HYPERVELOCITY IMPACTS AND PROTECTION

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ABSTRACT

Starting with an introduction into the field of hypervelocity impacts this paper will give an overview over current research in the area of protection against space debris. In a second part emphasis will be put on pointing out trends and strategies to further develop know-how in protection technology. One purpose is to demonstrate that improvements in shield efficiency can be expected. To achieve this aim, a strategy is outlined, which tries to avoid adjustment of numerical and material parameters by fits to penetration experiments. Instead, it is suggested to determine material parameters from carefully selected laboratory tests, covering a broad range of strains, strain rates and stress states. Knowledge of the dynamic material behaviour then can be used for the development of new shield concepts by means of numerical simulation.

1. INTRODUCTION: SPACE DEBRIS AND HYPERVELOCITY IMPACTS

Independent of the scenario used models of the number of objects in low earth orbits predict an essential increase of the debris population (Fig. 1). Therefore, protection against the impact of space debris is a topic of continuously increasing importance.

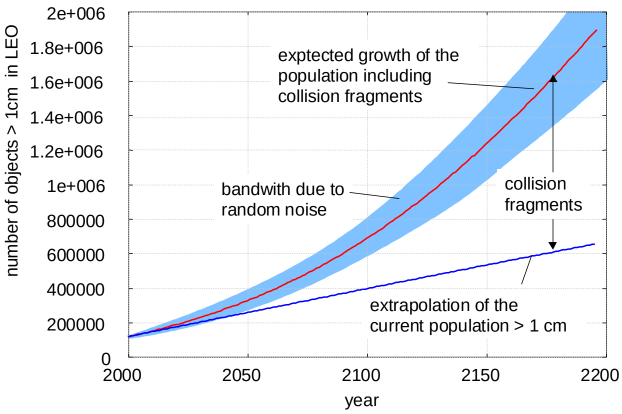


Fig. 1. The principal growth of the future debris population > 1 cm in LEO [1]

Despite this significance, research in the area of design of protection in space has been rather limited, in contrast for example to the tremendous efforts done in conventional protection of earth-based vehicles (protection of vehicles, ships, airplanes against ballistic impacts). Constraints for the additional weight of protection are strong in all mentioned fields, but there is a clear difference in impact velocities. Typical impact velocities in low earth orbits range between 2000 and 15000 m/s, well above the velocity range of about 700 to 8000 m/s considered in ballistic protection. Nevertheless, most of the methods applied in ballistic research can be extended to the field hypervelocity impacts, though with modifications. Table 1 gives an overview of typical pressures and strain rates, characterizing impacts as a function of impact velocity.

Table 1. Typical physical quantities for a range of impact velocities

Physical entity/ Application	velocity	strain rate	pressure
Statical loads	0	$<10^{-5}$ /s	150 MPa
Wind, earth quakes	1 m/s	$<10^{-3}$ /s	150 MPa
Drill hammer	5 m/s	1 /s	150 MPa
Train-, car crash	60 m/s	500 /s	500 MPa
Ballistic protection	800-8000 m/s	10^5 -10^6 /s	1-150 GPa
Space debris impact	10 km/s	10^6 /s	150 GPa

Typical phenomena of a hypervelocity impact are shown in Fig. 2. The simulation (here done with a smooth particle method, see e.g. references [2], [3],[4] for this method) shows the physical processes involved. After a first shock phase, release waves cause a rapid pressure decrease, often accompanied by spall effects. Material may go through phase transitions, can evaporate or melt, depending on impact velocity and the equation of state of the materials involved (Fig. 3, Fig. 4). In addition to equation of state (EOS), the strength of materials is

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

of fundamental importance. Hypervelocity impacted target materials are loaded initially with strong shocks, but in later phases of the impact process, they experience loads down to quasi-static forces, see for example the “frozen” lips of the crater in Fig. 5. This has consequences with respect to the necessary characterization of materials, as will be described later.

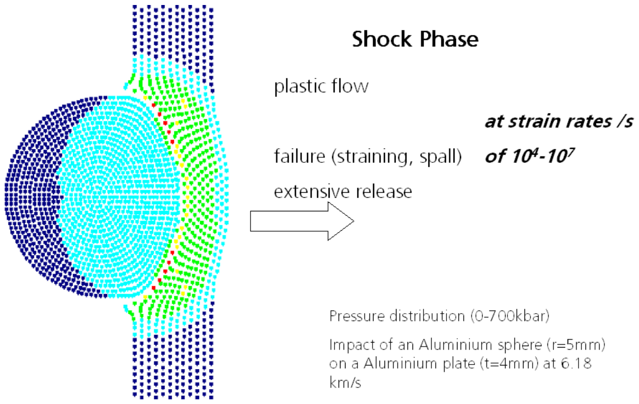


Fig. 2. Hypervelocity impact on a thin plate showing typical phenomena (SPH simulation)

