SEVENTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 66

QUASI-STATIC AND DYNAMIC CRUSHING OF ENERGY ABSORBING MATERIALS AND STRUCTURAL COMPONENTS WITH THE AIM OF IMPROVING HELICOPTER CRASHWORTHINESS

C. Kindervater

Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt
Stuttgart, Germany

September 8 - 11, 1981

Garmisch-Partenkirchen
Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.V.

Goethestr. 10, D-5000 Köln 51, F.R.G.

QUASI-STATIC AND DYNAMIC CRUSHING OF ENERGY ABSORBING MATERIALS AND STRUCTURAL COMPONENTS WITH THE AIM OF IMPROVING HELICOPTER CRASHWORTHINESS

C. Kindervater

Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.
Stuttgart, Germany

Abstract

Designing a crashworthy helicopter structure among others fundamental knowledge of the energy absorbing process and failure behaviour of the involved materials and structural elements is required.

Experimental investigations are done with some selected materials and structural elements such as aluminum honeycomb, thinwalled aluminum- and steel-cylinders, PUR-foam cylinders, and cylindrical tubes fabricated of reinforced plastics (GFRP, CFRP, Kev/ep). So far only the axial crushing of structural components is examined. This is done under quasi-static as well as impact loading. Key parameters such as specific energy, energy dissipation density, stroke efficiency and operating stress are determined and compared. Dynamic to static crushforce levels are considered. Differences in the static and dynamic failure mode are of special interest. The influence of the impact velocity is investigated for some components.

A crash-teststructure is drop tested with some selected structural elements acting as energy absorbers. Parallel to the drop test the crash case is simulated with computer program "KRASH". A correlation is done to the experimental results.

1. Introduction

Primary requirements when designing a modern state-of-the-art helicopter are

- Structural efficiency
- Safety
- Fail-safe
- Producibility and cost
- Satisfaction of mission/operating requirements

As secondary requirements can be considered

- Repairability
- Maintainability
- Use of standard parts
- Survivability

Survivability in terms of reduction of detectability and low vulnerability plays a major role only in military designs. Increased crashworthiness, however, is important in military as well as in civil concepts and is absolutely applicable to fixed-wing aircraft, too. Experience gained in helicopter crashes in the US Army in the early seventies resulted in guide lines to improve helicopter crashworthiness. These guide lines are documented in the "Crash Survival Design Guide" and the MIL-STD-1290 (AV).

The impact velocity beyond which occupant survival becomes statistically remote is limited. However, the operating speeds of most helicopters combined with their autorotational capability place most rotary-wing crashes in the survivable region.

Some typical US Army helicopter design requirements for survivable impact velocities are given in the following table, reference 1.

95% Survivable Impact Velocities		
	ft/s	m/s
Longitudinal	20.	6.1
Vertical	42.	12.8
Lateral	30.	9.2
15° Nose down	60.	18,3

In any crash there are many uncontrollable factors. Highly dangerous are rollover crashes and lateral impacts, the last being very similar to the lateral automotive crash where minor stopping distance is available to reduce high deceleration forces for the occupants. Critical, too, is the longitudinal impact against an obstacle. Following other design requirements no or limited crushable structure can be placed in front of the cockpit.

In a vertical or flat nose down impact where structural distortion and friction are the dominant energy absorbing processes the main features of a crashworthy helicopter design are

- High energy absorbing landing gear
- Crushable structure in the underfloor region
- Skidding surface in the nose region to avoid 'earth scooping' effect
- Energy absorbing seat system
- Strong and stiff occupant compartment to maintain a living space

It is our responsibility to fulfill these requirements of a 'people packing' design without increasing the total structural mass above a nontolerable value. Therefore, the aspects of a crashworthy design must be considered in an early design stage and structural concepts must be found which endure normal operational loads as well as impact loads.

2. Designing a crashworthy concept

An overview of principles realizing a crashworthy helicopter concept is presented in Fig. 1.

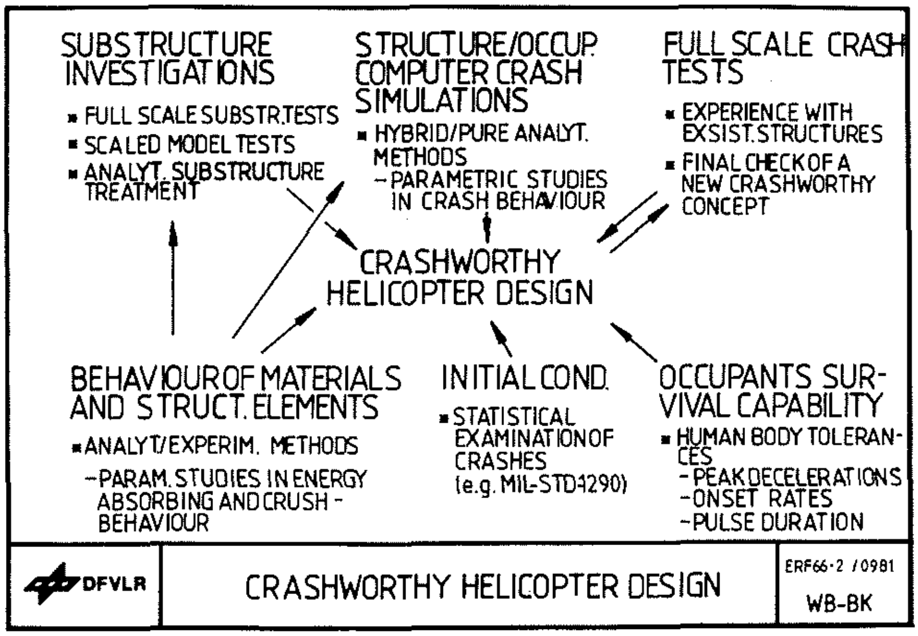


Fig. 1

Starting point of the design is the aim of protecting the occupant. We have to consider the loading limits of the human body under deceleration forces. These limits provide the requirements to the structural analyst how to stop the occupant.

In the next step we have to examine statistical studies of crash cases to find out the most potentialy survivable initial crash conditions. This usually forms the subject of regulations drawn up by the relevant authorities, one example being MIL-STD 1290 (AV) which defines the most probable impact conditions.

Valuable information for a new design can be provided by full scale crash tests done with existing helicopter structures. The 'weak' zones in a structure can be examined and improvements can be incorporated into the new concept. On the other hand a full scale crash test is clearly the best method to check a new concept for fulfilling design requirements.

A valuable tool in designing is the computer crash simulation. Structural dynamic response due to impact loading as well as the occupant behaviour can be simulated. In use are hybrid and pure analytical methods. Normaly simulated is the global crash behaviour including decelaration-time, velocity-time and displacement-time histories of selected structural parts.

Finally investigations done with substructures are a further method to come to a good design. Analytical as well as experimental treatment is possible. Tests can be done with full scale substructures or cheaper with down scaled models. Structural parts which can be optimized in energy absorption and failure mechanisms are, for example, landing gear, parts of the subfloor structure, seat system, particular absorbing units or structural junction elements.

Of fundamental nature is the investigation of materials and simple structural elements such as tubes, beams or stiffeners as to energy absorbing capability and failure modes. Due to the complexity of the energy absorbing process in structural distortion it seems to be senseful to use simple and cheap sepcimens. With simple elements parametric studies should be done with regard to the influence of the impact velocity, differences in static versus dynamic failure modes or possibilities in reducing peak loads. In an energy absorbing process the configuration of the structure is often more important than the materials involved. To examine such fundamental influences a larger structure is too expensive. Often structures are assembled of simple elements and the behaviour of the elements can give a first information on the behaviour of the total structure.

The treatment of these problems can be of analytical or experimental nature, whichever is best.

On the next pages some investigations will be presented with selected materials and simple structural elements tested quasi-static as well as under impact loads. The intent was to make some parametric studies concerning energy absorbing processes and large distortion behaviour which can be helpful for further developments of crashworthy substructures or crashworthy structural concepts.

3. Important terms in energy absorption

One way of absorbing mechanical energy is the collapse of structural shapes including tubes, honeycombs and foams. Designing for aircraft application it seems to make sense to use one-shot absorbing devices because standard reversible pneumatic or hydraulic absorbers are usually too heavy. The use of almost the entire volume of a failure-based absorber is another advantage.

Terms to define the performance of energy absorbing structural elements are based on their load-deflection curves. The ideal case would be a rectangularly shaped curve. Key parameters, as summarized in reference 2, enable the comparison of the performance of different absorbing materials and structural elements, Fig. 2.

