CONCEPTS FOR ENERGY ABSORBING SUPPORT STRUCTURES AND APPROPRIATE MATERIALS

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Abstract

The paper describes two concepts and appropriate materials for energy absorbing support structures for aircraft (A/C) cabin interior. The maximum loads applicable to the A/C structure and overhead stowage compartment (OHSC) could be reduced using the described energy absorbing force limiters.

1 Motivation for developing new support structures

In case of hard landing or turbulence Overhead Stowage Compartments (OHSC´s) may be subjected to high loads due to heavy baggage. During design these loads are represented up to now by static loads equivalent to 9g acceleration.

Because of the transient nature of hard landing or turbulence conditions an approach towards dynamic load cases, as used for certification of A/C seats was investigated during a joint research project with Airbus Germany[1].

Since the load varies with time, force-limiters can be used to lessen the maximum stress in A/C structures and OHSCs. Therefore the development was aiming towards force limiting supports which are capable of absorbing high amounts of energy but having light weight, thus leading inevitable to the design of innovative supports / attachments which comprise energy-absorbing materials.

2 New concepts for support structures

Exemplarily yaw-axis and lateral-axis supports of an OHSC are depicted in Fig. 1 (showcases), to give an impression about the geometric boundary conditions, which includes a rather confined design space. The later discussed energy absorbing support concepts can also be used for supports in longitudinal axes (not shown).

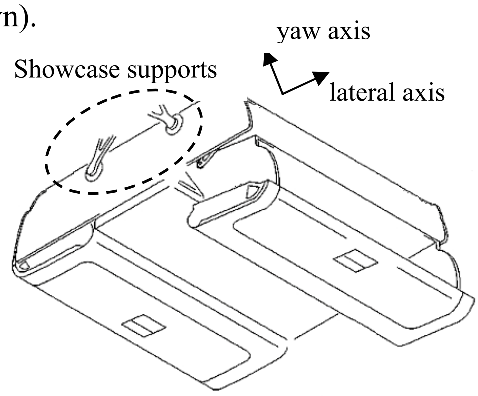

Fig. 1. Showcase overhead stowage compart ment

Using force limiters has two main advantages,

- first the supported overhead stowage compartment has to be designed only up to the triggering force of the force limiter, including a fitting factor, and
- second the primary aircraft structure does not have to be designed up to the possible forces with fixed supports, but only to the triggering force of the force limiters.

[1] The conducted research was part of a joint research project with Airbus Germany / EADS which was funded by the Ministry for Economic and Labour Affairs of Hamburg.

Both latter effects lessen the amount of additional weight caused by the energy absorbing devices.

2.1 Applicable energy absorbing materials

An analysis of the state of the art of patented energy absorbing devices with focus on aircraft application showed that more than 70 % of the patents were using plastic deformation as the principle for energy absorption. Taking physical as well as geometric and environment boundary conditions into consideration the plastic deformation of materials is the most promising method to absorb large amounts of energy, because concepts using friction are prone to fouling / corrosion which must be prevented to ensure a faultless and predictable function over several years.

Therefore lightweight energy absorbing materials (Fig. 2) were tested within the joint research project for their suitability, e.g. their specific energy absorption, which is defined as the correlation between absorbed energy to the mass of the destroyed material, or the efficiency, which is calculated by dividing the absorbed amount of energy through the maximum possible absorbed energy derived from the maximum force times maximum absorption movement.

Especially the specific energy absorption is one the most useful ratios, since it gives a rough idea how much weight has to be invested in order to absorb the calculated energy.

