DYNAMIC IMPACT TESTING

Servohydraulic High Rate Testing Machines

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Abstract. Currently dynamic impact testing is facing a strong demand, mainly caused by special requests from the automotive industry; it is not the only industry interested in dynamic data, but it is the driving force behind the presently seen developments.

Time to develop a new car and to bring it to the market is continuously reduced. Less time is available for experimentally proof-testing of all parts and components. More and more development steps will be done by numerical simulations. This requires models and/or constitutive laws to describe complex interactions between materials, structures and loads; but all of these numerical descriptions are at the end in need of an adaptation to the real world of the materials used. Experimental tests under well defined conditions must be conducted to satisfy those needs.

If cars – or structures in general – are to be designed according to crashworthiness, the mechanical properties of materials under impact conditions must be known. Relations between mechanical properties and strain rate are not linear and extrapolations of the known static behaviour to impact conditions is risky, not to say dangerous. This is especially valid for the automotive industry, where new materials – like composites or light weight materials – are used, whose impact behaviour is totally unknown.

In close cooperation with experts from various industries and research institutes Instron has developed throughout the past years a new family of servohydraulic testing machines specifically designed to cope with the dynamics of a high rate test. The presentation will show the main development efforts and reflect these versus their experimental necessities. Typical test results will be shown and discussed.

Key words: Dynamic impact testing, crash simulation, automotive industry, servohydraulics, strain rate sensitivity, high strain rate testing machine, mathematical models, iteratively profiled drive signals, energy transfer concept, open loop control, closed loop control

1.Why is there currently an interest in Dynamic Impact Testing?

Validation of the usefulness of consumer goods and technical articles as well has always been of interest. *Fig.1* shows an early attempt to proof test guns (1443 [1]). A cannonball was placed on a post with black powder poured on it and a cannon barrel placed on top. When the powder was lit, the cannon barrel was shot vertically – and was damaged occasionally at splash down because of the heavy landing. This drawing is not only one of the first showing a material test in its true sense, but it shows also the first reported IMPACT TEST.

Testing technology, also impact testing has seen a lot of improvements since. But the intentions behind those tests remained the same – then and now the usefulness of structures under sudden load impact should be studied and described.

Fig. 1 ***Gun testing – 1st reported display of a material test in the true sense, 1443***

Different terminology's are used to describe sudden load impacts – high speed tests, high rate tests; this report will use DYNAMIC IMPACT as the more general term and will refer to dynamic tension, compression, bending and puncture tests as special dynamic impact applications. This definition should help to make a clear difference to fatigue and quasi-static tests.

All kinds of industry – railway, aircraft, steel, plastic, light weight materials, semi-conductor and bio-medical, but leading by some distance the automotive industry – shows a great demand in proper dynamic impact data for all kinds of materials. The reason why can be seen easily in *Fig.2,3*. Crashworthiness of cars must be proven.

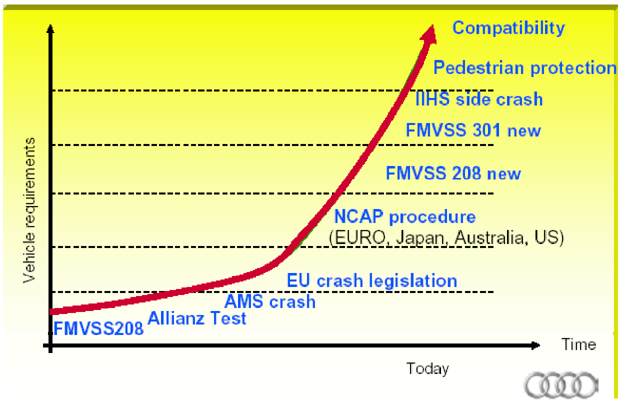


Fig.2 ***Increasing Requirements for Crashworthiness by Legislation [2]***

The number of crash tests has increased steadily over the years and the targets of those became more and more specific. A visit to the homepage of the European New Car Assessment Program [3] will show details. But besides crashworthiness other design concepts must be proof tested as well. *Fig.3* shows some of those and it is clear that the fulfilment of all explained in [4] that the time needed to develop a new car is mainly determined by the time needed to manufacture prototype cars (body-in-white cars; b.i.w.) for proof testing.

