

# Energy Absorption in Aircraft Structures

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## **Abstract:**

Energy absorption is an important and necessary topic in aircraft engineering and relevant for several transient, dynamic load cases in terms of foreign object impact, explosive blast or crash. Since the corresponding requirements and regulations by the aviation authorities are relatively strict for safety reasons, various concepts for energy absorbers have been developed and utilised in the past decades, using high-performance materials or structures. Besides being suitable for the specific load case in terms of adequate absorption capabilities, energy absorbers in aircraft structures typically have to be extremely lightweight, cost-efficient and beneficial regarding fatigue, maintenance and repair. Current concepts are often based on fibre-reinforced composite materials and their intralaminar, interlaminar and crushing failure behaviour, cellular core structures like honeycombs, foams or foldcore, metallic absorbers with their plasticity behaviour or metallic-composite hybrid solutions. In the context of energy absorber development, numerical simulations play an increasing role to substitute more and more the time- and cost-expensive experimental testing efforts by more efficient virtual numerical testing.

An overview of specific load cases like bird strike, impact of tire rubber or runway debris, rim release, fan engine blade-off, explosive detonation, crash landing or water ditching and the respective energy absorption mechanisms is given, allowing for an insight into the problems and solutions of aircraft industry in energy absorption of the last decades.

## **1. Introduction**

Energy absorption is an important discipline in aircraft design as it is for other industries like automotive, ground transportation or mining. The load cases are often not very different with a certain amount of kinetic energy acting on a target structure (e.g. rock falls, collapse of ceilings or gas explosions in underground mining vs. foreign object impact, crash and explosive blast in aircraft engineering), but different priorities and requirements in the selection of appropriate energy absorbers may apply. The following paper gives an insight into the problems, solutions and experiences of aircraft industry in energy absorption of the last decades.

The vulnerability of aircraft structures against dynamic loadings from impact, explosive blast or crash makes the understanding of structural energy absorption and implementation of specific energy absorbers an important aspect in aircraft design. Safety of crew and passengers is of highest importance, which is reflected in strict regulations and requirements of the aviation authorities that need to be met by the aircraft manufacturer. Different lightweight energy-absorbing materials and structures are employed and under further investigation, which are suitable for the specific load case. Besides experimental testing, numerical simulations and virtual testing are becoming more and more important to increase efficiency and reduce development and experimentation costs. These topics and some specific examples of energy absorbers for different load cases in aircraft design will be presented in this paper.

## **2. Allowables and requirements for energy absorption**

Energy absorption typically is not an abstract term in aircraft design but aims at a very specific amount of (kinetic) energy that needs to be absorbed in order to meet a very specific target (e.g. a certain deceleration pulse at the passenger seat in a hard/crash landing, a certain performance of the leading edge after bird strike with protection of the wing front spar or a certain indentation depth after low velocity impact).

These targets are specified in aviation regulations. A great number of such regulations for dynamic load cases were introduced by the authorities to ensure aircraft safety in critical situations. In order to meet these requirements, energy absorption is an important aspect for the aircraft manufacturer and adequate energy absorption mechanisms need to be involved in aircraft structural design.

*Example - bird strike:*

A typical example for such regulations is bird strike. A collision with a bird during flight can lead to serious damage to the aircraft. All forward facing components are concerned, i.e. the engine fan blades and inlet, the windshield, window frame, radome and forward fuselage skin as well as the leading edges of the wings and empennage. For helicopters the windshield, forward fuselage structure and rotor blades are especially vulnerable against bird strike.

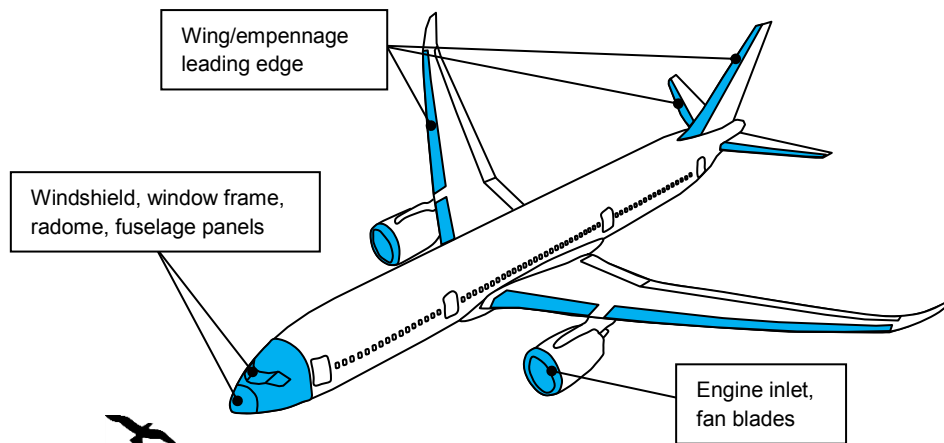


Fig. 1: Illustration of aircraft components exposed to the risk of bird strike

Consequently, the aviation authorities require that all forward facing components need to prove a certain level of bird strike resistance in certification tests before they are allowed for operational use. These requirements are compiled e.g. in the Federal Aviation Regulations (FAR), European Joint Aviation Regulations (JAR) and lately in the Certification Specifications (CS) of the European Aviation Safety Agency (EASA):