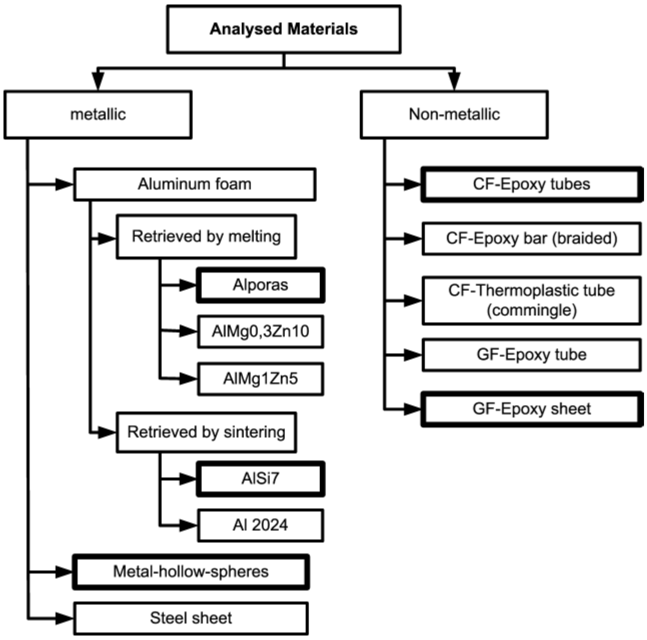

Fig. 2. Analysed materials

The broad bordered materials will be explained in detail in the following.

Aluminium foam “Alporas”

The used foam (tradename “Alporas”) is produced by gas-releasing particle decom-position in the melt [1], in conjunction with a controlled cooling of the melt. Because the mechanical property of the foam is a function of the local density, the compressive strength varies about the same amount as the density. The pore-size distribution, which is also a function of the density, further increases the variation.

Fig. 3. Alumium-Foam in different compression states

The analysed foam had an average density of 257 kg/m^3, which varied from specimen to specimen about ±30 %. Quasi-static tests with a deformation velocity of 50 mm/min as well as drop-tower tests with a maximum of 6 m/s drop weight velocity were carried out. In consistence with *Ashby* [1] no dependency of the properties from the deformation velocity inside the regarded velocity range could be observed.

Fig. 4 shows the measured compressive stress-strain curve, whereas the green lines indicate the upper and lower boundary, the red line indicates the mean value.

Further investigations concerning the influence of holes or the existence and influence of gliding planes were not conducted, since the material did not show the potential to meet the specified requirements.

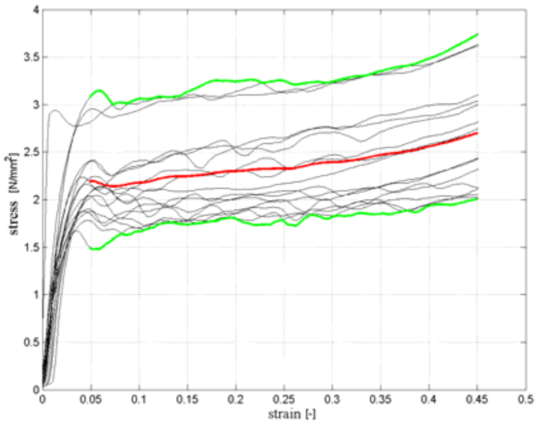

Fig. 4. Stress-Strain curve of Alporas samples

After initial triggering of the specimen, a stable deformation behavior is obtained with a low incline of the deformation stress. Usually the specimen can be deformed up to a strain of 0.6, after which the deformation stress can be approximated by an exponential function until total densification. The variation of the stress is about ± 30% of the mean value corresponding to the variation of the density.
Calculating the specific energy absorption of the foam as an assessment criterion, 5 kJ/kg can be achieved.

Since the primary objective is the development of an energy absorbing structure in order to reduce the force acting on the A/C structure resp. the OHSC, it has to be ensured that the triggering force of the force limiter adopt a low variance, because otherwise the weight reduction of the connected structures is lost due to large factors of safety. Because of the high variance of the compressive strength the use of aluminum foams is not recommended, if the trigger force shall be in a narrow scatter band. In addition the available design space between the OHSC is very narrow (in forward direction), so the influence of the pore size (which is about 3-5 mm) is increased which emphasizes the recommendation.

Aluminium foam AlSi7

To gain appliance specific information about the properties of a powder metallurgy based al-foam, test specimen made of AlSi 7 were obtained and tested. The specimens were foamed by mixing the Al-alloy powder with a hydrogen producing agent, pressing the mixture into a pellet and sintering in a mold (see [1]).