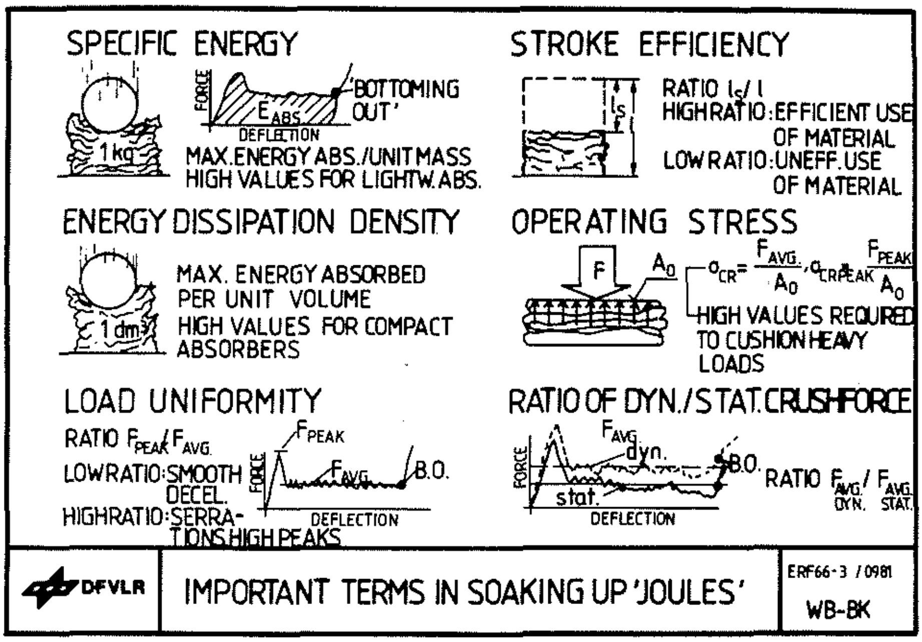


Fig. 2

Specific energy is the most important performance index and is defined as the *ratio of the maximum energy that can be dissipated in the specimen mass.* The maximum energy is the area under the load-deflection curve integrated to that point of the curve where a sharp increase occurs. This point is called the 'bottoming out' point of the material or structure beyond which no senseful energy absorption is available caused by the stiffening of the remaining structure. In many cases the positioning of the 'bottoming out' is not easy to do because of the lack of a sharp increase. For comparison with other configurations the value of the specific energy then must be related to a deflection which can be below the fixed 'bottoming out' point.

Energy dissipation density is the expression for the maximum energy that a unit volume of material can dissipate. If no large space for energy absorbing material or structure is available high values in the energy dissipation density are needed.

Load uniformity represents the ratio of the maximum load to average load level. A value reaching unity as the ratio of the ideal absorber indicates a smooth deceleration. High values of the load uniformity indicate high peaks or serrations in the load-deflection history which could be very dangerous in an absorbing unit stopping an occupant by exceeding the tolerable limits of the human body.

Stroke efficiency is the ratio of the collapsed structure height to the initial one. The available stroke for a senseful energy absorption is also limited at the 'bottoming out' point. The stroke efficiency is an important performance index because it is a criterion of how much of the initial length can be used as 'stopping distance' i.e. what decelaration level can be expected for a given initial velocity.

Operating stress is strictly speaking not a performance index. Higher operating stresses are required in stopping high density objects or vehicles than stopping low density objects at the same deceleration. The required operating stress is determined from object mass, size, deceleration tolerance and initial impact velocity.

The ratio of dynamic to static crushforce levels is determined in impact and quasi-static investigations indicating dynamic effects in the crush behaviour of materials and structures.

4. Selection of Materials and Structural Elements

The materials and structural elements selected for our experimental parametric investigations on the energy absorbing capability and the main aspects which were examined are listed in Table 1 and 2.

MAIN ASPECTS OF INVESTIGATION

- AXIAL COMPRESSION
  - Quasi-static loading
  - Impact loading
- COMPARISON OF KEY PARAMETERS
  - Specific energy
  - Energy dissipation density
  - Load uniformity
  - Stroke efficiency
  - Operating stress
- COMPARISON OF QUASI-STATIC TO IMPACT LOAD - DEFLECTION CHARACTERISTICS AND FAILURE MODES
- EXAMINATION OF ABSORBER CONCEPTS IN A CRASH - TESTSTRUCTURE
  - Correlation of the drop test results with a computer calculation (PRGM 'KRASH')

DFVLR	MATERIALS AND STRUCTURAL ELEMENTS	ERF66-4 /0981 WB-BK

Table 1

MATERIALS AND STRUCTURAL ELEMENTS

SPECIAL ASPECTS OF INVESTIGATION

- ALUMINUM HONEYCOMB
  - Various honeycomb densities, cellsizes, foil thicknesses
  - Reduction of initial peaks
  - Influence of the impact velocity
- THINWALLED ALUMINUM - STEELCYLINDERS
  - Variation of the T/D - ratio
  - Influence foam filling
  - Influence of air compression
  - Influence of impact velocity (foam filled conf.)
- PUR - FOAM - CYLINDERS
  - Variation of foam densities (only Q. S. - loading)
- FIBER REINFORCED PLASTIC TUBES
  - Filament wound GFRP-, CFRP-, Kev/Ep - tubes
  - Variation of fiber orientation (+/-15°, +/-45°, 90°)
  - Examination of various failure trigger mechanisms

DFVLR	SELECTION OF MATERIALS AND STRUCTURAL ELEMENTS SPECIAL ASPECTS OF INVESTIGATION	ERF66-5/0981 WB-BK

Table 2

The selection of the materials was not done under the sole aspect of a direct use in an energy absorbing substructure. All investigations are of fundamental nature and should be treated as a further contribution to existing experience in this field. Specimen sizes where chosen in accordance with our testing equipment. On the other hand all investigated materials and structural elements offer the possibility of being used in a larger structural assembly or as absorber units themselves.

Aluminum honeycomb was chosen because it is one of the most useful materials avialable for mechanical energy absorption. Honeycomb core is available in several metals, plastics and papers in a wide range of densities offering various operating stresses. By varying the cell sizes, foil thicknesses and geometrical shapes the honeycomb core can be tailored to a required performance.

Much information on the performance of aluminium honeycomb is available relating to compression -, shear- and crush-strength usually gained in quasi-static tests. Our intention was to get some more data in the fields where not much information is available, i.e. the static versus dynamic impact behaviour, the influence of the impact velocity and the possibilities of the reduction of the peak occuring often at the beginning of force-deflection curves.

Other elements tested were thinwalled aluminum- and steel cylinders offering a high energy absorbing capability caused by a surprisingly regular failure mode both under quasi-static and impact loads. Of special interest was the influence of foam filling with variation of the foam densities, the influence of air compression in closed cylinders, the treatment of two wall thickness to outer diameter ratios and the examination of the impact velocity in one foam-filled configuration.

Separately tested under quasi-static loading were some PUR-foam cylinders with different densities. These tests were to give some information on the energy absorbing capability of the foam itself and in combination with thinwalled metal cylinders.

Some energy absorbing qualities of fiber reinforced tubes were also tested influenced by the increasing use of composite materials in helicopter primary and secondary structure due to their superior specific strength and stiffness.

Information on the crash impact behaviour of composite materials is rather limited but first studies in this field show that with innovative design composite materials could function efficiently as energy absorbers.

To gain some information about the energy absorbing capability of composite structures a very simple geometrical shape - the tube - was chosen for some parametric studies. Filament winding was used as fabrication process. Table 3 gives an overview on the fibers and the resin system used.

TUBE	GFRP	CFRP	Kevlar/Ep
FIBER (ROVING)	GEVETEX EC-10-80K43	TORAYCA T300 B300x40B	DU PONT 494560 TYPE-969
RESIN	CIBA LY556/HY917/DY062		
CURING PROCESS	4 h at 80 °C		
TEMP. TREATMENT	4 h at 120 °C		

Table 3 Fiber/Resin Systems

Tested were GFRP-, CFRP- and Kev/ep-tubes of nearly the same geometrical shape, 28 mm outer diameter, 1,5 mm wall thickness and 100 mm length. For simplicity an equivalent strength or mass criterion was not realized.

The variation of the fiber orientation $+/-15^{o}$, $+/-45^{o}$ and 90^{o} was to give first information on the energy absorbing process and the involved failure mechanisms due to fiber orientation. First tests showed that most of the tubes failed in a progressive manner only when the right trigger mechanism for failure initiation was used.

All materials and structures were investigated in axial compression under quasi-static as well as impact loads. Key parameters such as specific energy, energy dissipation density, load uniformity, stroke efficiency and operating stress were compared. Of special interest was the examination of the differences in static and dynamic load-deflection characteristics and failure modes.

Absorber concepts were treated as part of a crash test structure and the dynamic response of the structure was examined in a drop test. The crash test structure behaviour was simulated with the computer program 'KRASH'. The simulation was done first with the statically gained load-deflection characteristic of the absorber, in a second run the dynamic load-deflection curve was used. Both results were compared to the experimental results of the drop test.