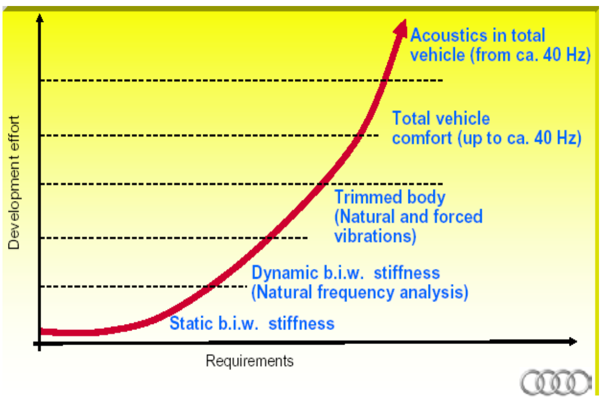


Fig.3 ***Increasing test requirements in other technical disciplines of car development [2]***

Significant additional improvements are not expected on this traditional path. Improvements are only expected as a consequence of integrated virtual, i.e. CA (computer aided) design technologies and tools (*Fig.4*). This does

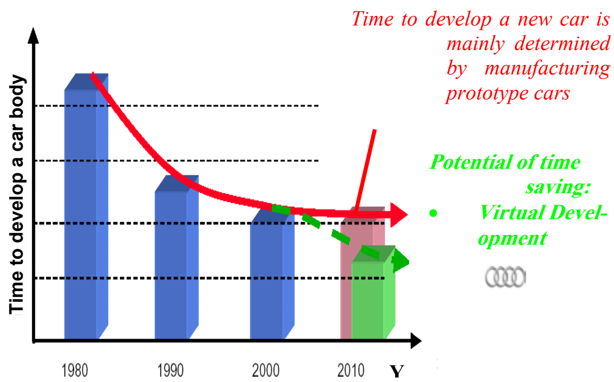
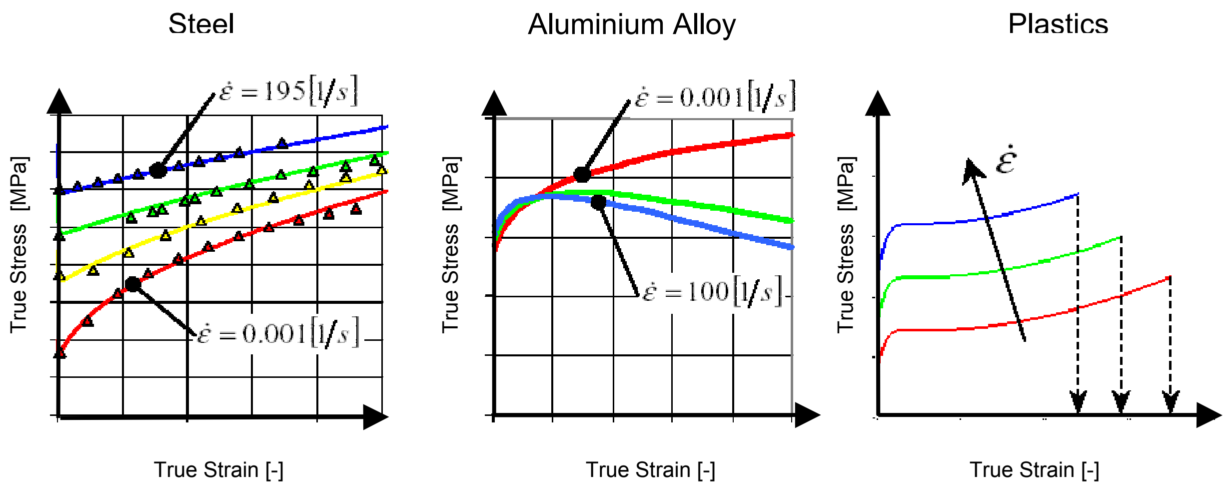


Fig. 4 Increasing design complexity requires virtual development tools

not mean that CA techniques will or should substitute a real prototype test fully. This will always be the final step in the development chain – to finally proof test and validate a design.

It is the basic subject of crash simulations to evaluate and improve design concepts to protect car passengers and pedestrians. The key to this task is the space-, cost- and weight-efficient transformation of kinetic energy into predominantly irreversible deformations of structural components. As the characteristic time periods of crash events are typically in the range of a few milliseconds, it is important to consider materials' behaviour at higher strain rates. *Fig. 5* shows the influence of strain rate on the mechanical behaviour of various types of materials; the difference in strain rate dependent strain hardening behaviour between Fe- and Al-materials is obvious. The graphs in *Fig.5a* show a numerical approximation of experimental data and indicates clearly a positive strain rate sensitivity of the tested flat steel metal throughout the tested range of strain rates. The tested aluminium alloy (*Fig.5b*) is characterised by a different behaviour; after an initial positive strain rate influence as well, the strain hardening effect is reduced at higher strain rates and can in its extreme be changed into a kind of strain softening. The later is due to the adiabatic heating up of the specimen. Engineering plastic materials show a positive strain rate sensitivity as well (*Fig.5c*) – the yield stress increases steadily in most cases, while the rupture strain is reduced. Temperature influence is opposite.