Because of the geometric boundaries the foam was produced as a cylinder with 50 mm diameter and a length of 300 mm. The cylinder was cut into three specimen of equal length.

Fig. 5 shows three test specimen cut from one cylinder, lathed to remove the boundary face skin which is a result of collapsed bubbles at the mould face.

Fig. 5. AlSi7 test specimen (same basic cylinder, from l.to.r: top, middle, bottom)

As can be seen, the pore size varies within the original cylinder, creating a density gradient from the middle of the cylinder to the end caps, resulting in a test specimen taken out of the middle (center), which was nearly twice as heavy as the test specimen cut from the end caps (average density of the depicted specimen 670 kg/m^3, middle part of the cylinder). This density deviation is clearly seen in Fig. 6 (depicted 6 specimen, cut from two cylinders), where the center specimens have virtually no plateau with constant compressive stress. No calculation concerning specific energy absorption was conducted, as the possibility for using this material in energy absorbing concepts is not reasonable as long as the manufacturing process cannot provide specimen with an equally distributed density and pore size.

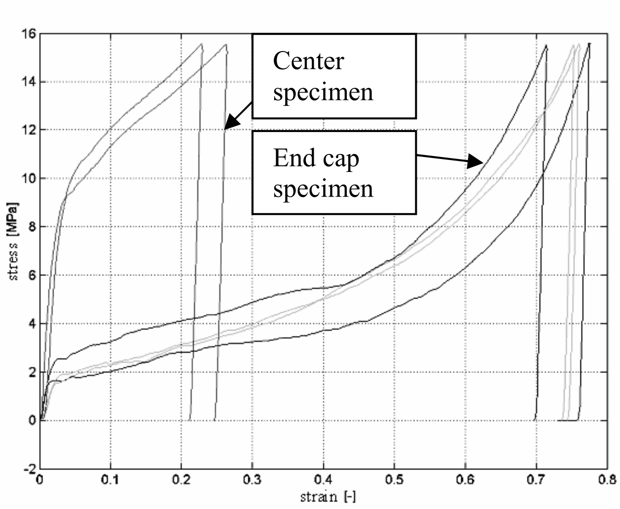

Fig. 6. Compressive stress-strain curve of AlSi7 foam specimen

2.3 Metal hollow sphere

Due to the requirement that usable porous materials must have an equally distributed density and pore size, metal hollow sphere structures were investigated concerning application specific properties.

Metal hollow spheres are produced by applying a metal slurry to polystyrene balls followed by sintering (see [2]).

Structures can be shaped by sintering the balls inside a mould or simply gluing them. Cylindrical test specimens made of mild steel with a ball diameter of 1 mm were obtained and tested. For analyzing the influence of central holes on the global deformation behavior, which are necessary for simple implementation in energy absorbing concepts for tensional loads, the specimens were drilled with different diameters.

Fig. 7. Test specimen with different bore diameters

The specimens had a density of 470 kg/m^3 with a variation less than 4 % based upon the mean value.

As can be seen in Fig. 8 the deformation stress (mean 6.7 N/mm^2) of the metal hollow sphere specimens varies with a scatter of ±10% (related to the mean value) which is less than the values of Al-foams and is not affected by the bores. The slope of the stress begins to rise from 0.4 strain, which is less in comparison to the Al-foams (0.6 strain).

The presence of preferred gliding planes could not be observed, but eularian buckling is a problem for long, slim specimen, because the drilled specimen tended to buckle and fracture (Fig. 9). Buckling and shearing along gliding planes establishes usually a contact between the energy absorbing material and the surrounding support structure producing an undesired behavior of the force limiter, so knowledge about these effects are important for designing energy absorbing concepts comprising these materials.