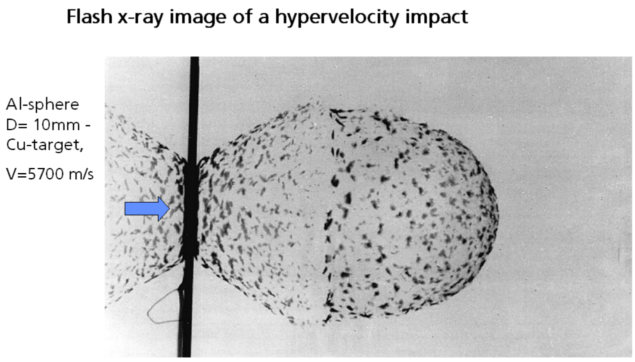


Fig. 3. Flash x-ray picture of an Al-sphere impact on a Copper plate

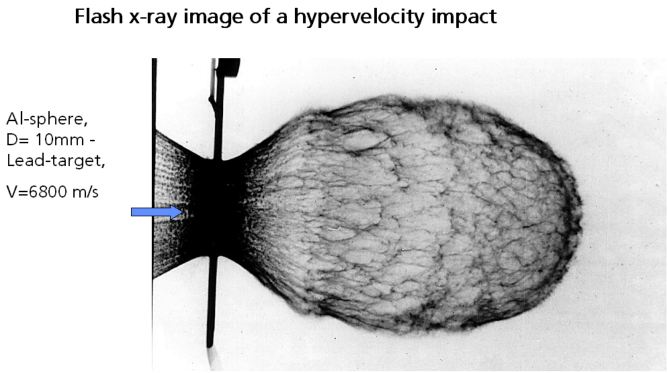


Fig. 4. Flash x-ray picture of an Al-sphere impact on a lead plate

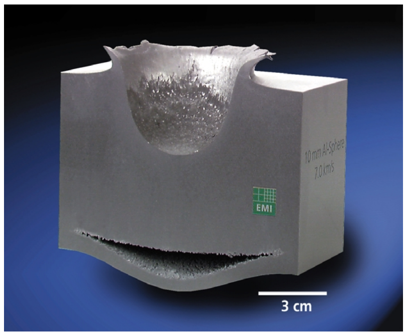


Fig. 5. Crater profile of a hypervelocity impact on a thick Al-target showing the "frozen" crater lips (Al-projectile 10 mm dia., impact velocity 7 km/s)

2. SHIELDS FOR SPACECRAFT AGAINST SPACE DEBRIS AND MICRO-METEOROIDS

The standard design of a shield is based on the principle of a spaced target or Whipple shield. Fig. 6 demonstrates how the impacting mass is fractured and energy and momentum concentrated initially in the impacting sphere is distributed onto a bigger area with multiple fragment impacts.

The protection performance of such simple designs could be improved, for example, by using impedance mismatches in metallic double layers. To demonstrate this, a hypervelocity impact of an Aluminium sphere on a plate, consisting of 2 stacked metal layers, Titanium and Tungsten, was investigated. As Fig. 7 shows, mass and velocity of the debris behind the double layer is influenced by the stacking sequence (despite of an identical areal weight one configuration gives a better protection). This can be explained of course by simple shock wave physics.

The Inter Agency Debris Committee Protection Manual (IADC PM) describes a few shielding concepts like honeycombs, stuffed Whipple shields and multi-shock shields.

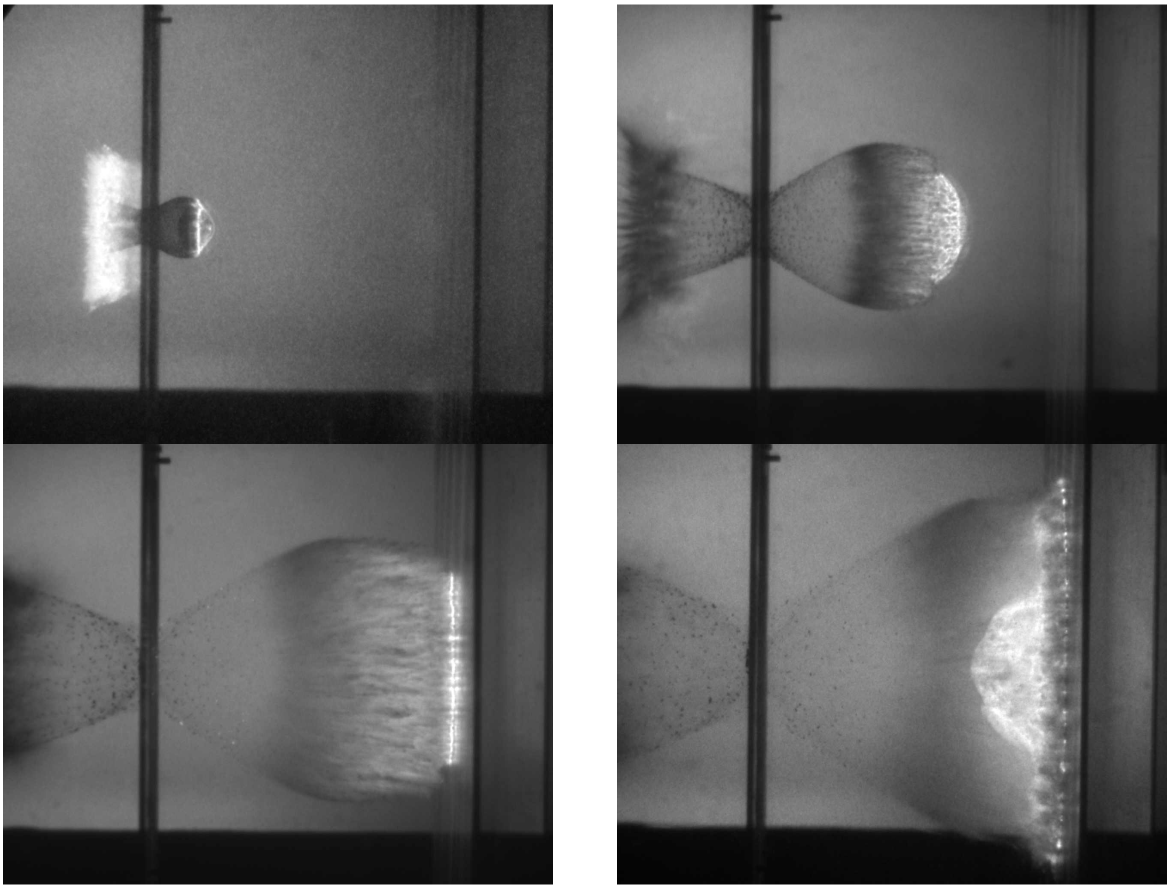


Fig. 6. High-speed video shadowgraphs of a hypervelocity impact on an all aluminium Whipple shield: Al-sphere (6 mm, 6.7 km/s), bumper: 1.2 mm, back-up wall: 3.0 mm, stand-off: 128 mm, pressure in target chamber 0.1 bar (EMI)

The progress in shield design made during the development for the Columbus module of ISS [6], [7], is demonstrated in Fig. 8.