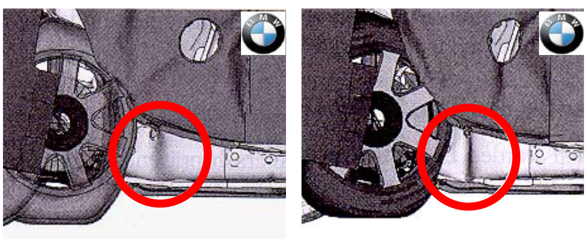


- Continuous increase of yield stress in dependence on strain rate
- Adiabatic heating effects at higher strain rates can cause stress softening
- Continuous increase of yield stress in dependence on strain rate
- Tendency for reduced fracture strain

Fig. 5 ***Influence of strain rate on mechanical behaviour of engineering materials [5]***

Simulation and evaluation of crashworthiness of structures requires the knowledge of strain rate influence on materials behaviour.

These examples show that the quasistatic behaviour of engineering materials is not a sufficient criterion to select materials concerning crash requirements. Werner discusses this in [5] and *Fig.6* may explain the consequences. *Fig.6* shows the simulated deformation behaviour of the door threshold when being intruded by the left front wheel due to an offset front crash. Whilst there is only a small depression in *Fig.6a, Fig.6b* reveals a remarkable instability. The differences in the assumptions on material behaviour are striking. Simulation "*a*" considers a positive strain-rate dependence of the material's behaviour, simulation "*b*" reflects purely quasistatic behaviour only. With respect to the latter, a design engineer would stiffen this area as a consequence; passengers would be subjected to too high g-forces in cases of an accident and a direct consequence would be wrong tuning of the airbag sensors [5].



a) b)

Fig. 6 ***Simulated impact of left front wheel into a threshold [5]***
a – consideration of strain rate influence
b – consideration of purely quasistatic prop-

2.Testing Systems for Investigations of Strain Rate Influence

As it has been discussed before, the mechanical properties of materials are found to be sensitive to the rate of loading. The spectrum of available strain rates is shown in *Fig. 7.* Also shown is the characteristic time, corresponding to the time required to produce 1% strain at the corresponding strain rate. Creep and quasistatic testing is done with dead-weight, hydraulic or electromechanical testing machines. The tests are carried out under essentially isothermal conditions. From a strain rate from above 10^0 s^{-1} on up, the deformation becomes adiabatic. The internal heat generated during plastic deformation does not have time to dissipate [7]. In the range of lower impact speeds pendulum impact machines, drop-weight testers and servohydraulic testing machines are considered. Impact bars (Hopkinson bars) are usually used in the range of 10^2 to 10^4 s^{-1}. At the highest strain rates testing usually involves explosively driven plate impact where measurements are made of the propagation and reflection of shock waves [7].

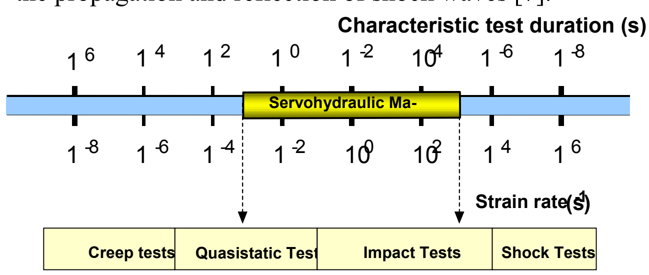


Fig. 7 Spectrum of strain rates for mechanical testing

The latest developments of servohydraulic testing machines enable to cover strain rates between 10^{-3} and 10^{3} s^{-1} within one machine. This wide range of test speeds makes this type of testing machine extremely versatile. Modern machines can cover impact forces up to 100 kN at max. speeds at impact of 25 m/s.

3.Servohydraulic High Rate Testing Machines

The principles of servohydraulic testing machines are sufficiently well-known. They can be transferred to high rate testing machines; but the principle of load transfer

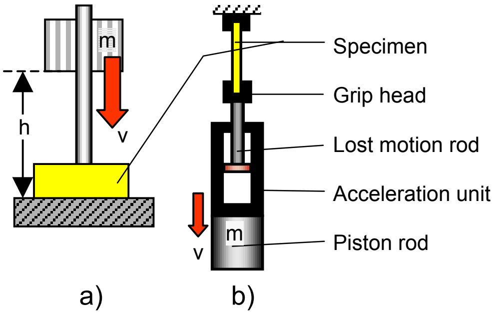


Fig. 7 ***a – Dynamic load impact***
b – Principle of load transfer

is different. The specimen is not firmly gripped by a grip head, which is rigidly connected to the piston rod (*Fig.7b*). The specimen and piston rod of the servohydraulic actuator are decoupled. The piston is servohydraulically accelerated to the desired test speed and at the end of the acceleration distance, i.e. when the end of the "lost motion rod" (slack rod) is reached, a coupling between the actuator piston and the specimen takes place and the specimen is loaded according to the principle of energy transfer (*Fig.7a*). Kinetic piston rod energy is instantaneously transformed into deformation work to deform the specimen. In order to ensure optimum alignment of the piston rod in combination with a maintenance-free service life, hydrostatic bearings with separated oil feed-in are preferably used. In order to meet the requests for different maximum speeds at impact and the corresponding impact force, different sizes of actuators in combination with large three-stage servovalves are available; commercial high rate machines range from 10 to 100 kN.