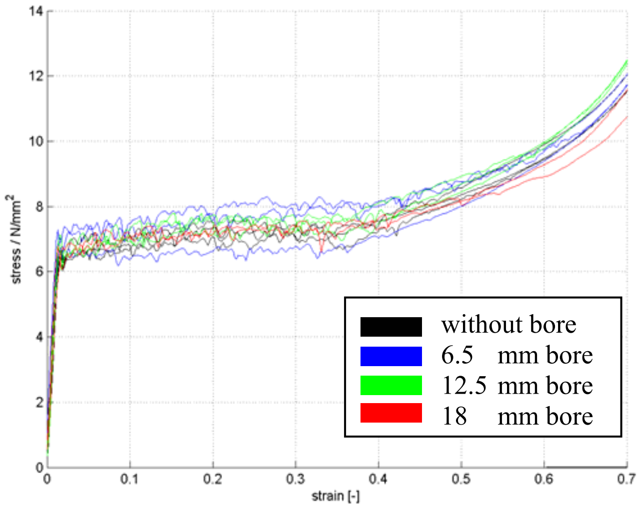

Fig. 8. Stress-Strain-curves of metal hollow spheres test specimen

The calculated specific energy absorption is for a strain up to 0.6 (equals approx. 1.5 times the trigger force) 10 kJ/kg, which is twice as high as for the Al-foams.

Fig. 9. Specimens after test (same specimen size)

Taking the test rigs accuracies into account no influence of the deformation velocity on the global deformation behavior or compressive stress could be observed.
Summarizing the information, the use of cellular materials like al-foam or metal-hollow-spheres can be recommended for applications with

- unpredictable loading directions, e.g. for instance cargo- or cabin-wall linings for improving the impact characteristic and
- large volumes where the pore-size influence can be neglected.

Furthermore the bigger the impacted area, the more the density variations will be compensated. For the use in geometrical confined support structures the following materials show better performance.

2.4 Carbon fiber epoxy tubes

Porous materials as shown do not have any preferred direction of usage, since they are nearly isotropic. Because the considered application requires no isotropic material, the focus for further investigations was put on ortho- and an-isotropic materials like fiber reinforced plastics (FRP), see [3], [4], [5], [6], [7]. Since most of the research was done for applications in automotive or helicopter crashworthiness with loads usually higher than 20 kN, a parameter analysis of carbon fiber reinforced plastic tubes (CFRP) was conducted for a load range up to 20 kN. The tubes were manufactured using uni-directional (UD) tapes (T300) at the inner diameter and CF-Prepreg fabric (HTS/HTA, 0°/90°) at the outside diameter in ratio of 1 (fabric) to 3 (UD), according to [8] with an epoxy matrix.

Diameters ranged from 12 mm to 24 mm, with a thickness variation of 0.5 mm to 2 mm, see Fig. 10.

Fig. 10. CFRP tubes with different wall thickness

The tubes were tested quasi-static with a deformation velocity of 50 mm/min and dynamic in a drop tower with up to 6.5 m/s. Fig 11 shows a specimen with a wall thickness of 0.5 mm after drop tower impact. As can be seen the fragments are small, with a powdery characteristic. Since the main energy absorbing effect is the generation of free surfaces, along with friction, the specific energy absorption of the analyzed specimen is about 115 kJ/kg with a variation from 100 kJ/kg to 130 kJ/kg depending on wall thickness to diameter ratio and deformation velocity.

During deformation the tube is filled up with fragments, thus reducing the usable length of the tube. This effect is naturally more distinct at tubes of smaller diameter with thick walls.

Fig 11: CFRP-tube after Impact

Using a 45° chamfer as a trigger, the entire specimens showed a low triggering peak. Fig. 12 depicts a typical force-deformation curve.