5. Test Methods

All quasi-static tests were done in a standard tension/compression testing machine. The crosshead speed of the testing machine up to the first failure was 2 mm/min and was increased for further distortion up to 10 mm/min.

The impact tests were made in a drop test facility in the institute as shown in Fig. 3.

The specimens were mounted on a clamping plate at the bottom of the facility. The specimen itself is impacted by a drop weight released at a specific height to reach the necessary kinetic energy. Impact velocities up to 17 m/s can be realized and drop weights up to 60 kg can be used. The actual impact velocity is measured via a signal flag at the drop weight with light barriers.

The data recording and evaluation of a drop test is presented in Fig. 4.

On top of the drop weight a piezoelectric accelerometer is mounted which transmits the deceleration-time history of the drop weight during impact to a transient-recorder.

Here the signal is stored for further treatment in digital as well as analog form. The generation of the force-deflection curve and the absorbed energy-deflection curve is done by a computer as shown in Fig. 4.

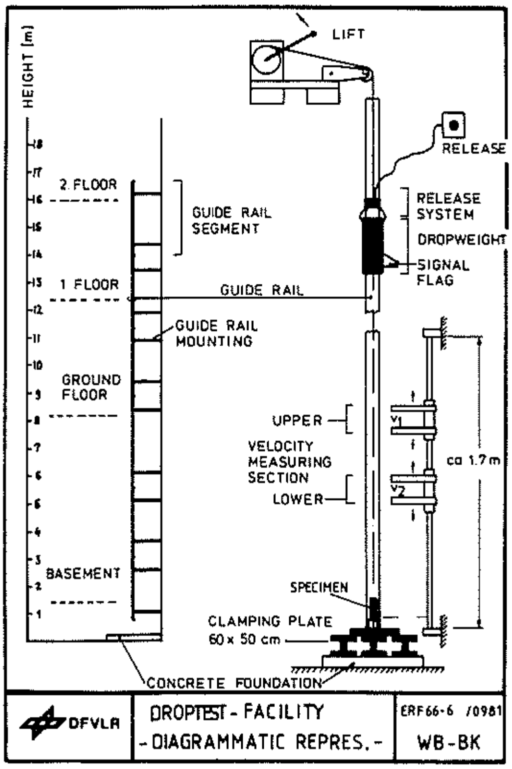


Fig. 3

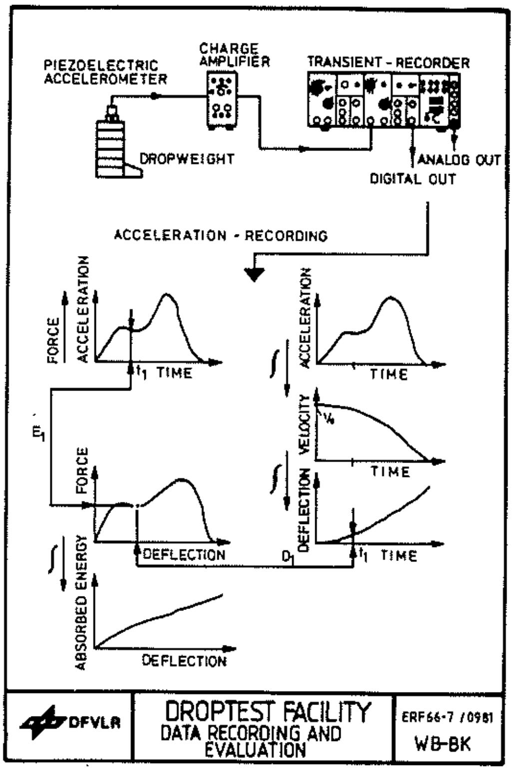


Fig. 4

6. Results

Aluminum Honeycomb

The excellent energy absorbing capability of aluminum honeycomb is caused by the regular folding of the cell walls as shown in Fig. 5.

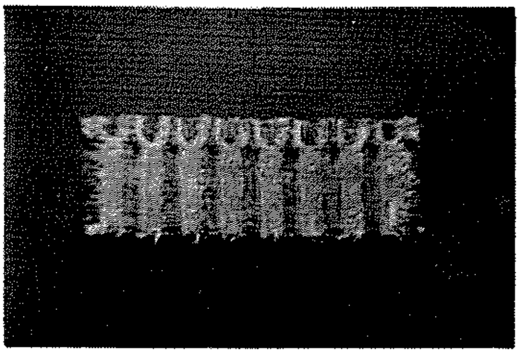


Fig. 5 Failure mode of aluminum honeycomb

The regular failure mode is obtained in quasi-static as well as in impact loading.
The energy absorbing performance of three tested honeycomb cores is summarized in Fig. 6.

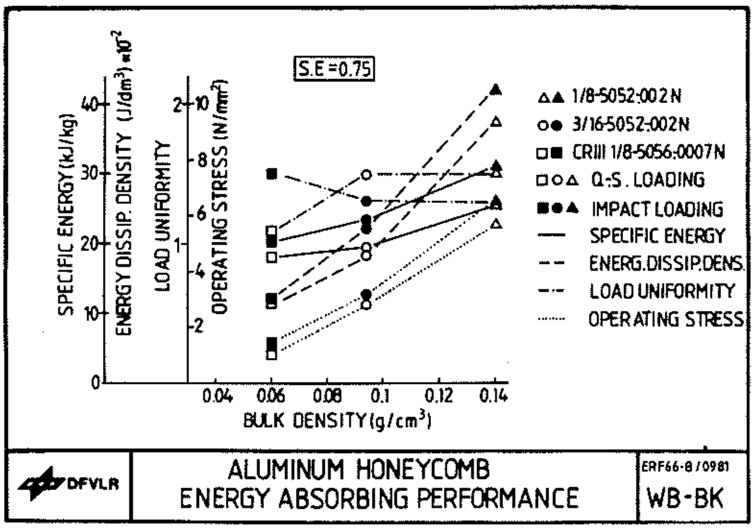


Fig. 6

By reason of comparison results are based on a stroke efficiency of 0.75. The actual stroke efficiency of all tested honeycombs is about 0.8.

Regarding specific energy, energy dissipation density, and operating stress, all impact values are above the static values. The dynamic specific energy for CR III 1/8-5056-0007 N-honeycomb is about 10 % higher than the static one. With increasing density the difference between the static and dynamic values reaches 23 %. Regarding the dynamic values a lightweight solution for energy absorption is CR III 1/8-5056-0007 reaching 64 % of the specific energy of the 1/8-5056-002 N-honeycomb with 42 % of bulk density.
When little volume of the absorber is a criterion the 1/8-5056-002-material is superior, offering an energy dissipation density of about 4000 (J/dm^3).

As for load uniformity no such trend can be recognized. Relatively high is the dynamic load uniformity of the 0.06 g/cm^3-density material compared to the static values. With increasing bulk density the dynamic values fall below the static values.

As for the influence of the impact velocity one honeycomb material (1/8-5052-002 N) was tested with three different impact speeds with constant initial kinetic energy. This was achieved by varying the drop weight mass.
Within the investigated velocity range no distinct trends of the performance parameters can be observed, see Fig. 7. All values are within

a scatter of 12 % of the max. value. Further tests should be done at higher impact speeds to examine strain rate effects and aircompression in the cells.

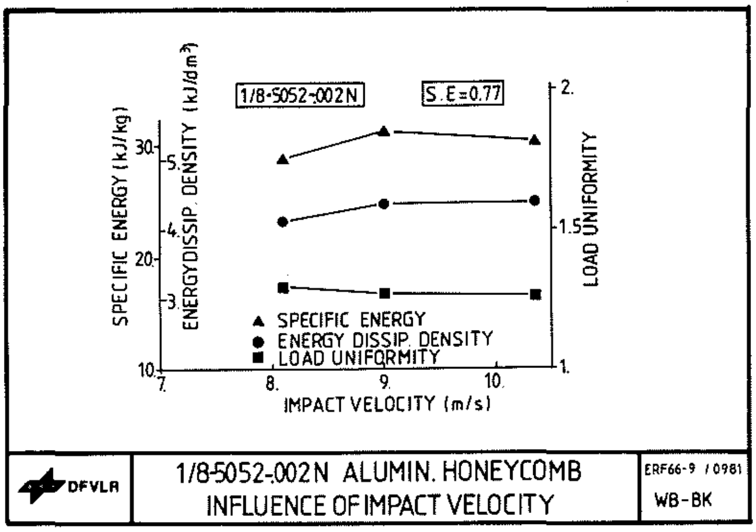


Fig. 7

At the initiation of the buckling process of honeycomb often a peak load occurs. Fig. 8 summarizes the possibilities tested to reduce peak loads under quasi-static as well as impact loading.