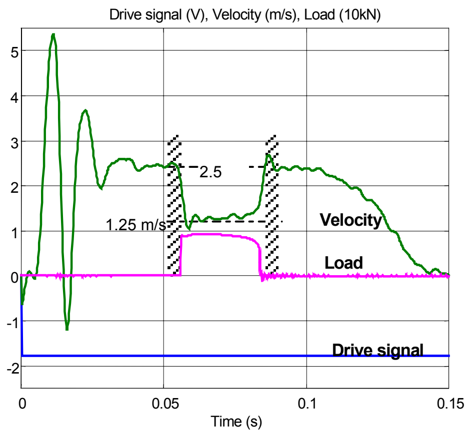


Fig. 8 ***Typical drop in speed at lower testing speeds, due to deformation***

Following the principle of energy transfer, one would easily assume that a heavy piston rod will be an advantage since the kinetic piston energy is directly influenced by the piston mass. As long as the energy level is sufficient in comparison with the energy needed to deform the specimen, the piston speed will at least not be dramatically reduced during impact. Dependent on the design principle of the actuator, this can be assumed in general at speeds above 10 m/s. But at mid-speeds and especially at low speeds the drop in the testing speed can no longer be neglected. As is shown in *Fig.8*, the velocity drop can be quite remarkable; with a constant drive signal, set for a target speed of 2.5 m/s, the piston speed is decelerated down to 1.25 m/s [1] during the time of specimen loading (*Fig.8*: time range between the shaded columns). Obviously there is a big mismatch between target and achieved testing speed.

According to the rules of physics this phenomenon can not be avoided, unless an additional energy source can be made available. But closed-loop-control technology is inappropriate to solve this problem, since the loop closure time is much longer than the test duration. In order to solve it, an iterative control approach should be used [8].

The objective of the iterative control algorithm is to determine a valve drive signal which will keep the actuator moving at the specified target velocity while deforming the specimen. The first test run uses a constant valve drive signal calculated according to a measured velocity/voltage relationship related to the valve flow characteristic. The velocity error is then used to calculate a new valve drive signal. Further iterations may be used if the velocity is still not sufficiently close to the target (*Fig.9*). To calculate the new valve drive signal, a discrete-time inverse model is required, enabling the valve drive to be calculated from a velocity signal. Extensive testing has shown that this model is able to linearise the very non-linear relationship of fluid dynamics and that it helps to minimise speed errors. At the current state of the art these can not be totally avoided.

Iterative corrections of the drive signal is not the only design feature to be considered to ensure improved dynamic impact tests. Using profiled drive signals means that whilst the piston rod is moving additional pressure oil will be fed in. Heavy masses will not be able to react spontaneously on changes in the drive signals; before those will become effective the test will have passed. The initial approach mentioned using a heavy piston rod is not correct. All dynamic parts must utilise optimal low mass designs. This concept in combination with iteratively profiled drive signals ensures that the target

[1] ***The figures shown in* Fig.8 *are only relevant for a given actuator design and can not be generalised.***