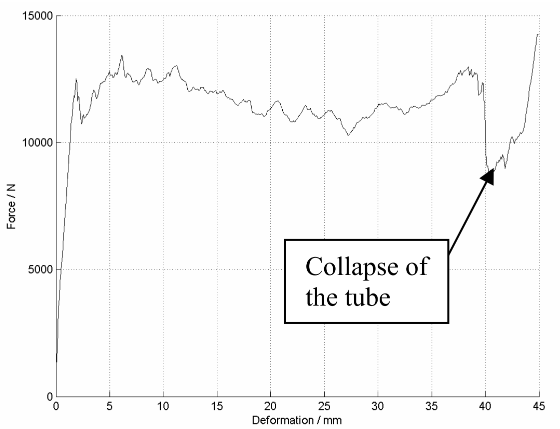

Fig. 12: Typical force-deformation curve of a CFRP-tube (14 mm outer diameter, 1.5 mm wall thickness, quasi-static)

Most of the specimens showed a acceptable deformation behavior, except the specimen with a wall thickness of 0.5 mm, which were prone to catastrophic failure due to instabilities and pre-existing damages through cutting. The radial strength of the tubes is very low, so wrong handling / manufacturing can result in damages which cannot be easily identified, but leading to catastrophic failure by ripping or buckling. Consequently the depicted triangle in Fig. 13 should not be used for designing crush tubes. In general the diameter to wall thickness ratio should be smaller than 25 for this specific fiber/matrix configuration.

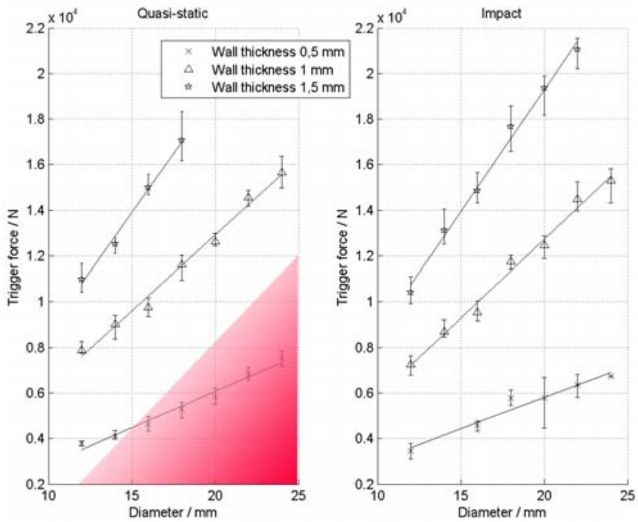

Fig. 13: Trigger forces for quasi-static / impact loads

As can be seen the trigger force for small diameters of the impact tests is slightly below the forces of the quasi-static tests, the reason is not fully understood yet, but since a brittle crushing mode with increasing part of lamina bending mode (see [10]) for thicker walled tubes was observed, most likely friction between the loading surface and the specimen influences the occurring forces.

The slight decrease of the trigger force can also be seen in Fig. 14, depicting the trigger stress. The deviation between the stresses at different deformation velocities is about 5 to 15 MPa, e.g. for 1.5 mm wall thickness. The reason for the raising trend line is unclear, but will be further subject of investigation.

Apart form the slight deviation between quasi-static and impact testing, the trigger stress seems to be no function of the geometry, thus simplifying the design of crush-tubes for implementation in energy absorbing structures.

But as Marsolek [11] pointed out, the calculability of the crash-behavior of FRPs is still restricted, so new designs inevitably require experimental verification.

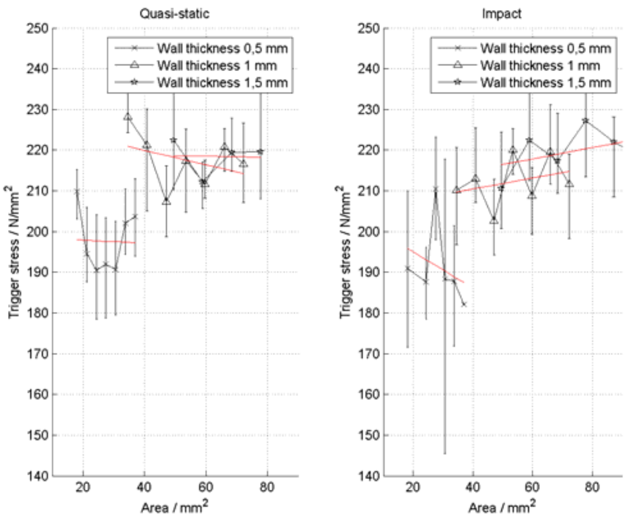

Fig. 14: Trigger stress with best fit straight line quasi-static / impact

In comparison to cellular metals the fiber reinforced plastics exhibit a specific energy absorption, which is approx. 20 times higher, allowing light weight support structures, if the external guidance, which is required due to anisotropic material behavior, is weight-optimized.