- For wing leading edges the certification criteria require that even in case of penetration of the leading edge skin no critical damage may be introduced to the front spar elements or the wing box, assuring a continued safe flight and landing after impact. This has to be proven for 4 lb. birds impacting the wing and 8 lb. birds impacting the empennage leading edge at operational speed (FAR/JAR/CS 25.571, 25.631). In these cases, the impact energy is mainly absorbed by structural deformation of the leading edge in terms of metal plasticity or composite material damage. Other advanced concepts for energy absorption in leading edge structures are addressed in chapter 5.

- All gas turbine engines and particularly turbofan engines must be durable in order to withstand ingested birds. For small and medium birds the certification regulation requires the demonstration of structural integrity and a continued thrust level of 75% power. For large 4 lb. birds it has to be proven that the engine can be shut down in a controlled manner without fire. This must be shown in a certification test on an entire engine, although manufacturers usually perform bird strike tests on single or multiple fan blades for design studies. The engine inlet also has to withstand a 4 lb. bird impact without damage of critical components (FAR/JAR/CS 25.571, 33.76).

The regulations for military aircraft are specified by the customer and are typically very similar.

*Example - crash:*

The specifications for hard landings and survivable crash scenarios are summarised in FAR/JAR/CS 25.562 'Emergency landing dynamic conditions'. Within these regulations, maximum g-pulses are defined for forward (16g after 90 ms) and downward loadings (14g after 80 ms) that occur at the passenger seat and allow for survivability. The goal of the aircraft manufacturer is to use adequate energy absorption systems in order not to exceed these target deceleration pulses in defined crash loading conditions.

Besides these specific requirements, some further general regulations apply to the structural design in terms of damage tolerance. Certain levels of residual strength or structural integrity need to be maintained after the occurrence of the damaging load case. For example, the 2-bay-crack criterion states that even in case of damage or crack spanning the distance of two frame bays of a commercial airliner, structural integrity needs to be maintained to ensure safe landing.

When developing energy absorbers for aircraft applications, further requirements are important besides the sole achievement of the targeted, specific performance. Weight is a key factor in aircraft design, and all developed absorber concepts need to be as lightweight as possible. Cost efficiency, slightly less important in the past, is at eye level with weight efficiency today and also a main factor. Furthermore, fatigue, maintenance, repair, reproducibility and robustness against changing loading conditions are important criteria as well to distinguish different absorber systems and to select the appropriate solution.

### 3. Energy-absorbing materials and structures

When it comes to energy absorption in a dynamic load case, two general options are possible for structural design and structural performance. Either the energy is absorbed directly by the aircraft structure by ductile deformation through the selection of appropriate skin materials (e.g. thermoplastic composites made of glass fibre/PPS in the wing leading edge of Airbus A340 and A380, or general metallic ductility in past wing or fuselage skins) or the energy is absorbed by separate energy absorber elements, which typically do not carry any static loads but are additional weight only for the absorption load case (e.g. crash absorber elements in aircraft and helicopter floors).

In general, the absorbed energy is represented by the area under the force-displacement curve as a result of a compression or tensile test of any absorber material or structure. The weight-specific energy absorption value in [kJ/kg] is often used to compare performance and weight benefits of absorber concepts in lightweight design. An ideal absorber, consequently, shows a constant plateau stress level, allowing for the maximum area under the curve. Most real absorbers, however, show initial load peaks and oscillations, which ideally need to be reduced as much as possible. In aircraft design, the following materials are typically used in existing absorber systems or absorber concepts:

- Metals: energy absorption by yielding and plasticity. Typically aluminium, titanium or eventually steel.
- Fibre-reinforced composite materials: energy absorption by matrix cracking, delamination, fibre fracture or crushing/fragmentation. Typically carbon, glass, quartz or aramid fibres with epoxy or thermoplastic matrix.
- Synthetic high-performance fibres: ultra-high-molecular-weight polyethylene (UHMWPE) like Dyneema or Spectra with strength-to-weight ratios of about 8-15 times that of steel, in dry or resin-infiltrated configuration, e.g. in vehicle armour or engine containments.

Many energy-absorbing structures for impact, crash or blast loads are based on cellular structures, either used separately or in a sandwich configuration with face sheets. Their main benefit is their extremely low weight and often ideal absorber-performance with nearly constant crushing load levels for highest efficiency.

#### *Honeycomb:*

Hexagonal honeycomb structures are the state-of-the-art cellular structure for such applications. Made either from Nomex, aluminium or thermoplastics like polypropylene, they can be found in numerous aircraft applications. For example, the Airbus A380 uses about 4000 m<sup>2</sup> of honeycomb in its structural design, of course not solely indented as energy absorbers. Typical honeycomb crushing curves show a rather constant crushing load level until compaction with minor strain rate effects (Fig. 2) [1]. Typical values for specific energy absorption are given on the right hand side in Fig. 2.