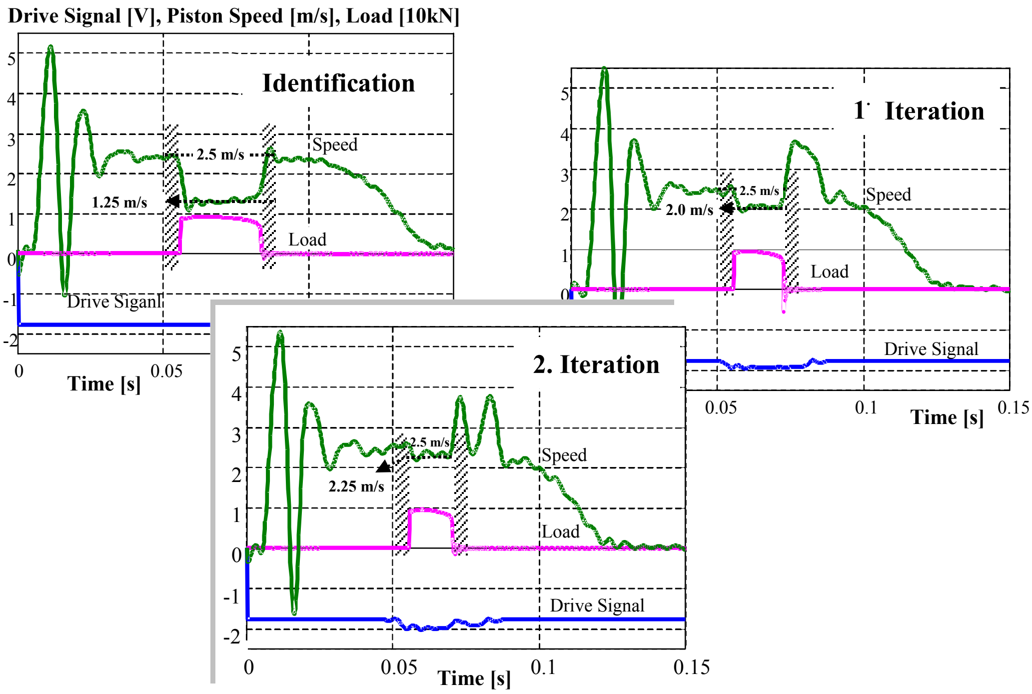


Fig.9 ***Iterative correction of profiled drive signals for high rate tests in open loop control***

test speeds can be achieved within defined tolerance band [2].

Though the loading speed during a real crash is not constant – it can change spontaneously – numerical models require experimental data, based on constant speed (strain rate) test conditions. Variable speeds, as seen in reality, are considered by discrete speed selections.

4. Load Transfer, Force Measurement, Strain Measurement

As discussed before (*Fig.7b*), high rate tests require acceleration units. Various design concepts of those are shown in *Fig. 10*

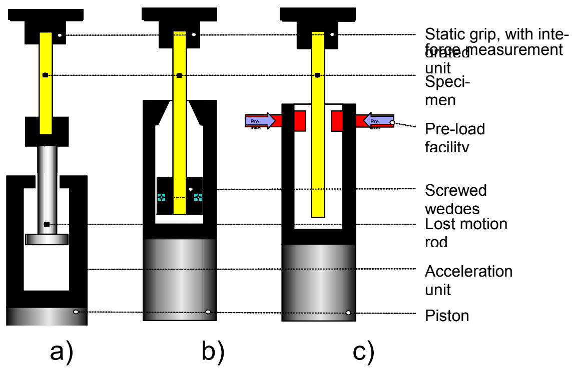


Fig. 10 Design concepts for acceleration units

Solution *a* is the traditional one, but it does not guarantee a firm, rigid load transfer during impact. The small mass of the lost motion rod rebounds, when hit by the accelerated piston rod and bounces continuously between the speed of the piston rod and an unpredictable higher speed. Nevertheless, this acceleration unit can be useful for materials with a higher damping behaviour, such as soft plastic materials. Solution *b* can provide proper gripping, but it is very sensitive concerning matching geometries and alignments of the transfer wedges. Only solution *c* , the patented *Fast Jaw Grips*, can ensure proper firm gripping of the specimen instantaneously after the load impact.

Fig. 11 shows set-up details of the static (*a*) and the dynamic (moving) grip head (*b*). The flexure arms of the "Fast Jaw Grip" are pre-loaded by screws. Before the test is run and whilst the Dynamic grip is being accelerated the moving grip is held open using so-called knock-out wedges. At the end of the acceleration distance of the piston rod these wedges are "knocked out" and the pre-loaded flexure arms grip the specimen like a mouse-trap, instantaneously and firmly. Investigations of the gripping marks on the specimen surface show that the gripping process takes max. 15 µs.

Force measurements at high test speeds are challenging. Compact and low-mass systems are requested. Again, light-weight design criteria are mandatory (*Fig.11a*).

But even under consideration of these conditions and utilisation of extremely stiff piezo-washers, the natural frequency of the fixed unit amounts at its best to approx. 15 kHz; for high load capacities even less. As a consequence, the load cell is ringing at its natural frequency when hit by an impact load (*Fig. 12*). The ringing period in the piezo signal in different time zones of the recorded signal, amounts roughly 125 µs. This indicates a

[2] Simulation of forming processes requires an extended version of drive signal correction; the target speed profile is described by a progressive speed reduction.

natural frequency of this specific gripping / measuring system of 8 kHz. Integrated light-weight design makes a contribution to the reduction of the load ringing, but inertia effects are mostly still too distinct at high impact speeds. To minimise these it is common to use instrumented, strain-gauged specimens, i.e. the specimen with its own dynamometer area. The advantage of those measures is obvious from *Fig.12.* It additionally gives evidence of the efficiency of the Fast Jaw Grip – piezo