Whereas such types of developments follow a mostly empirical procedure (driven by impact tests, typically using light gas guns), one of the first big efforts to understand and describe material behaviour in a complicated, realistic shield, was started by an ESA project in 1998, managed by Ernst-Mach-Institut (EMI) [8]. Despite of the complexity of the materials involved, detailed material models including non-linear equations of state, and strain, strain rate and temperature dependent strength models could be derived. Of fundamental importance was the determination of appropriate material data. Computational results, using these data are shown in Fig. 9 (CJ.Hayhurst et al. 9]).

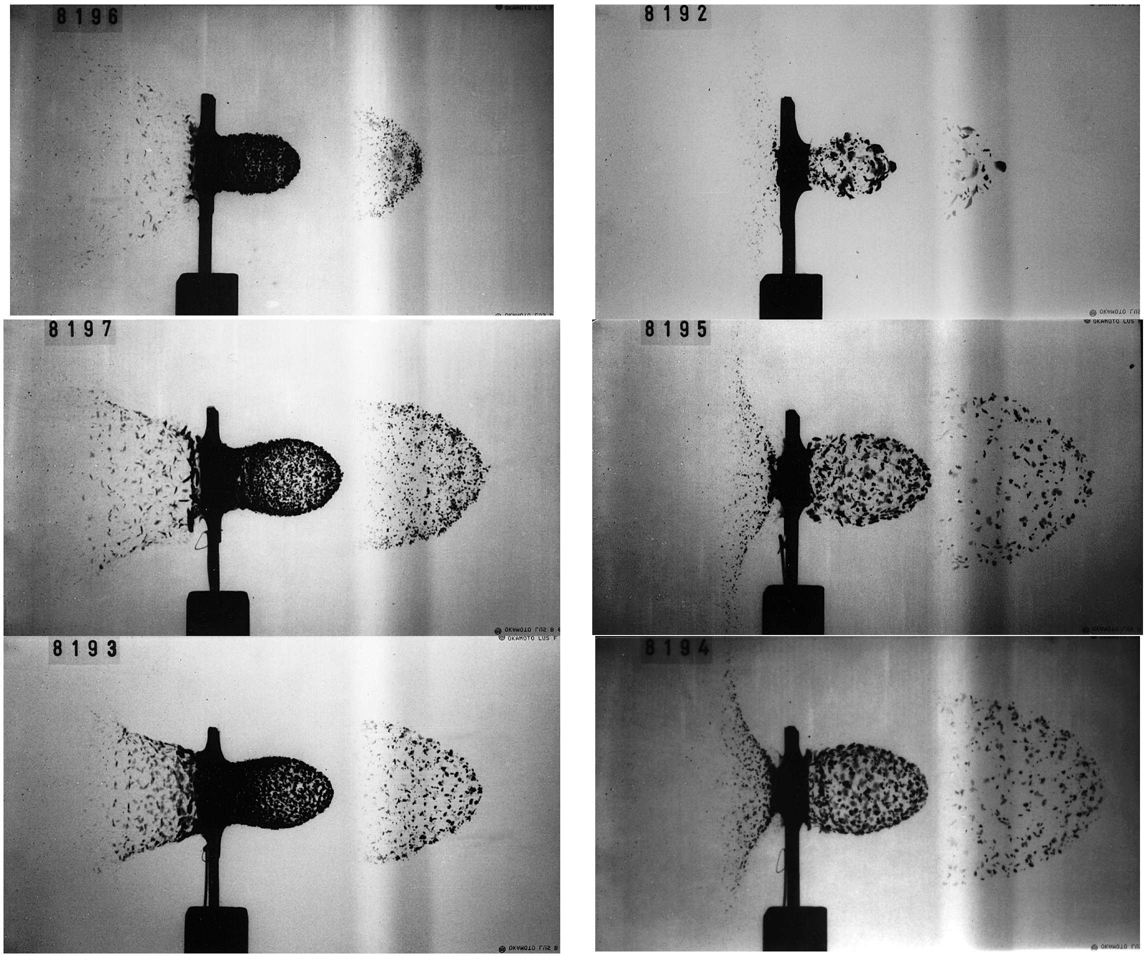


Fig. 7. Perforation of a stacked Titanium/Tungsten target by an Al sphere with diameter 10 mm. By changing the stacking sequence, the distribution of mass and momentum can be influenced, as the comparison of left and right hand pictures shows [5].