2.5 Glass fiber epoxy plates

Due to the different supports of an OHSC another possibility of energy absorption was investigated, based upon the patent application publication DE 199 26 085, implementing fiber reinforced plastic (FRP) plates.

Dubey and Vizzini analyzed in [9] the usage of tubes and plates for energy absorption, comparing both geometries regarding energy absorption and sustained crush stress. Using an external fixture the whole plate was crushed in in-plane direction. The patent proposed instead of crushing the whole plate a pin, which is torn in-plane through the plate, leaving a slot, as depicted in Fig. 15.

Different pin diameters, plate thicknesses and fiber/matrix configurations were analyzed showing promising results regarding the force/deformation curve (Fig. 16), global behavior and specific energy absorption. Further investigations will be conducted to provide a better understanding of the predominant crush modes, the influence of fiber orientation and the possibilities to reduce the trigger peak at the beginning of the deformation. Anticipating a solution for the open questions, concepts comprising the discussed energy absorbing materials were developed.

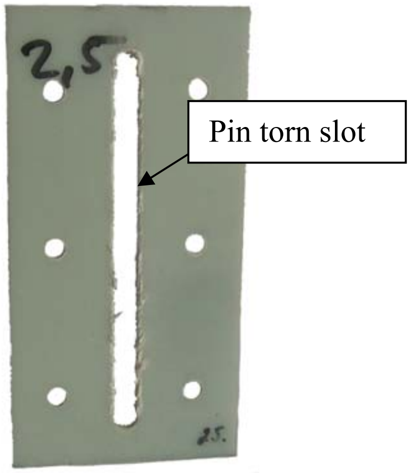

Fig. 15: FRP plate after test

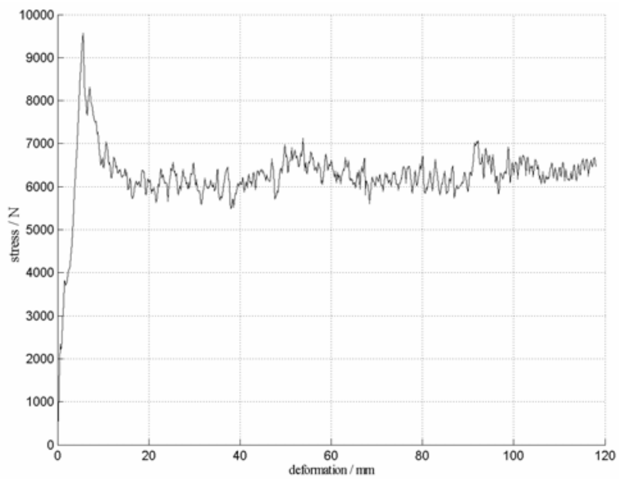

Fig. 16: Force/deformation curve of FRP plate

3 Applicable concepts for an energy absorbing support

Because all of the focused supports for OHSC are tensionally loaded, a structure has to be developed which converts the tensional forces into compressive forces in order to use porous metals or crush-tubes. A simple concept is the piston/cylinder configuration (Fig. 17), as it can be found in hydraulic actuators.

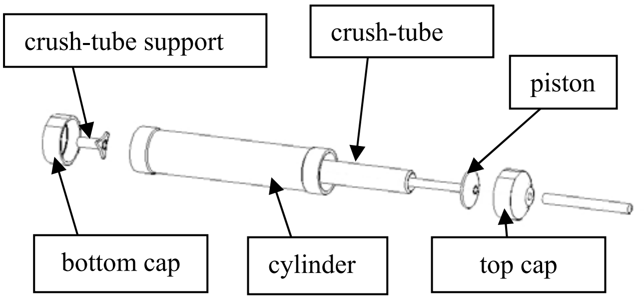

Fig. 17: piston/cylinder concept comprising FRP crush-tube

For implementation of porous metals in this concept it has to be considered, that buckling of the energy absorbing material leads to a dramatically decreased energy absorption. In case of a surrounding housing the contrary might occur: the material establishes a contact with the housing and based on the relative motion between material and housing friction absorbs a high amount of energy but with an unpredictable height.