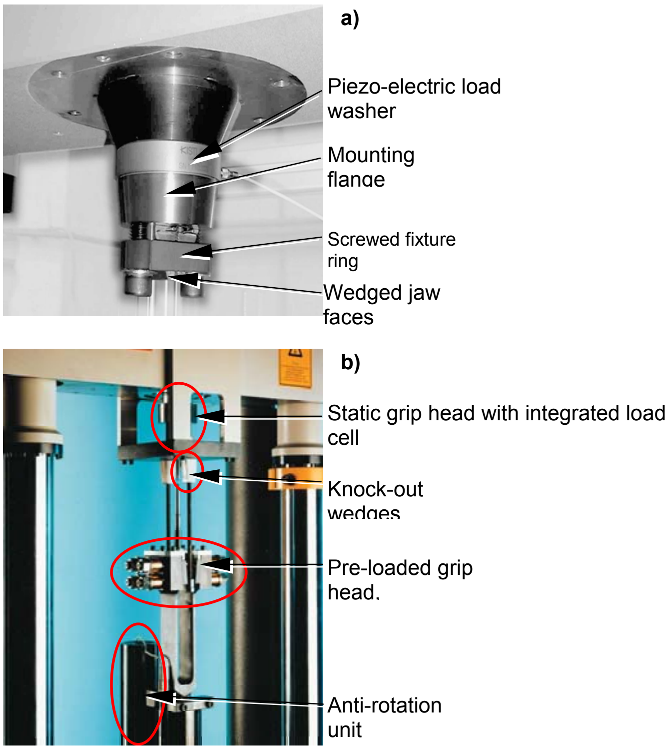


Fig. 11 a) Static grip head with integrated dynamic load measuring unit
b) Arrangement of patented „Fast Jaw Grip“

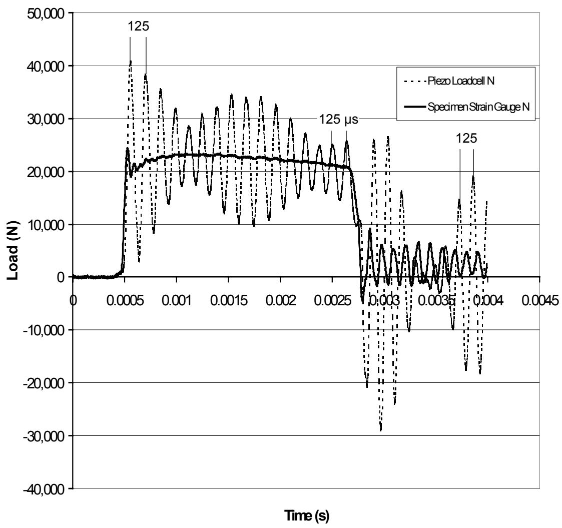


Fig. 12 Load measurement: Piezo Loadcell vs. Strain-gauged specimen

load signal and strain gauge signal show the same initial gradient. This comparison contains additional important information – the ringing is only seen by the load measuring system, not by the specimen; which allows modifications of the original test signals in order to minimise/reduce the influence of erroneous signals and to ease signal analysis.

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A typical size of specimen with an integrated accelera

tion part for the Fast Jaw Grip is shown in *Fig.13.* If the specimen can not be manufactured with a length as shown, it is possible to use re-usable extenders instead. The “static” part of the specimen can be used for strain-gauge instrumentation in the shaded “Dynamometer range” for dynamic force measurements. If prepared such, each specimen must be specifically calibrated for those force measurements.

Dynamic strain measurements shall only be discussed briefly. Mechanically fixed clip-on extensometers, as conventionally used in quasistatic and fatigue tests, are not applicable in dynamic impact tests. G-values above 1000 m/s^2 ban this technique. The LVDT of the actuator can be by its best used for piston positioning, but not for global deformation measurements. Its resolution is too inaccurate and – besides when using the Fast Jaw Grips – a permanent contact between the specimen and the piston rod can not be ensured throughout the entire test. Early steps taken to understand the specimen deformation in a dynamic tensile test used direct displacement measurements between the dynamic and the static grip head; a technique that could be improved with respect to strain measurements by specimen markings with optical fibres. But reliable strain measurements could not be ensured even with those ultra-light markings. This technique is now redundant and state of the art is now non-contact optical systems, as these are shown in principle in *Fig.14* [9, 10]. It is a relatively young measuring technique and not many published papers are available. Most information is to be found in the hand-outs of work-shops and conferences. Strain gauges, fixed in the gauge section of the specimen (*Fig.13*), can be used for total strain values of max. 10% and thus are often used for high resolution strain measurements when none of the described non-contact extensometers is available. Because of the dynamics of the impact strain signals, broadband signal conditioner units (>100 kHz) are required.