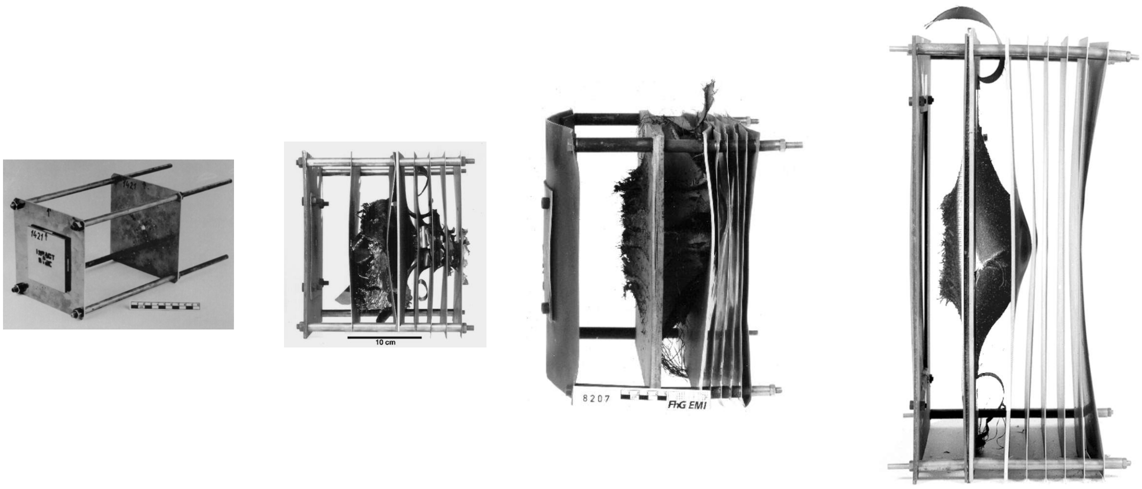
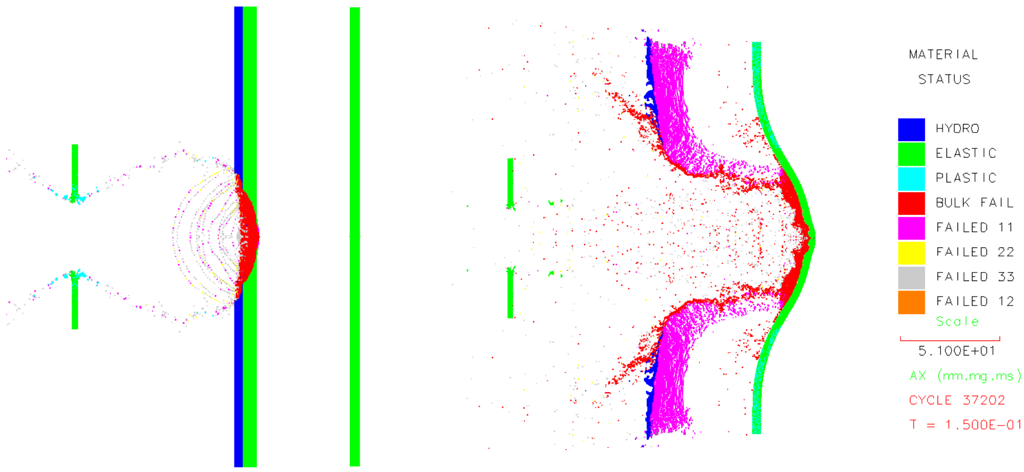


Fig. 8. Progress in shield design, demonstrated by the development for the Columbus module of ISS; Ballistic limit diameter at ca. 7 km/s as a function of shield design



15 µs 150 µs

Fig. 9. Simulation of the hypervelocity impact on a realistic shield configuration (simulation by Century Dynamics)

3. THE FUTURE OF PROTECTIVE DESIGN

3.1 What Needs to Be Done and How to Proceed

As described before, the development of effective shields will become a major task for future research. Because of the big variety of types of spacecraft, the multitude of materials used and because of the immense range of physical quantities which must be covered, a considerable amount of work remains to be accomplished. One example concerns the influence of the shape of the impacting mass on the performance of a shield: Mostly spherical impactors were used in research up to now, but as shown by Schäfer et al., the influence of shape cannot be neglected [10].

Various types of pressure vessels are needed for the operation of spacecraft. In order to develop a suitable protection, a detailed understanding of the failure mechanisms following hypervelocity impact is necessary. Fig. 10 shows an experimental set-up to analyse the phenomena that occur in the interior of a vessel after having been hit by a debris particle. Numerical results are compared to experiments in Fig. 11 [11]. A complete analysis of impact effects in pressure vessel systems, including a wealth of experimental data accompanied by a quantitative analysis of the physical phenomena involved, is given in [12].

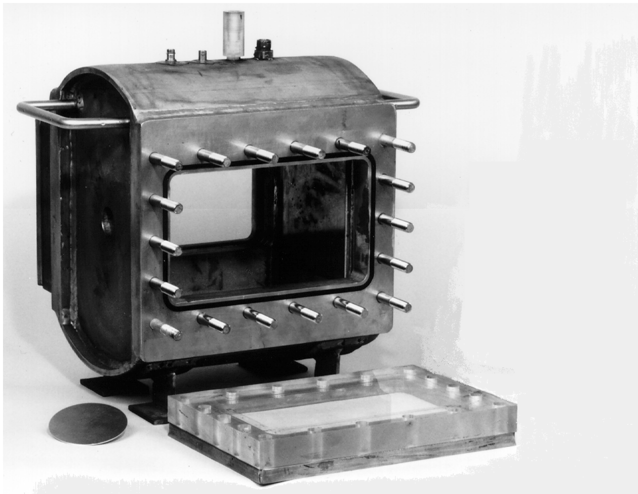
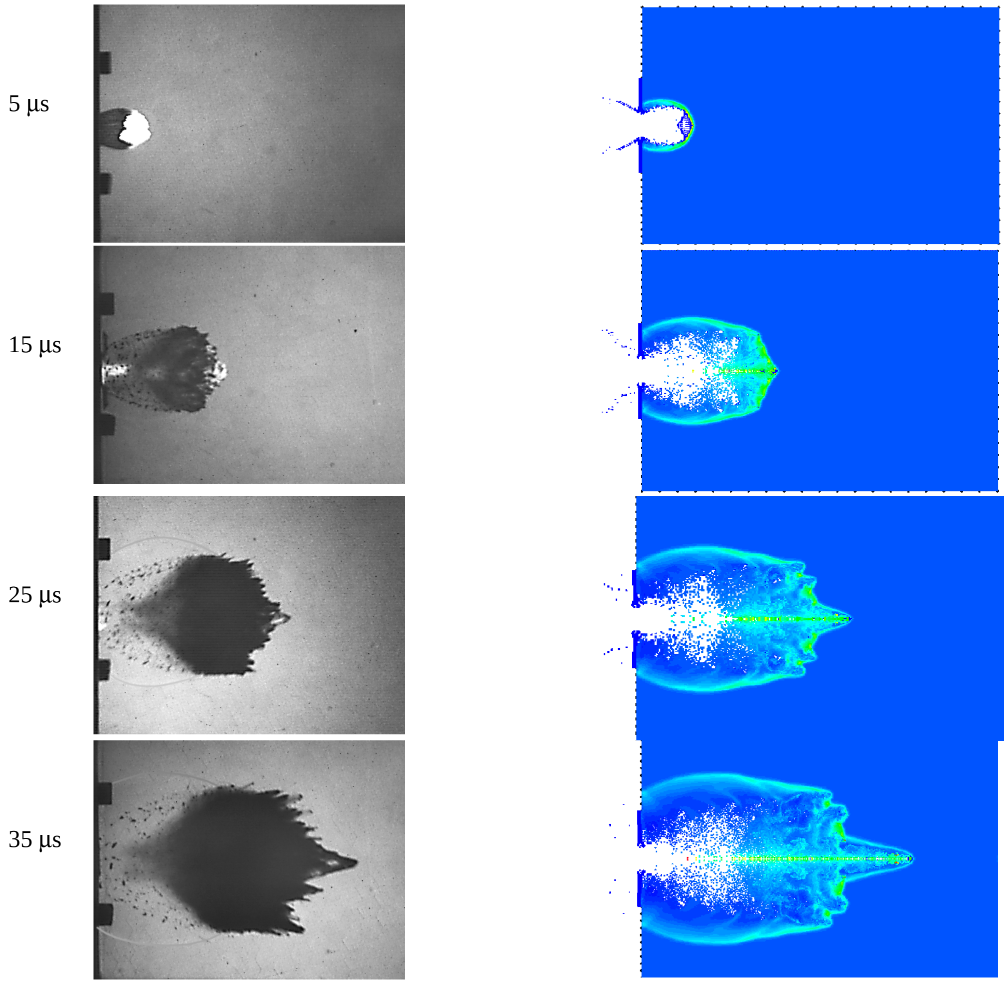


