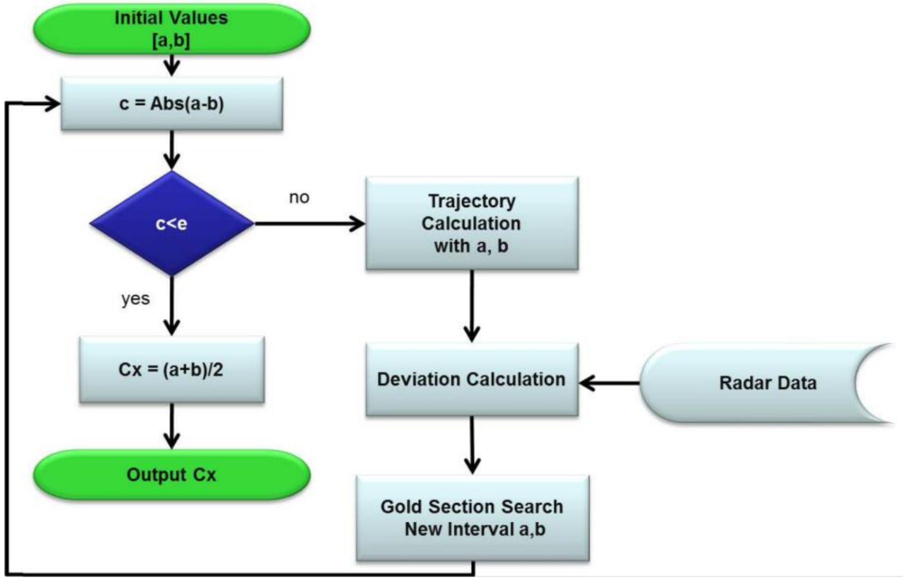
- **Goal**:
  - Trajectory prediction
  - Detect and/or destroy incoming artillery, rockets and mortar rounds in the air before they hit their ground targets, or simply provide early warning
  - Calculation and representation of trajectories based on radar data

- **Background**:
  - Both active and passive systems are based on the prediction of the trajectory of the artillery, rocket or mortar (RAM)
  - So far, there are only a few systems to counter RAM threats

Trajectory Prediction

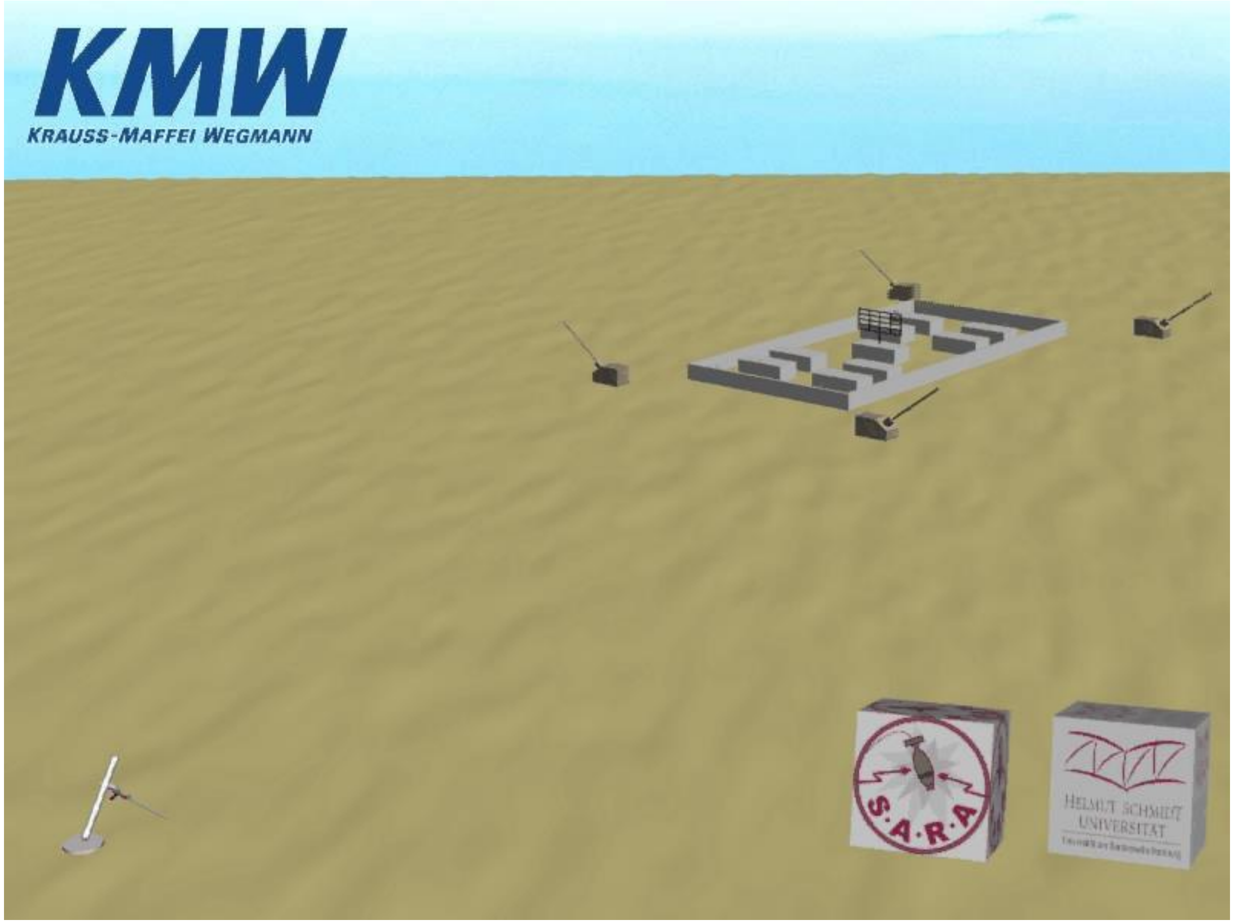
Encampment Protection

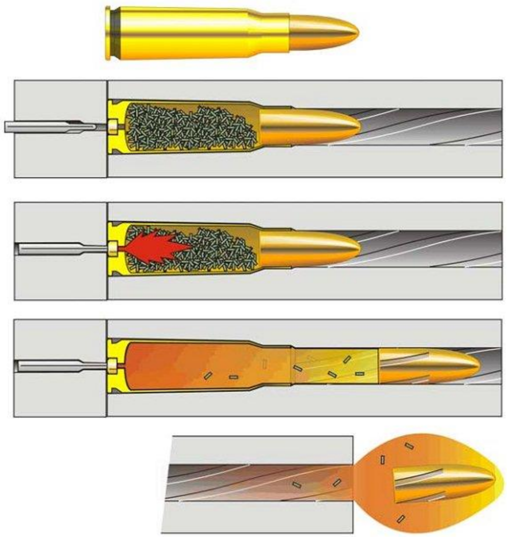
- Optimization:
  - Determination of the ballistic coefficient
- Calculation:
  - Selection of a numerical or analytical method
- Error estimation:
  - At the point of impact or in the middle of the trajectory



Trajectory Prediction

Feldlagerschutz





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