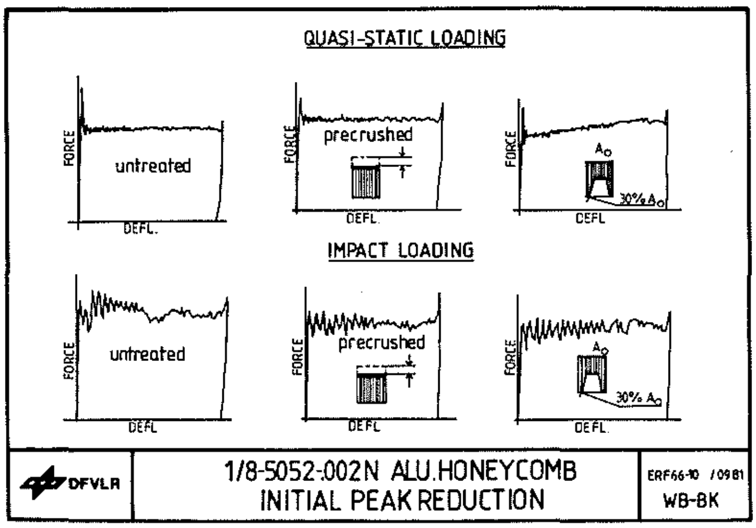


Fig. 8

The untreated specimen shows a peak load above 50 % of the average crush force level. The same dynamically tested specimen shows no initial peak. The average crush force level is about 20 % higher than the static level.

Precrushing the material by about 10 % of the initial length before further testing reduces the initial peak to 20 % above the average force level. No initial peak can be observed in dynamic testing of precrushed specimens.

Another possibility of peak reduction are slightly increasing cross sectional areas as shwon in Fig. 9.

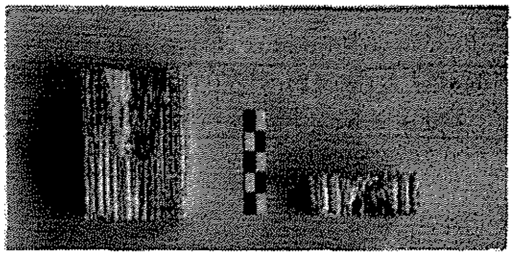


Fig. 9 Aluminum honeycomb test specimen with increasing cross sectional area

The static loading curve has a peak, too, initiating the buckling failure and folding of the cell walls. After the peak the crushforce is slightly increasing until acting on the full cross sectional area. The reduced cross sectional area at one end was about 30 % of the full cross section. The dynamic tests of these specimens show no initial peak and gradually increasing of the force level is not obvious as in the static behaviour.

Thinwalled Aluminum- and Steel-Cylinders, PUR-Foam-Cylinders

The results of the energy performance of thinwalled aluminum- and steel cylinders and polyurethane foam cylinders are presented in Fig. 10 and 11.

Looking at specific energy, energy dissipation density and load uniformity the effect of foam filling thinwalled metal cylinders is obvious. Comparing the unfilled steel cylinder with a t/D-ratio of .0015 to the foam filled cylinder (foam density = .08 g/cm^3) the specific energy is more than three times higher in the filled configuration with about twice the bulk density. The reason for this are the good specific energies of the foams themselves reaching values up to 1000 J/kg in a density range of .06 to .09 g/cm^3. Pure foam cylinders were only statically tested because catastrophic failure occured in some impact tests presumably caused by the lack of an outer casing. In all configurations the impact values are higher than the static ones. The maximum value in specific energy is reached by a foam filled aluminum cylinder.

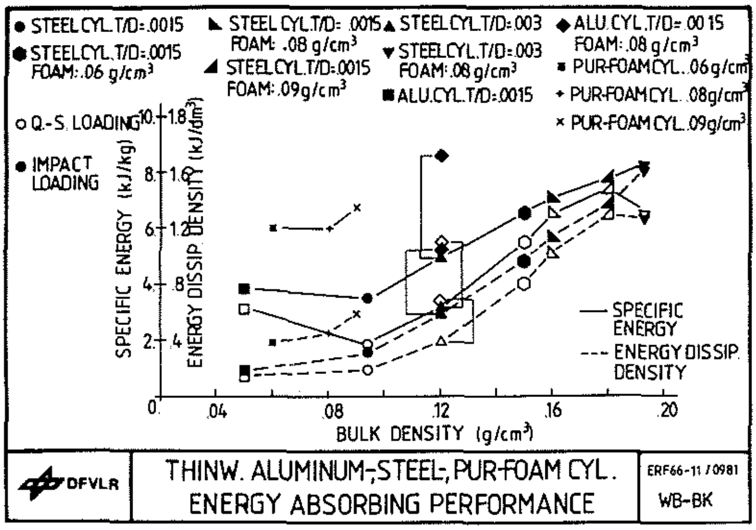


Fig. 10

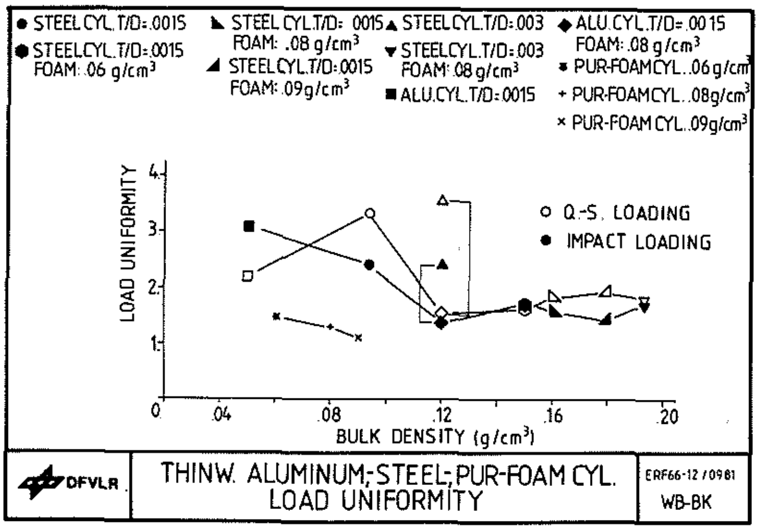


Fig. 11

The influence of increasing the t/D-ratio or supporting the cylinders with a foam to improve energy absorption can be studied in Fig. 10, too. Foam fillings are of advantage here but we must consider that an optimized t/D-ratio may result in the same improvements.

One reason for the good energy absorbing capability of thinwalled metal cylinders is the 'accordion-like' buckling failure.

The picture series in Fig. 12 shows the progressive buckling behaviour observed in a static test, which is the same under impact loading.

The buckling starts at both ends, but then continues only at one side up to a stroke of 70 mm.

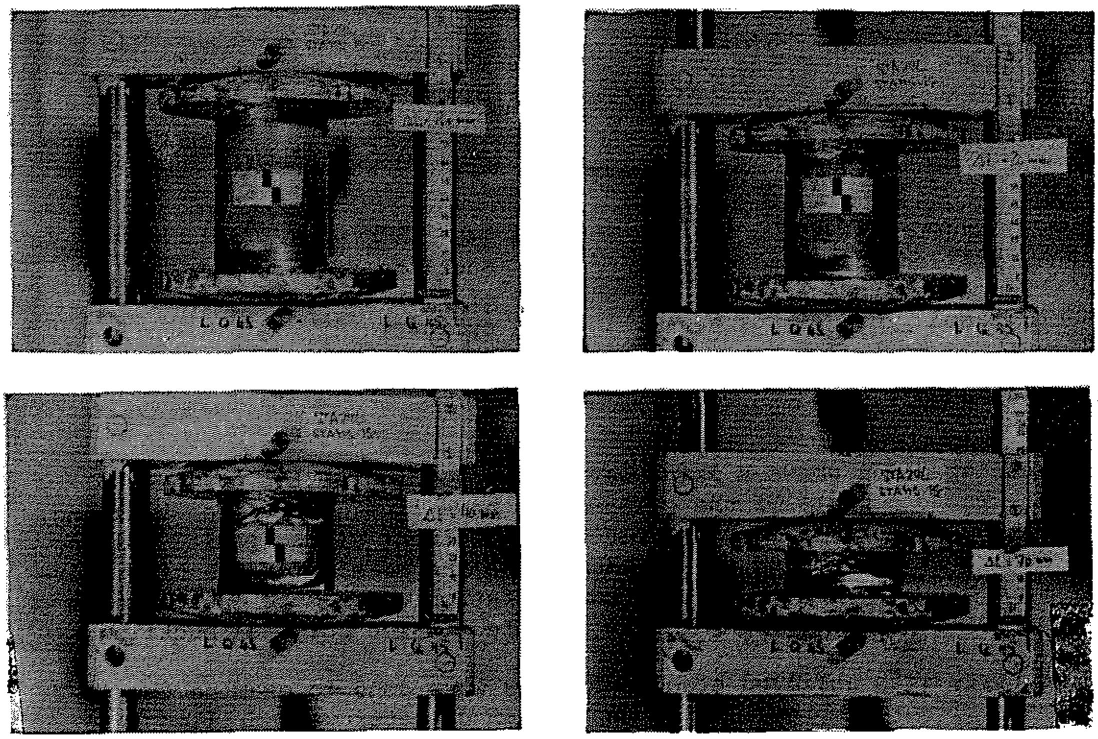


Fig. 12 Typical buckling failure of a thinwalled steel cylinder (foam filled)

Typical for metal cylinders is the 'inside-outside' folding. The effect of foam fillings on the buckling mode of steel cylinders is demonstrated in Fig. 13.