Both effects have to be avoided, so care has to be taken to prevent buckling.

Because of the large geometrical moment of inertia of tubes, tests have shown that buckling is no problem using CFRP crush tubes. Nevertheless a crush tube support, as depicted in Fig. 17, has to be implemented to prevent a misalignment of the tube during crushing. Furthermore the support has to have large openings to provide an unobstructed way for fragments or fronds inside the tube, in order to prevent a blockage at crucial areas as the crush-front. Additionally care should be taken to prevent fragments from jamming the piston bore.

Making use of the fragmentation of a FRP plate (s. Chap. 2.5), the number of loaded parts is reduced, because no conversion from tension to compression is necessary. As shown in Fig. 18 the only loaded part is the tension rod, which connects to the tear-pin, because the linear bearing is stressed only during transversal accelerations.

Since most of the OHSC are made of FRP sandwich panels this concept leads to a low function specific added weight due to the fact that no further energy absorbing material is necessary, because the hatrack itself can be used for energy absorption. Precondition is the preparation of a monolithic pocket where the core of the sandwich panel is removed and further reinforcement patches are applied.

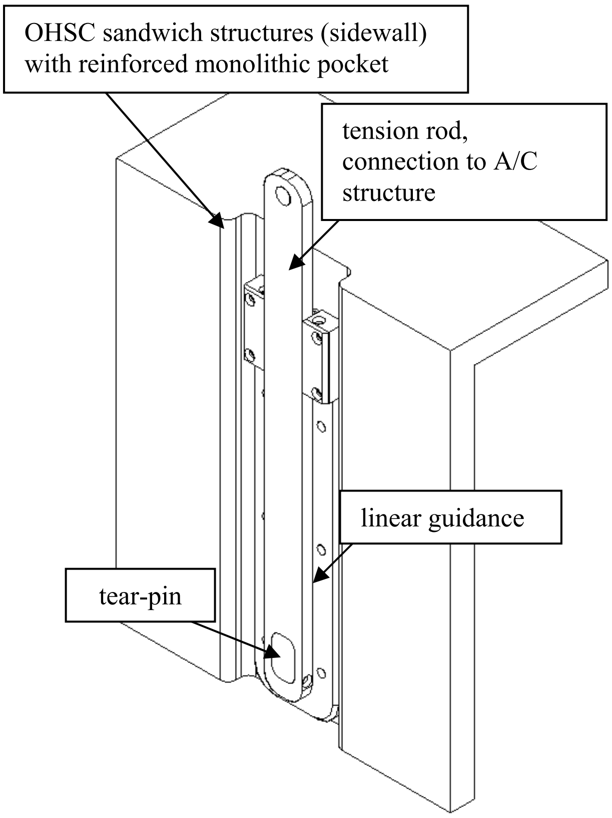

Fig. 18: Pin/plate absorbing concept with part of an OHSC sandwich structure

Fig. 19 shows a section of the pin/plate absorber. The depicted concept is subject to change, because the pin is exchangeable for quick variations of the pin diameter.