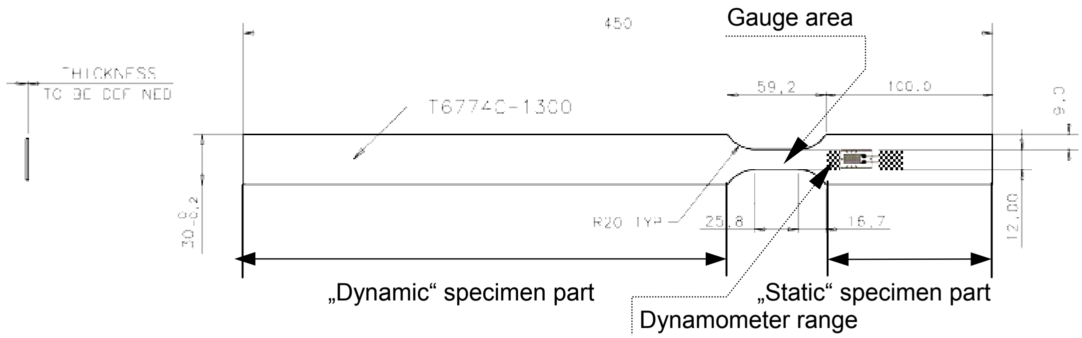
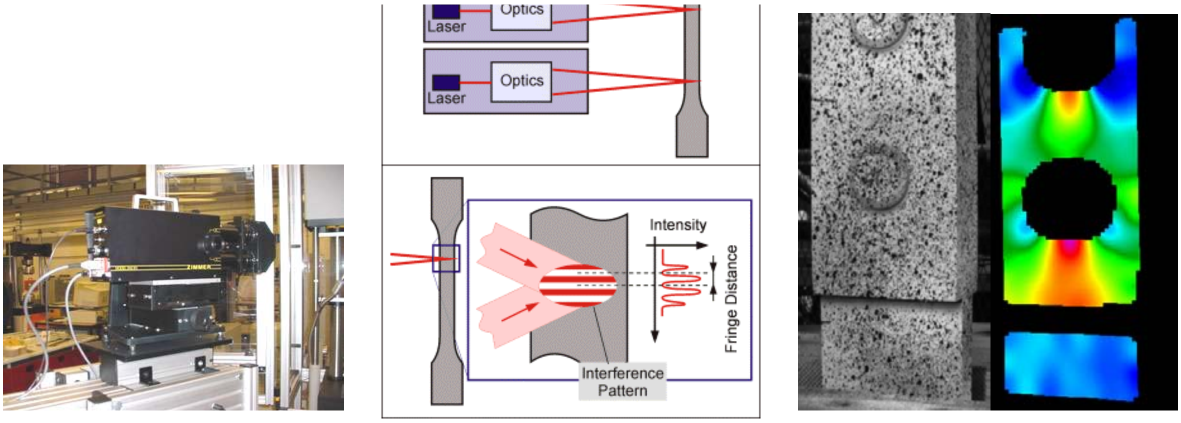


Fig. 13 High Strain rate Specimen with integrated acceleration stretch and dynamometer area



a) b) c)

Fig. 14 Dynamic, non-contact High Rate Strain Measuring Systems

a – High speed camera, measuring the displacement of surface markings: *integral strain*

b – Laser Doppler Extensometer, measuring the surface speed of a specimen within an interference volume: *integral strain* [10]

c – Gray-scale correlation, determination of the movements of randomly distributed surface markings with ultra-high speed camera and subsequent analysis with specific search algorithms: *integral and local strain distribution* [9]

5. Data Acquisition, Data Analysis

The dynamics of impact signals require wideband data acquisition systems. Because of the burst-like character of those signals, transient recording cards with corner frequencies of 1 MHz and above are mandatory. Those DAC-cards should be integrated into the High Rate Testing System for ease of handling and logic of data flow.

The data, once recorded, contains information about all of the test system – the tested specimen and the testing machine incl. its measuring systems as well. The piezo load signal in *Fig.12* is an example. Many numerical attempts are undertaken to eliminate the erroneous signal content; smoothing algorithms as well digital filtering are also used. But the application of those algorithms is not without problems, as can be taken from *Fig.15*. The original measurements see multiple changes when different analysis tools are used; additional influences are caused by different tool parameters. An effect to be seen clearly in *Fig.15* is the magnitude and location of the maximum tools are not to be used to transform inappropriate raw signals into signals proper for analysis.