The left cylinder (Fig. 13) shows a very regular 'inside-outside' buckling forming a diamond pattern of deformation around the tube. The foam filling of the tube influences the folding process in so far that no dominant 'inside-outside' buckling is observed. The cylinder wall tends to buckle in regular circumferential folds. This effect of a foam filling is more obvious when we look at the impact loaded foam supported aluminum cylinder in Fig. 14.

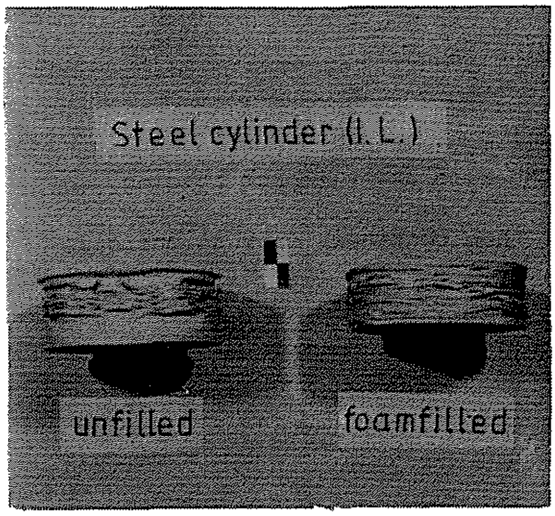


Fig. 13
Unfilled and foam filled steel cylinder-impact loaded

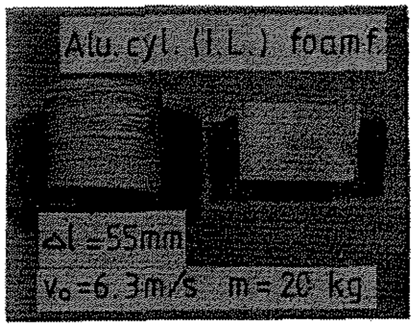


Fig. 14
Buckling failure mode of foam filled aluminum cylinder

The cut specimen shows a 'sine-wave'-like folding of the cylinder walls. In some parts of the cylinder we have 'inside-outside' buckling, too. This mixture of buckling mode with dominant circumfential folding of foam filled aluminum cylinders must be the reason for the high energy absorbing capability of this configuration where more energy seems to be absorbed in plasticity than in pure 'inside-outside' buckling.

Some tests with unfilled steel cylinders were done to examine the influence of air compression. Holes of 4 mm diameter were drilled into the cylinder walls close to top and bottom for better air escape.

The typical double peak at the beginning of crushing due to buckling initiation at both ends of the cylinder vanished. When ventilation is improved, only one peak with reduced force level occurs. In the unventilated version after the initial peaks the force level increased slightly caused by air compression in the cylinder. After ventilation the crush force level remained nearly constant till 'bottoming out'.

One foam filled steel cylinder was tested at several impact speeds. Fig. 15 shows the key parameters depending on impact velocity. The specific energy increases rapidly at 8 m/s, nearly so does the energy dissipation density curve. Further testing should be done to give more information at higher impact speeds.

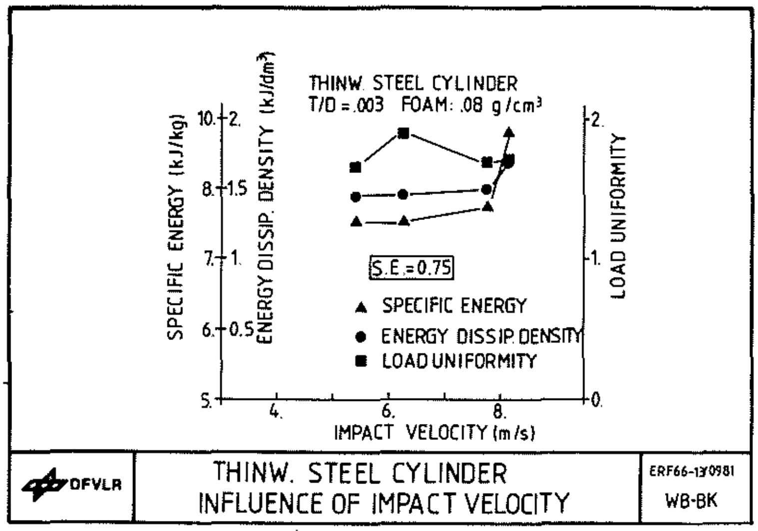


Fig. 15

Fiber Reinforced Tubes

Static compression tests with fiber reinforced tubes indicated that most of the tubes failed catastrophically when compressed between flat surfaces. For this reason cones (Fig. 16) with 15^{o}, 30^{o} and 45^{o} cone angle were introduced as trigger mechanisms for collapse initiation. The sideward fixing of the specimens was done by a bolt as shown in Fig. 17.

Fig. 16 Metal cones with various cone angles

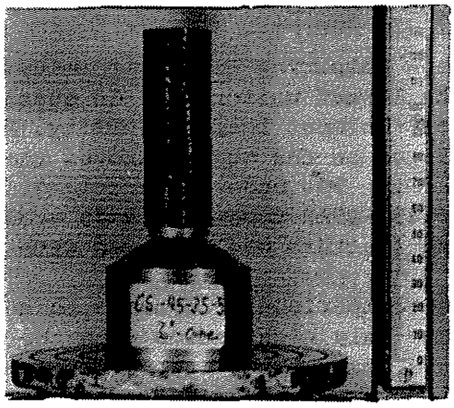


Fig. 17 Sideward specimen fixing

The results in energy absorbing performance of the filament wound reinforced plastic tubes are presented in Fig. 18-21. By reason of giving a better overview of the results no absolute values are presented except the maximum value which is set to 100 %.

All other values are related to the maximum value. The results were based on a stroke efficiency of 0.75. The possible stroke efficiencies of fiber reinforced plastic tubes can be about 90 % depending on the clamping of the tubes and the fact they cannot be compressed to nothingness.

During the impact tests the drop weight was held constant at 19 kg and the drop height was chosen to reach a minimum stroke of 75 %. The impact velocities were within the range of 2.5 - 9 m/s, depending on the necessary initial kinetic energy.

Looking at the relative specific energies and operating stresses in quasi-static and impact loading, Fig. 18 and 21, the CFRP-tube with $0/-45^{\circ}$ fiber orientation loaded between flat supports, further called 0°-cone, shows an optimum. Many of the tubes, especially those with $+/-15^{\circ}$ orientation in combination with the 0°-cone, failed in global buckling or fracture (GBF) but nevertheless retained some absorbing capability. Except for the optimal combination most of the 90°-tubes show good energy absorbing capability nearly independent of the trigger mechanism. The specific energies of the 90°-tubes are decreasing under impact loads in comparison to the other tubes.

Regarding the relative energy dissipation densities, Fig. 19, the $+/-45^{\circ}/0^{\circ}$-cone combination is only superior in quasi-static loading. The most compact absorber under impact loading is a 90°-GFRP-tube impacted over a 30-cone.

When comparing load uniformity, Fig. 20, the maximum value indicates the lowest uniformity. In quasi-static compression a +/-15 Kev/ep-tube has the best load uniformity. Additional beveling of the end which is placed on the cone improves the load uniformity of GFRP-tubes as shown in Fig. 20. Under impact loading the best load uniformity occurs in $+/-45^{\circ}$-GFRP-tubes and a 45°-cone. A high peak caused by global buckling and fracture was observed with $+/-15^{\circ}$GFRP-tubes and a 0°-cone.

The comparison of dynamic to static average crushforce levels (Fig. 22) show only high ratios when the tubes failed in global buckling or fracture. Many tubes have a ratio below unity i.e. the static crushforce is higher than the dynamic force level.