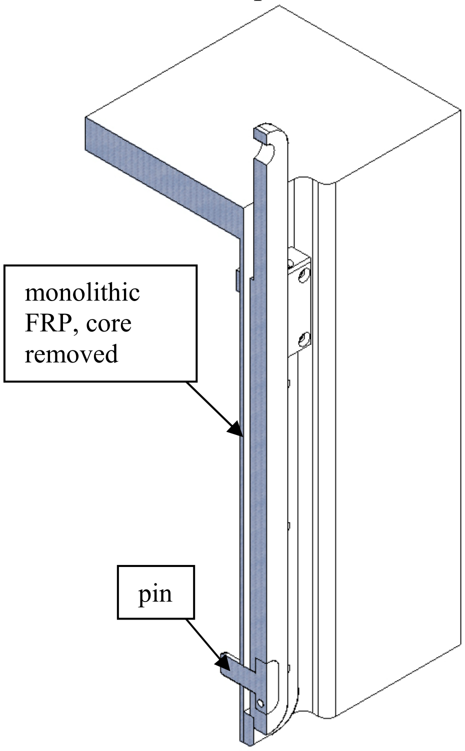

Fig. 19: Section of the pin/plate absorber

As said before a drainage must be provided for the fragments / fronds to prevent a blocking of the fragments inside of the linear bearing.
From the design point of view for implementing energy-absorbing supports in A/C cabins an unobstructed way in front respective below of the hatrack is required to provide an absorption movement for the force limiters, which leads to some restrictions for the cabin design if force limiters are implemented.

4 Conclusions

Various materials for innovative energy absorbing support structures for overhead stowage compartments have been analyzed and the most promising were shown in detail. Because the support structures allow the restriction to one primary loading direction, an-isotropic materials such as fiber reinforced plastics can be used, showing a high potential for implementation. Two energy absorbing concepts have been shown, partly making use of the OHSC itself thus reducing the additional weight. Conducted tests showed that carbon fiber reinforced tubes can be used in piston/cylinder concepts absorbing high amounts of energy. Further tests will be performed to deepen the knowledge about the presented pin/plate absorber.

References

[1] M.F.Ashby et al. : *Metal foams: a design guideline*. 1st edition, Butterworth Heinemann, Boston Oxford, 2000.

[2] U. Wagg et al.: *Metallische Hohlkugelstrukturen – Eigenschaften zur Schall- und Energieabsorption*. VDI-Berichte Band 1595, Tagung Würzburg 18. u. 19. 10.2001, VDI Verlag, 2001

[3] Gary L. Farley, Robert M. Jones: Crushing characteristics of continuous fiber-reinforced composite tubes. *Journal of composite Materials*, Vol. 26, No. 1, pp 37-50, 1992.

[4] JJ Carruthers, AP Kettle and AM Robinson: Energy absorption capability and crashworthiness of composite material structures: A review. *Journal of applied mechanics,* ASME Vol. 56, No. 10, Oct 1998

[5] Georg C. Jacob. et al.: Energy absorption in polymer composites for automotive crashworthiness. *Journal of composite Materials*, Vol. 36, No. 7, pp 813-849, 2002.

[6] A.F. Johnson, C.M. Kindervater, H. Thuis, J. Wiggenrad: Crash resistant composite subfloor structures for helicopters, papers presented at the FVP Symposium on ”Advances in rotorcraft technology”, Ottawa, Canada, 27-30 May 1996

[7] Hong-Wei-Song, Xing-Wen Du, Gui-Fan Zhao: Energy absorption behavior of double-chamfer triggered glass/epoxy circular tubes, *Journal of composite materials*, Vol. 36, No. 18/2002

[8] Manfred Flemming, Siegfried Roth, *Faserverbund-bauweisen*, Springer Verlag, 2003

[9] D.D. Dubey, A.J. Vizzini: Energy absorption of composite plates and tubes, *Journal of composite materials,* Vol. 32, No. 2/1998

[10] G.L. Farley, R.M. Jones: Analogy for the effect of material and geometrical variables on energy-absorption capability of composite tubes, *Journal of composite materials*, Vol.26 No.1/1992

[11] J.S. Marsolek: *Energieabsorptionsverhalten zylinder-schalenförmiger Strukturelemente aus Metall und Faserverbundwerkstoff,* Ph.D. Thesis, Aachen, Shaker Verlag, 2002

[12] W. Extra: *Mechanische Absorptionsvorrichtung*, Offenlegungsschrift DE 199 26 085, Deutsches Patent- und Markenamt, 2000