Fig. 10. Experimental set-up to analyse impact phenomena within pressure vessels (EMI)

The investigation of the effects of impacts on glass is of importance, as there are the surfaces of optical instruments that may degrade under multiple impacts from small debris or micrometeoroids, causing scatter of light and thus reducing the function [13].



Shadowgraphs 10.5 bar

Simulation 10.5 bar

Fig. 11. Impact of a 5 mm Al sphere at 5.2 km/s on a 1.5 mm thick Al-plate; vessel pressure 10.5 bar; Video-shadowgraphs and Autodyn SPH simulation (EMI)

Considering the complex nature and variety of materials used in spacecrafts, like fibre-reinforced systems or anisotropic metal alloys, a simple conventional shoot-and-look approach cannot be a successful strategy to evaluate the potential of these types of materials for application as protective shield. Therefore we strongly believe that a consistent approach, combining a variety of experimental and numerical methods into a well-defined strategy is necessary. This strategy, which will be explained in the following, is adopted and used for protective structures at EMI: It includes a set of material tests that are analysed numerically. Thus, material properties and data are determined, which are then used to simulate well-defined impact tests with light gas guns. Comparison of results of instrumented tests and numerical simulation explains the physical processes and shows the accuracy of the material descriptions used. Having derived and validated reliable material data and models, improved protection concepts can be developed, in conjunction with advanced numerical methods.

3.2 Characterization of Materials, Used in Protective Designs

Static and dynamic tension tests determine stress-strain curves and failure strains for strain rates up 500 s^{-1}. It should be mentioned that an optical determination of the strain distribution within the material is extremely important. Fig. 12 shows a set-up, allowing to measure the complete strain distribution within a sample as a function of time [14]. Fig. 13 compares the stress-strain curves, as they would appear for example from measurements with strain gages of different length, stressing the importance of an evaluation of the full strain field.
A modified taylor test with an optical high speed registration (resolution 2 ns) of elastic and plastic waves running through the test material, delivers strength and failure for strains up to a strain rate of about 3000 1/s, together with erosion data.

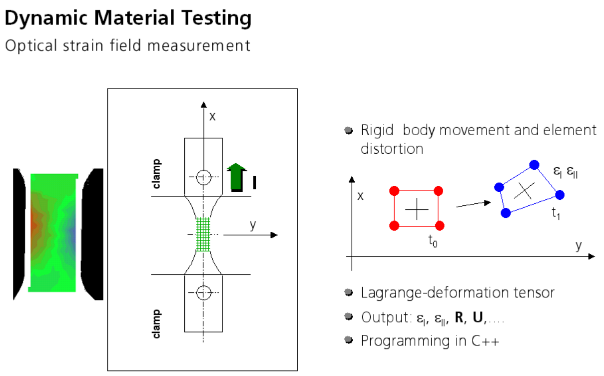


Fig. 12. Optical measurement of the strain field during a tensile material test (EMI)

Planar impact experiments are used to get a wealth of data: Yield strength, Hugoniot data, indication of phase transitions if existent, and spall strength for strain rates up to about 10^6 1/s. By multiple shocking, even low density materials can be loaded to high pressures and strain rates [20]. Inverse planar impacts are used to determine points on the release isentropes of a material. Newly developed pulse power sources allow the determination of EOS data up to the Mbar range [15]. Velocity wave profiles can be measured meanwhile to velocities up to 10 km/s [16].

Fig. 14 shows as an example the dynamic yield strength of a steel alloy, covering the full range of strain rates from quasi-static to extreme dynamics. This shows that it is possible to characterize a material consistently, covering the whole range of strain rates. Therefore the goal must be to develop and use material models being valid for the whole range of strain rates, covering the high pressure behaviour with possible phase transitions as well as the quasi-static behaviour. This approach is continuously applied at EMI for metals [17]. For non-metallic materials new test methods are being developed.