The failure modes of the tubes under static compression and impact loading resembled each other very much. In Fig. 23 two GFRP-tubes are compared. Especially the $\pm$ 45° orientation/15°-cone combination shows a remarkable 'inside-out' crushing, a highly efficient energy absorbing failure well known as an absorber principle with metal tubes. The similarity in static to dynamic failure behaviour of FRP-tubes is further evident when we compare the load-deflection curves of GFRP-tubes in Fig. 24.

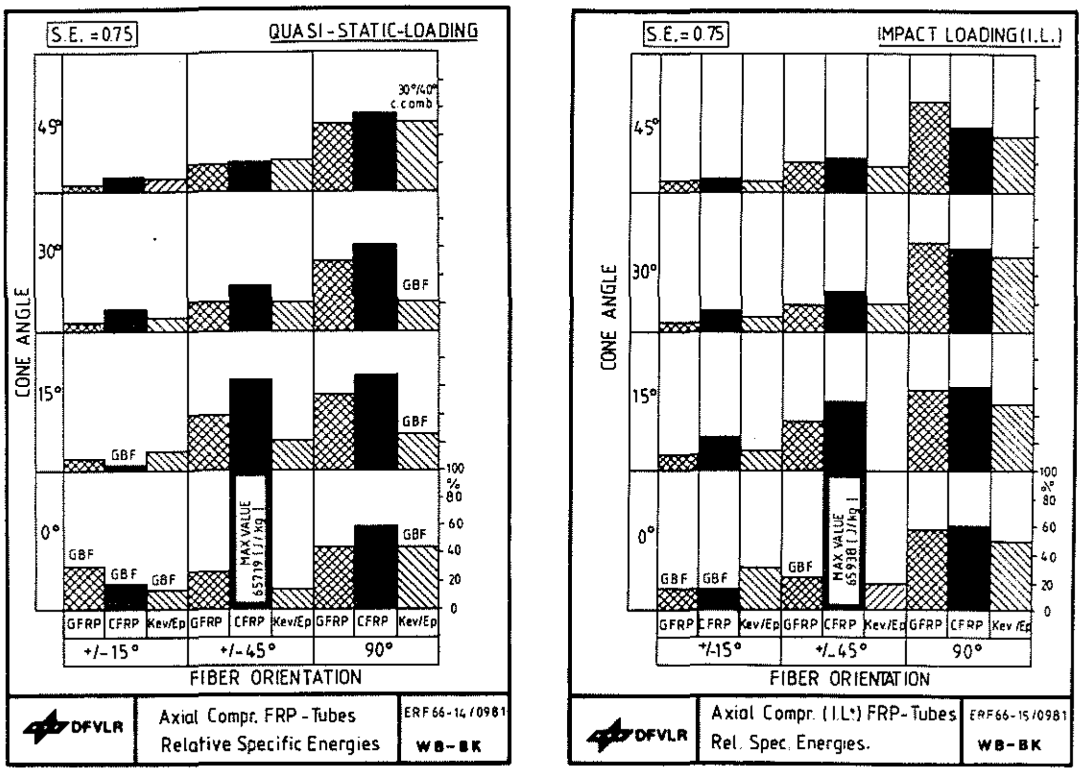


Fig. 18 Comparison of the specific energies of fiber reinforced plastic tubes

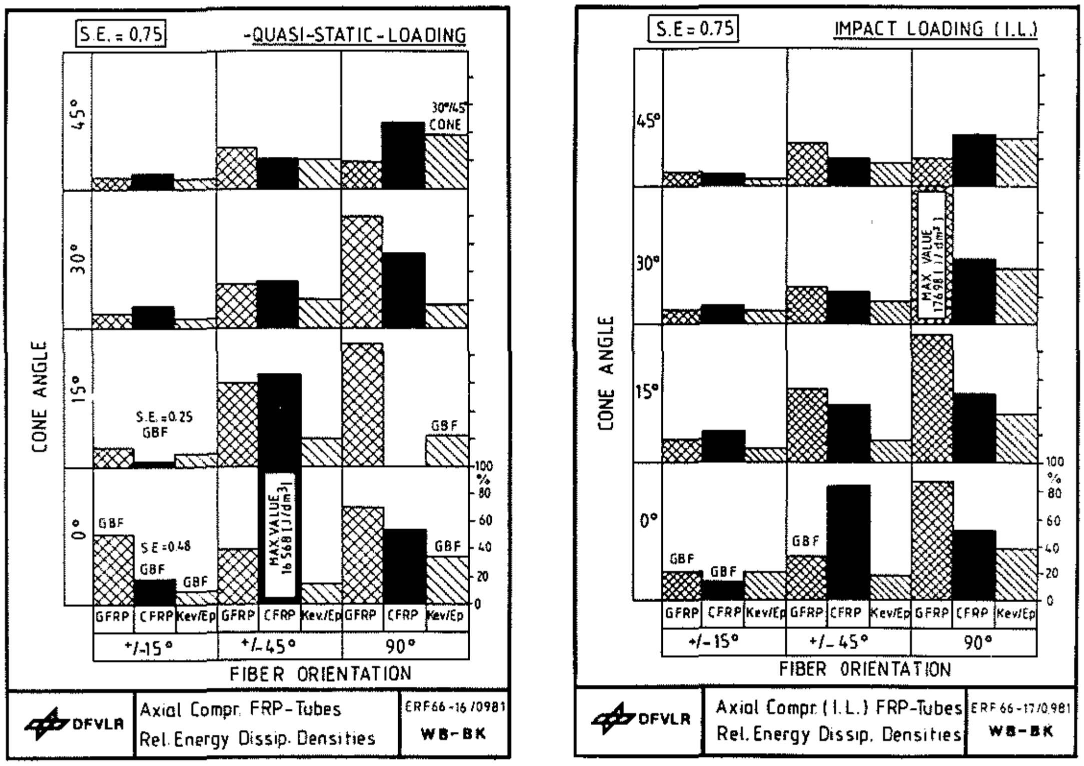


Fig. 19 Comparison of the energy dissipation densities of fiber reinforced plastic tubes