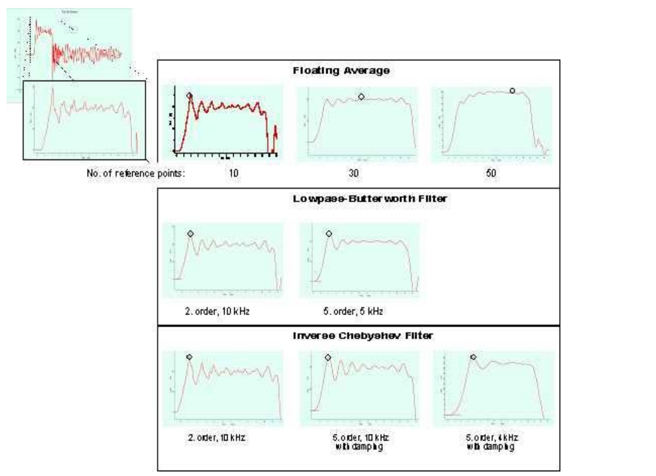


Fig. 15 Modifications of original test records Schematic display of influences by smoothing and digital filtering algorithms

6. Test Standards

Presently there are no existing test standards concerning impact tensile or compression tests. But the importance and necessity of those agreed practices can be taken from world-wide activities of working groups:

- *National:* Germany – VDEh (Steel Institute), DVM (German Association for Material Testing); England – UK Impact Group
- *Europe:* ESIS – TC5 [11, 12] (European Structural Integrity Society)
- *Global:* IISI (International Iron and Steel Institute)

Standardisation and agreed codes of practices are required to ease and harmonise the worldwide activities for supply of appropriate material data for crash and general impact simulations. The number of engineering materials and their influencing parameters show clearly the necessity of those agreements.

7. High Rate Test System

A commercial servohydraulic test system is shown in *Fig.16* – it is a 100 kN impact load machine, which can be operated up to a maximum speed of 25m/s. It is powered by a 280bar hydraulic power supply and controlled by a digital control system. Whilst this control system is not needed for the high rate test, it supports the setting-up procedure and enables the machine to run in full closed loop control mode and thus to run fatigue tests and quasistatic tests as well. With various test accessories the machine can be equipped for impact tension, impact compression, impact bending and impact puncture tests. For materials testing the machine is designed with a table-mounted actuator, while a machine with an upper crosshead mounted actuator (as shown in *Fig.16*) is more convenient if material and structural tests are to be run with one machine. A compact temperature chamber, specifically designed to meet the dynamic requirements of a dynamic impact test, is available for temperature simulations in a range from –100 to +300°C; designs for extended temperature ranges exist. A sophisticated software family supports the test set-up, test run and data acquisition. Iterative control techniques can be provided to generate profiled drive signals, to enable variable test speeds during an impact event. Up to eight data channels can be acquired and analysed. A software tool supporting for basic data analyses enables a quick view of the data and basic data manipulation procedures. For more detailed analyses those test data can be exported and transferred to commercial mathematical software tools.

The description above is to be read like a summary, but it should make it obvious that a High Rate Test System is complex and always requires to a certain extent co-operation between the manufacturer of the testing system and the end user.

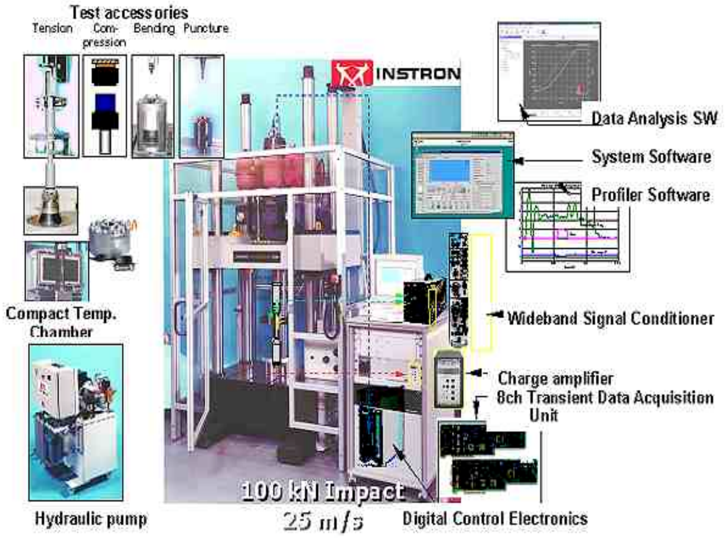


Fig.16 *Commercial servohydraulic, PC-based High Strain Rate Test System with various test accessories for different test procedures, signal conditioning and data acquisition and analysis*

Simulation techniques allow virtual product developments and help to reduce development times. Considerations of the automotive industry are picked up and used to show the close co-operation between design and test engineers in the field of crash testing and simulation. Numerical crash models need adaptation to the real world of material behaviour under high strain rate conditions. High dynamic servohydraulic testing machines close the gap between experimental and numerical crash tests.

Design features for high rate testing machines are discussed, their experimental needs are explained. A commercial high rate test system has been described.

9. Acknowledgement

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