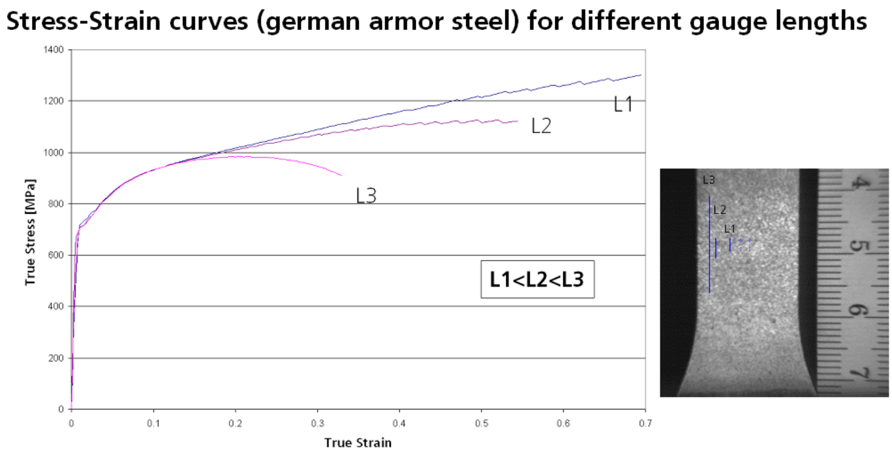


Fig. 13. Comparison of measured stress-strain curves, depending on the position of strain gages in comparison to the optical evaluation

Determination of yield stress (HZBL) as function strain rate, using a suite of different material tests

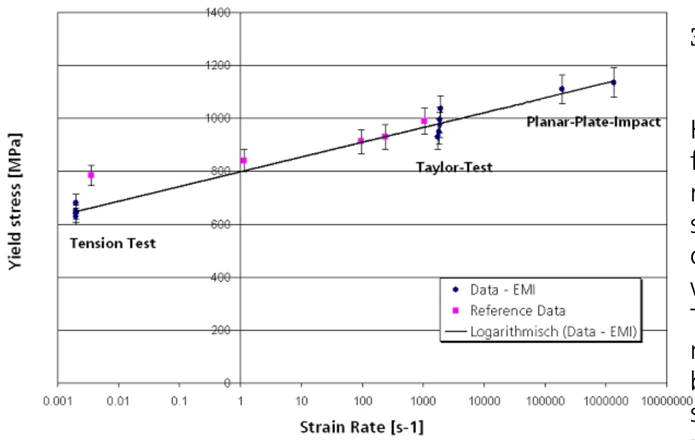


Fig. 14. Example of a measured yield strength of a steel alloy, covering a broad range of strain rates.

3.3 The Wealth of New Materials

To improve the efficiency of protective designs or to develop completely new concepts, definitely the wealth of upcoming new materials must be investigated. Existing applications of typical new materials are described e.g. in [18], [19]. Consequently, such materials must be analysed by the methods as described above. However, methods used for ductile, nonporous metals cannot be directly applied for example to fibre reinforced materials. For materials like Nextel and Kevlar/Epoxy, properties like anisotropy, brittle fibre failure, porosity, weave stretching, delamination and phase transitions must be considered.
Fig. 15 sketches a suite of test methods, which were developed to characterize this spectrum of material features. Note for example the different stress strain curves measured for weaves under 1D and 2D dynamic loads (Fig. 16). Compaction of porous materials must be measured statically and dynamically. Vaporization of resins may occur and can be characterized with plate impact tests (Figs. 17, 18).

Exciting opportunities for shield developments arise because of the rapid development of new materials within other areas of applications. Sub micron ceramics (more general nano materials), fibre reinforced ceramics, new fibre types, a big variety of newly designed metal alloys, must be evaluated with respect to their potential for debris protection. In analogy to ballistic protection design, an essential potential for improved protective shields can be assumed, allowing the design of much more effective shields without prohibitive additional weight.

3.4 Development of Material Models and their Validation

Having gone through a complete analysis process for each material involved in a shield concept, reliable data are available for a wide range of strains, strain rates, pressures, temperatures. Based on these data, material models must be developed, which are able to describe the full suite of test data. The material models are validated by simulating all material tests in detail, thus reproducing material behaviour including failure for a wide range of stress and strain states. Typically, Fig.18 shows measured data of plate impact tests on cloth material and their application to discriminate between different EOS models and data. Again, material model and data are used to cover all other tests, too.

Clearly, limitations are given by pressures and strain rates achievable in the material tests. But, as mentioned above, new methods like the application of pulsed power sources will expand the range of data, which can be used to derive material data and model validation test cases.

3.5 Application in Protective Design: Symbiosis of Numerical Simulation, Validated Material Models and Instrumented Experiments

Validated material models then can be used to an analyse and further develop new concepts for protection against debris and micrometeoroids. Numerically simulated impacts on shields yield "precise" results to an extent that is determined by the validity of the EOS and the accuracy of the material models used as well as the discretization of the structure and the type of code applied. In particular, no fitting of parameters or adjustment of material properties is needed as this would contradict the results from the material characterization. The output of a series of numerical simulations can be used i. e. to generate ballistic limit curves up to velocities that are not accessible for experiments.

Although this approach is extremely tedious and ambitious, it is a promising way for the further advancement of knowledge and results in protection of vehicles and spacecraft components.

Finally, an example of a shield development against low velocity - high mass threats is presented, which demonstrates the powerful possibilities obtained through a combination of dynamic material modelling with advanced measurement techniques [21]. A metallic fragment was shot against a basic bumper concept, consisting of a metal/weave combination. Fig. 19 shows high speed camera pictures of weave deformation during impact. Of course, a look into the interior of the shield would help to understand the protection mechanism. Therefore parallel to optical high speed photography, a soft x-ray source was used to look through the weave, showing details of the fragment/weave interaction (Fig. 20). Using material models and parameters developed according to the approach described above, the impact process was numerically simulated. The calculated weave deformation as seen optically as well as the internal fibre failure and fragment deformation as shown by the flash x-ray pictures compare well to the simulation (Fig. 21). In summary, ballistic limit data as well as the physics of the impact process could be numerically reproduced with the material data and description, as derived from independent material characterization tests.

As in the high velocity impact shown above, simulations also can be used for hypervelocity impacts to analyse physical details of the interaction process of impacting mass and protective material. Fig. 22 [8] demonstrates material failure and phase changes during target perforation for a hypervelocity impact. Such a detailed understanding of occurring phenomena, will lead the way to new concepts, the application of new materials and finally to more effective shielding.