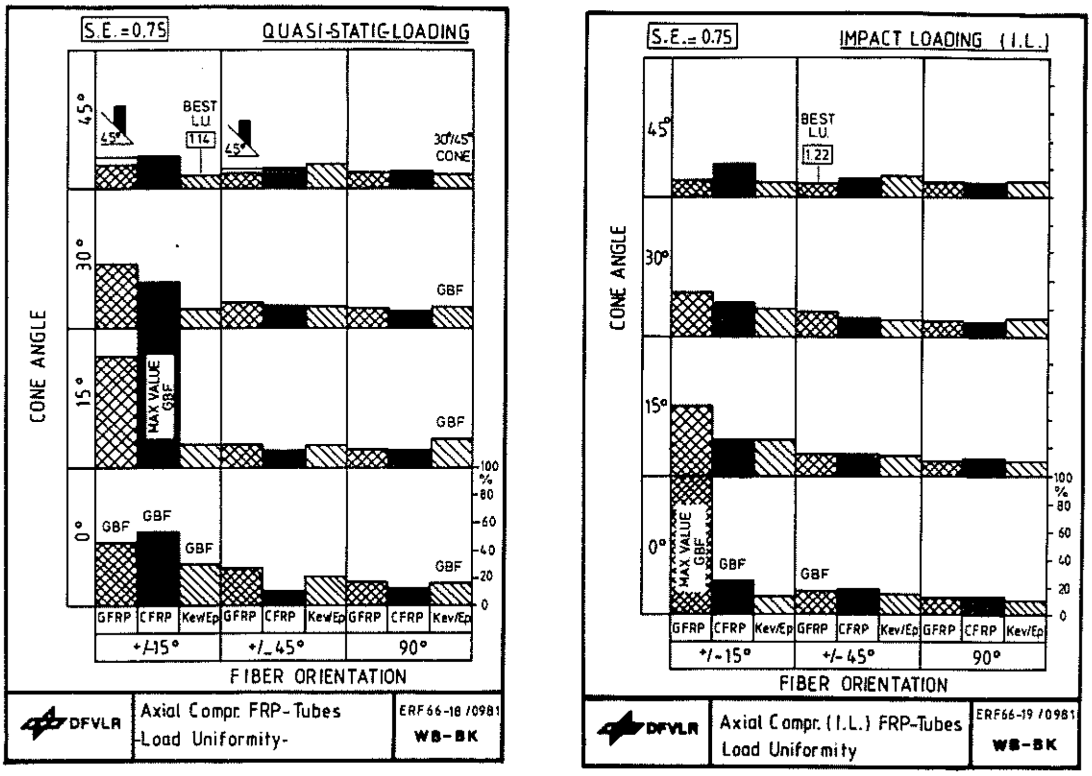


Fig. 20 Comparison of the load uniformities of fiber reinforced plastic tubes

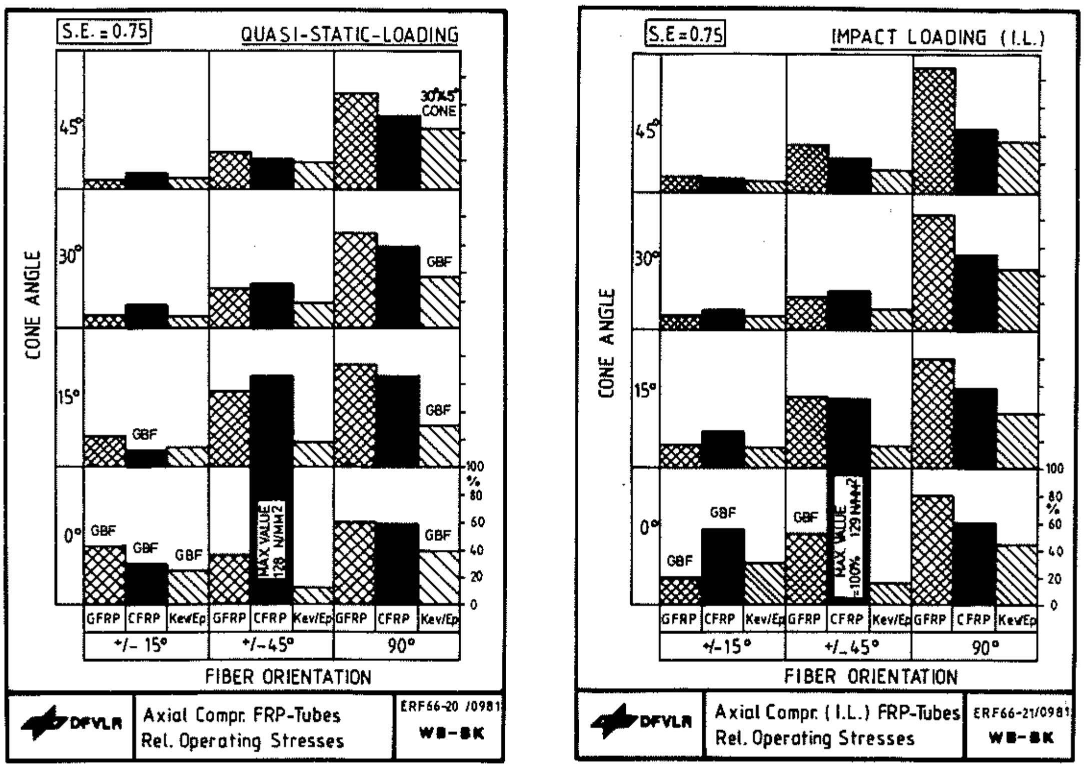


Fig. 21 Comparison of the operating stresses of fiber reinforced plastic tubes

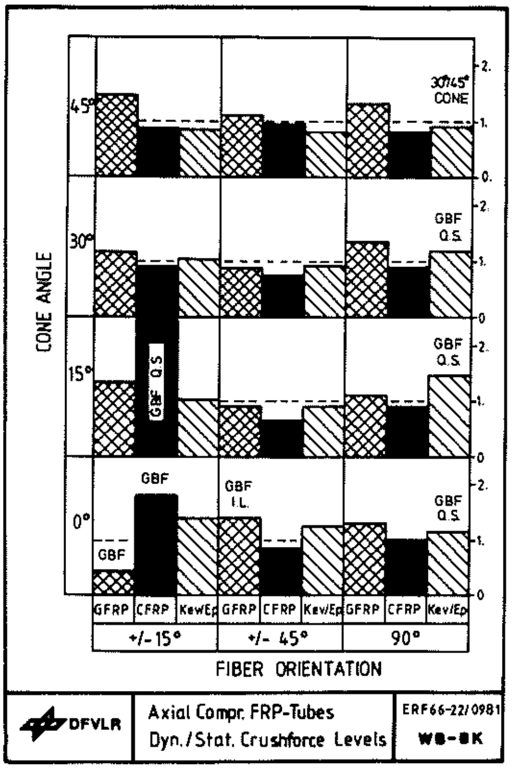


Fig. 22

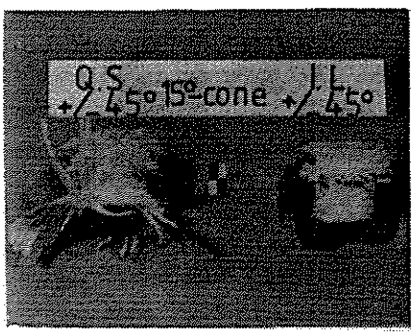


Fig. 23 Static to dyn. failure of +/-45°-GFRP-tubes

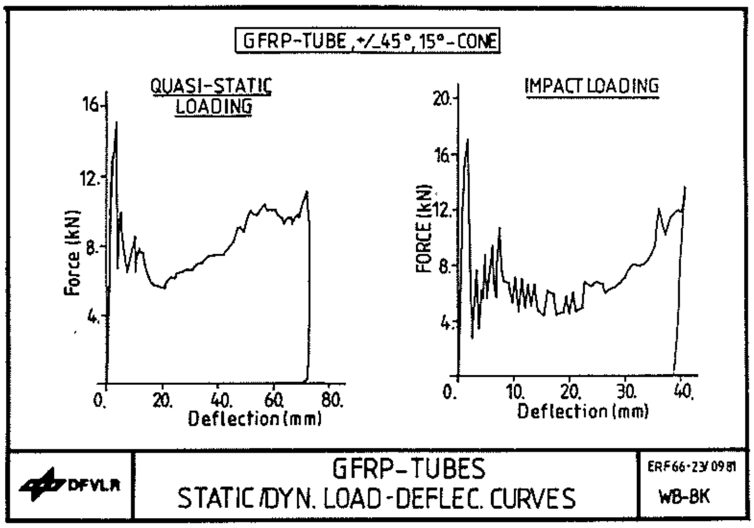


Fig. 24

A significant difference in static to dynamic failure behaviour resulted from $90^{\circ}/30^{\circ}$-cone Kev/ep.-tubes. In static loading no regular failure mechanism becomes apparent. At impact loading, however, a very regular failure was observed with a nearly constant crushforce level.

Representative for GFRP- and CFRP-tube failure modes depending on the fiber orientation is Fig. 26, showing statically compressed CFRP-tubes over a 30°-cone.

The $+/-15^{\circ}$-tubes failed by disintegration without remarkable fiber cracking.

The $+/-45^{\circ}$ oriented GFRP-tubes failed in an 'inside-out' behaviour whereas more fiber separation was observed in static loading. The $+/-45^{\circ}$-CFRP-tubes burst into small fragments or larger pieces depending on the cone angle used.

All 90°-GFRP- and CFRP-tubes, Fig. 26, fragmented into rings of 0.5 to 3 mm in height with additional circumferential fiber fracture. This failure mode occurs with all cone angles including the 0°-cone in static as well as under impact loading. The load-deflection curves show serrations very similar to the aluminum honeycomb curves. Serrations are more significant in CFRP-tubes.

Most of the Kevlar tubes failed in a predominantly buckling process without fiber cracking or separation into pieces. 90°-Kev/ep.-tubes showed a failure similar to the other 90°-tubes only when tested with a combination of 2 cones, viz. a 30°-cone at the top and a 45°-cone at the bottom. The $+/-15^{\circ}$-Kev/ep-tubes compressed on a 15°-cone showed another remarkable failure behaviour, Fig. 25. The tube failed in a 'rolling up' manner like a metal tube compressed over a die.