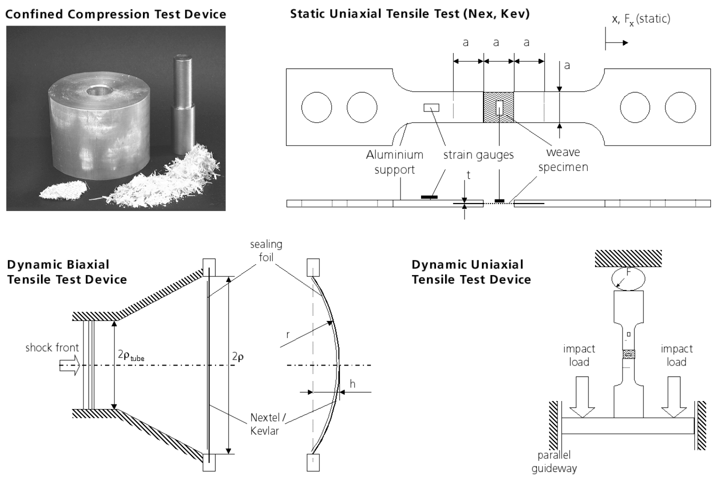


Fig. 15. Series of test methods for material characterization

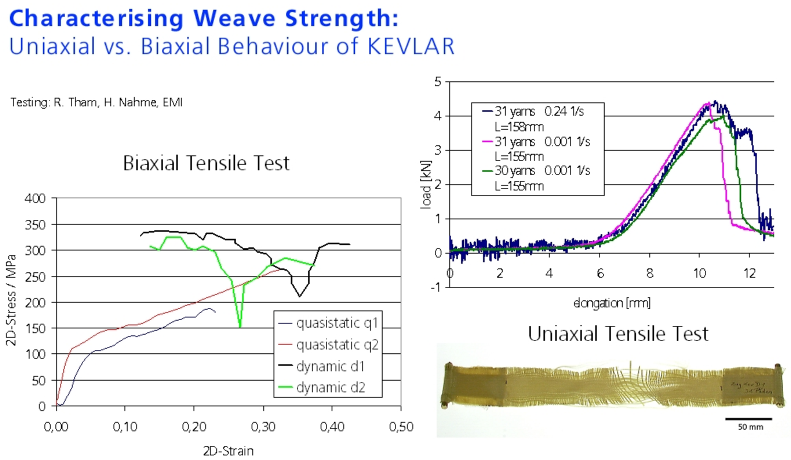


Fig. 16. Weave strength under one and two dimensional loads

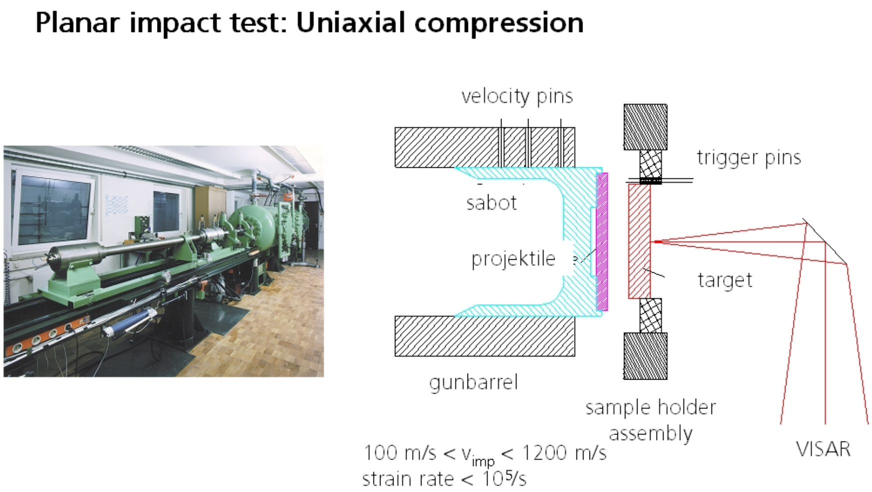


Fig. 17. Sketch of the Plate Impact Test

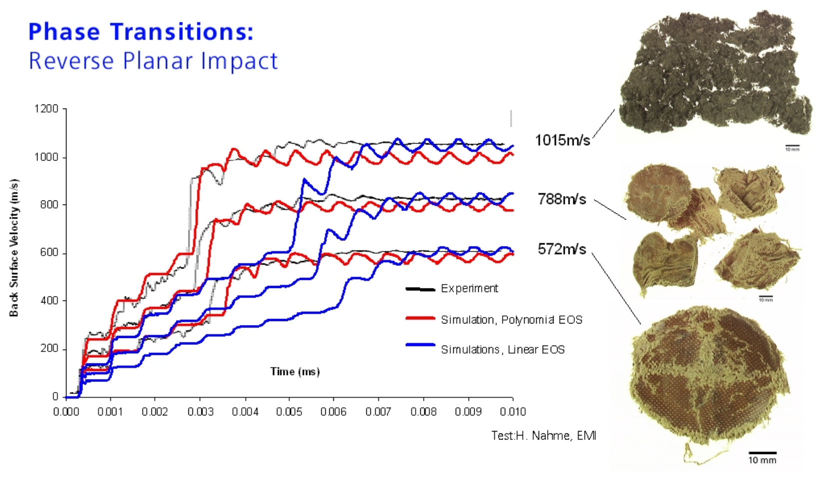


Fig. 18. Plate impact tests on Kevlar weave: Measured wave profiles and samples after test

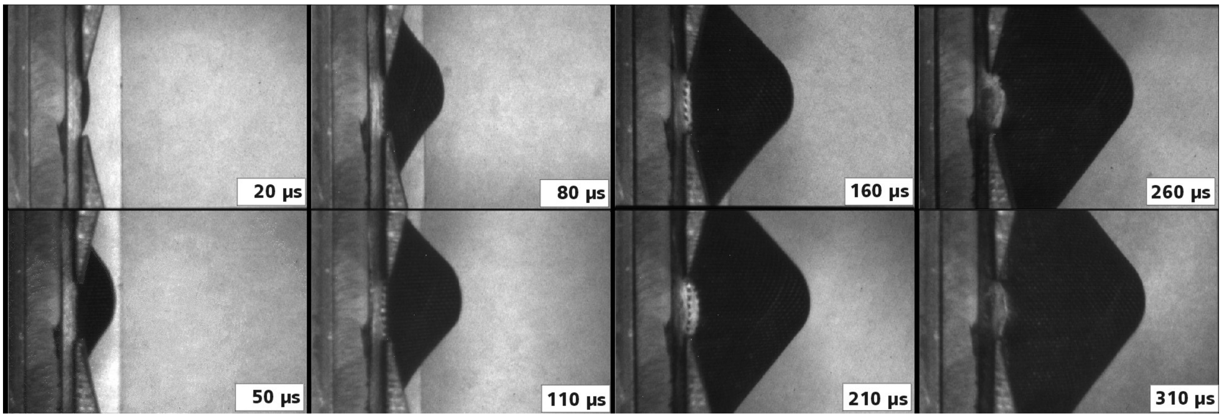


Fig. 19. Side-on look onto the deformation of a steel/Kevlar shield impacted by a metallic fragment with a velocity of 1350 m/s. Pictures made with a high speed video camera; impact from left side

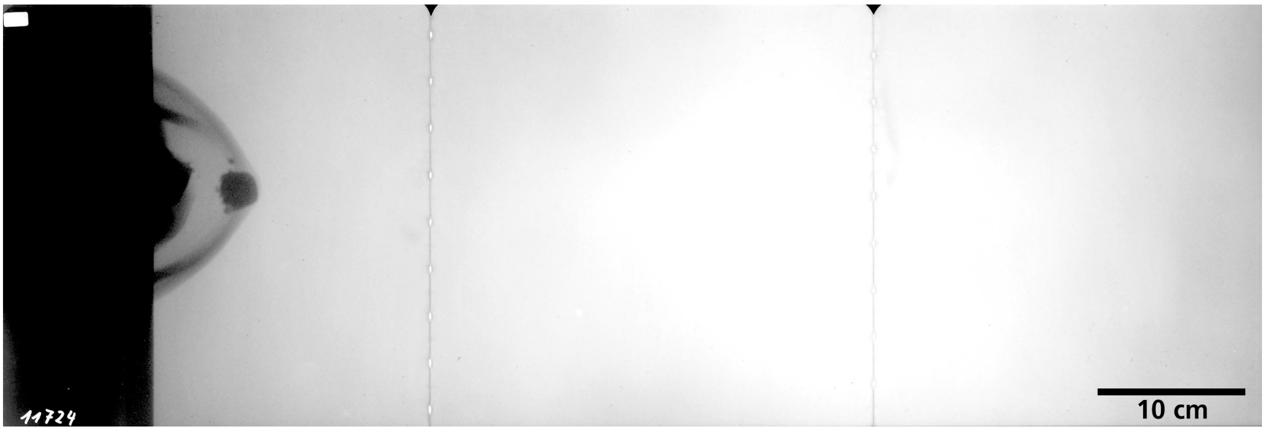


Fig. 20. View into the dynamic deformation of a weave during impact using a flash x-ray source.

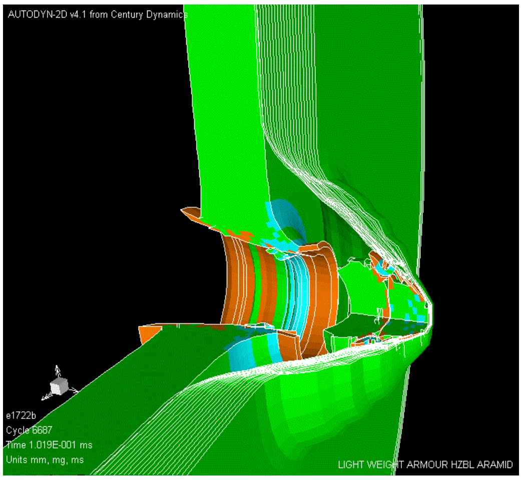


Fig. 21. Simulation of the penetration process, as observed in Figs. 19, 20.

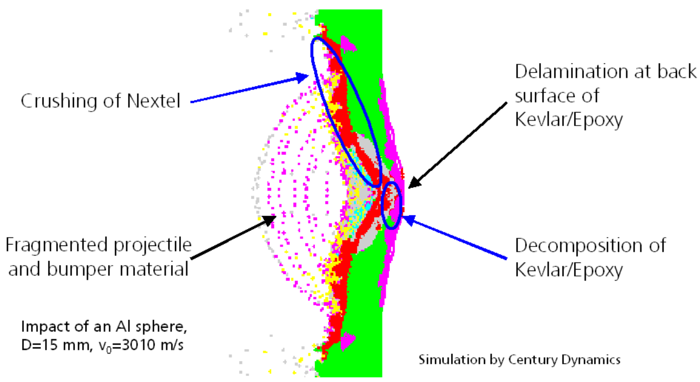


Fig. 22. Details of a target perforation by an Aluminium particle, impacting with a velocity of 3010 m/s

4. CONCLUSIONS

To achieve improvements in protection efficiency against space debris, a strategy is outlined, which tries to avoid adjustment of numerical and material parameters by fits to penetration experiments. Instead, it is suggested to determine material parameters from carefully selected laboratory tests, covering a broad range of strains, strain rates and stress states. Knowledge of the dynamic material behaviour then can be used for the development of new shield concepts by means of numerical simulation. The detailed characterization of all materials involved, the development of appropriate material models and the validation of these models is a very tedious effort. But, having gone through this effort, simulations of the shielding process without any adaptation of material parameter give confidence in the strategy used and justify the application of the simulation to improve existing shield configurations and analyse new shield concept ideas.

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