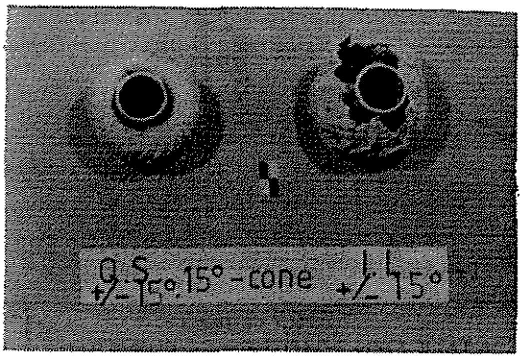


Fig. 25 Static and dynamic failure mode of a $+/-15^{\circ}/15^{\circ}$-cone Kev/ep-tube

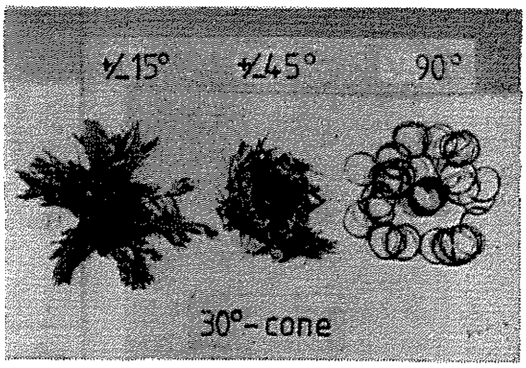
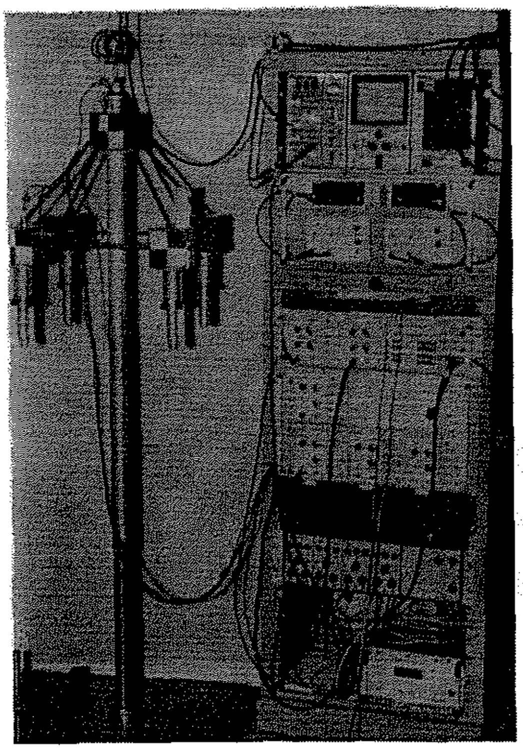
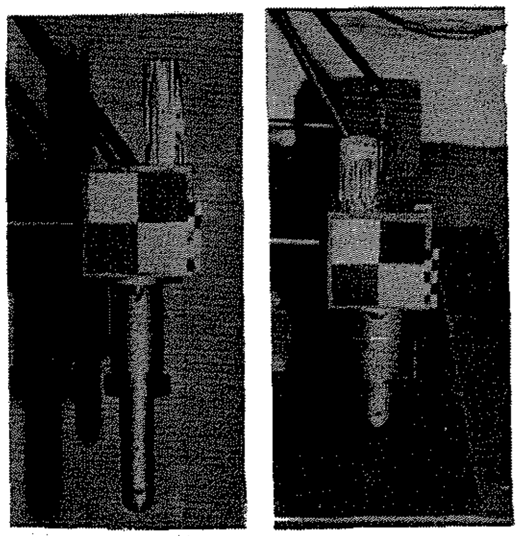


Fig. 26 Quasi-static failure modes of $+/-15^{\circ}$-$+/-45^{\circ}$-, 90°-CFRP-tubes compressed over a 30°-cone

Absorber Elements in a Crash-Teststructure

Two absorber concepts, one being a cylinder/piston type absorber with aluminum honeycomb as absorbing material the other a thinwalled unfilled steel cylinder, were used as absorbing elements in a crash test structure as shown in Fig. 27.





Precrash Postcrash

Fig. 27 Crash test structure

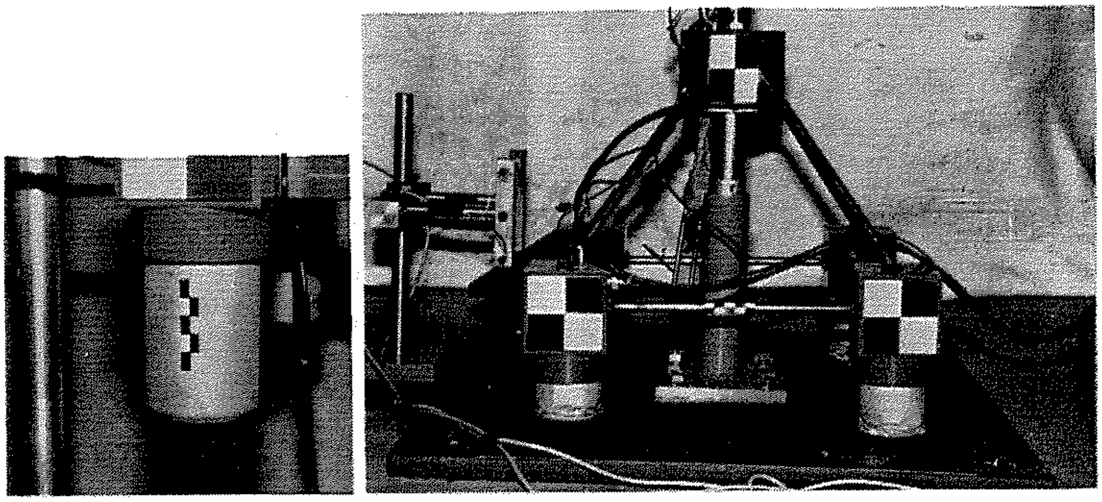
Fig. 28 Cylinder/piston type shock absorber

The test-structure was droptested with both absorber types, the pre- and post crash behaviours shown in Fig. 28 and Fig. 29.

The crash chases were simulated with the computer program 'KRASH', reference 3, developed by Loockheed Company, California, and the results were correlated to the drop test. The crashes were simulated on one hand with the statically determined load-deflection characteristics of the absorber units and on the other hand a calculation run with the dynamically gained curve was done.

Drop tests and calculation were compared regarding the deceleration-time histories of the top mass of the test structure.

The calculated response of the structure based on both the dynamic aluminum and steel cylinder absorber characteristics was too high in deceleration levels compared to the drop test results. On the other hand the calculations which used the static load-deflection characteristics of the absorbing elements show a good correlation to the drop test. This result indicates that to get a first information on the overall crash behaviour of simple structures in a crash simulation i.e. with simulation program 'KRASH', the statically determined load-deflection characteristics are adequate to reach rather accurate results in the dynamic response.



Precrash Postcrash

Fig. 29 Thinwalled steel cylinder shock absorber

7. Concluding Remarks

The tested aluminum honeycombs show an energy absorbing performance increasing with higher bulk densities. The dynamic specific energies, energy dissipation densities and operating stresses can be 25 % higher compared to the static values. In the regarded impact velocity range no influence on the specific energy absorbing capability was observed. Precrushing the aluminum honeycomb or using a slightly increasing cross sectional area in the specimens reduces the initial peakforces in static tests at the initiation of the first cell buckling. The dynamic crushing of the selected material shows no initial peak even in the untreated specimens.

Foam supporting of thinwalled metal cylinders essentially increases the specific energy absorbing performance. The increase is not only caused by the additional energy absorbing capability of the foam. Another effect is in inducing favorable buckling of the cylinderwalls i.e. the buckling mode is changed to a more circumferential folding of the walls. Sine-wave-like folding was found in foam filled aluminum cylinders with good energy absorbing capability only, not in the unfilled versions. The impact values in specific energy and energy dissipation density were higher than the static ones. Foam fillings improve the load uniformity, too. In the impact velocity range of 5 - 8 m/s a foam supported steel cylinder type showed an increasing energy absorbing capability towards higher velocities.

With the appropriate failure trigger mechanisms the tested FRP-tubes have surprisingly high specific energies depending on the fiber orientation/cone-combination. A superior specific energy was shown by +/-45°-CFRP-tubes compressed between flat supports. The tubes fragmented into smallest pieces failure modes being interlaminar shear, fiber cracking and matrix crushing. The specific energy value was about twice the maximum observed in aluminum honeycomb and about six times the best value in foam filled metal cylinders. The load uniformity on the other hand was relatively high compared to aluminum honeycomb metal cylinders.

Looking at the failure modes the static and impact behaviour of the tubes was very similar. Differences in the failure behaviour were only observed in Kev/ep tubes where buckling without essential fiber cracking was dominant. In all 90°-materials a typical failure mode occured nearly independent of the cone-angle used. The cracking into rings of 0.5-3 mm in height and following circumferential fiber cracking was even observed in compression between flat supports.

The simulation of a simple crast test structure and the comparison with the drop test showed that to reach rather accurate results statically determined load-deflection characteristics of the absorbing elements can be used for calculating the dynamic response of the total structural assembly.

Further parametric studies of the energy absorbing processes and failure mechanisms are planned, the crucial point being fiber reinforced structural elements, to examine the influence of impact velocity and various geometrical shapes. Further investigation should be done varying fiber orientation and trigger mechanisms. The existing results and further parametric investigations should be used to design larger structural parts which exhibit high energy absorbing capability on one hand and on the other fulfill all load-bearing requirements.

8. References

MIL-STD-1290 (AV), Military Standard, Light Fixed- and Rotary-Wing Aircraft Crashworthiness, 25 Januar 1974

2. Anthony P. Coppa New Ways to Soften Shock, Machine Design, March 28, 1968

3. M.A. Gamon General Aviation Airplane Structural Crashworthiness,
   Gil Wittlin Sept. 1979 (Revision)
   W.L. La Barge FAA-RD-77-189, I - III