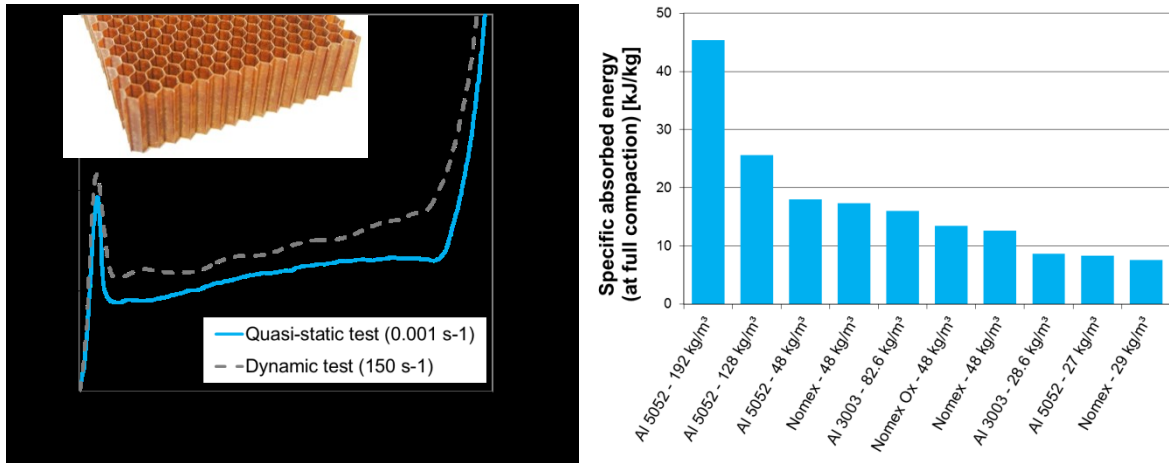


Fig. 2: Typical stress-strain curve of Nomex honeycomb (48 kg/m³) and comparison of specific absorbed energy at full compaction of different honeycomb structures

*Foam:*

Foams, either polymeric or e.g. metallic, are also well-known for their energy-absorbing and cushioning properties with an almost ideal constant crushing load level (Fig. 3). In aircraft engineering, only few types of foam are used, mainly due to FST (fire, smoke, toxicity) issues. Potential polymeric foams are PMI (Rohacell) or PVC (Divinycell) foams. Other foams like PI, PU or PE have significantly lower weight-specific mechanical properties (Fig. 3) and are, besides their FST behaviour, not attractive for lightweight aircraft applications.

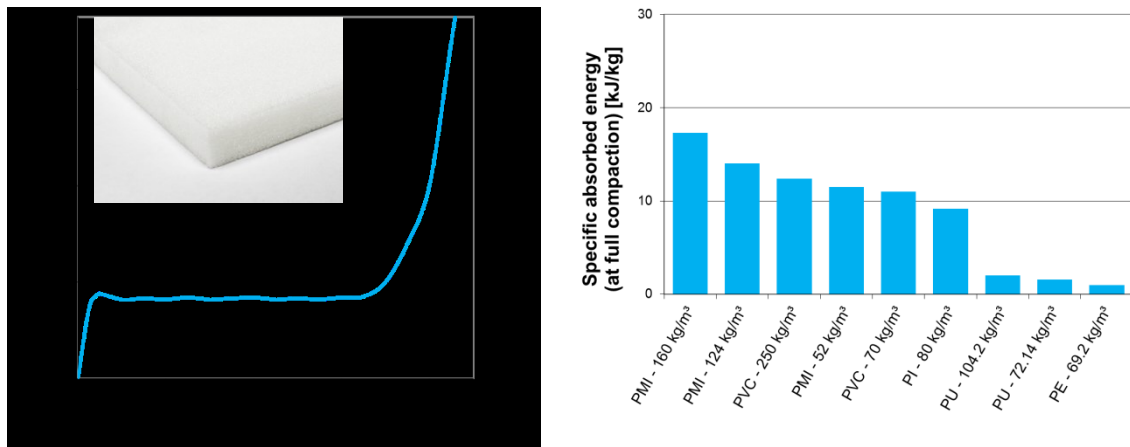


Fig. 3: Typical stress-strain curve of PMI foam and comparison of specific absorbed energy at full compaction of different polymeric foams

*Foldcore:*

A new generation of cellular structures was developed in the last years to overcome the drawbacks of water ingress of honeycombs in aircraft structures: so-called foldcores [2]. The basic idea of these folded cores is to produce three-dimensional structures from a flat sheet of material in an origami-like manner by a simple folding process. Almost any foldable material can be used and the unit cell geometry can be designed with respect to the specific mechanical requirements, offering a very large design space for tailored properties. Their use as impact protection layers for energy absorption was investigated for different cell wall materials like aluminium, aramid paper or aramid and carbon fibre composites [2, 3, 4]. Despite their non-perfect stress-strain curve (Fig. 4), the specific absorbed energy of carbon foldcore is very promising because the composite cell walls are crushed with material fragmentation, which absorbs a lot of energy.

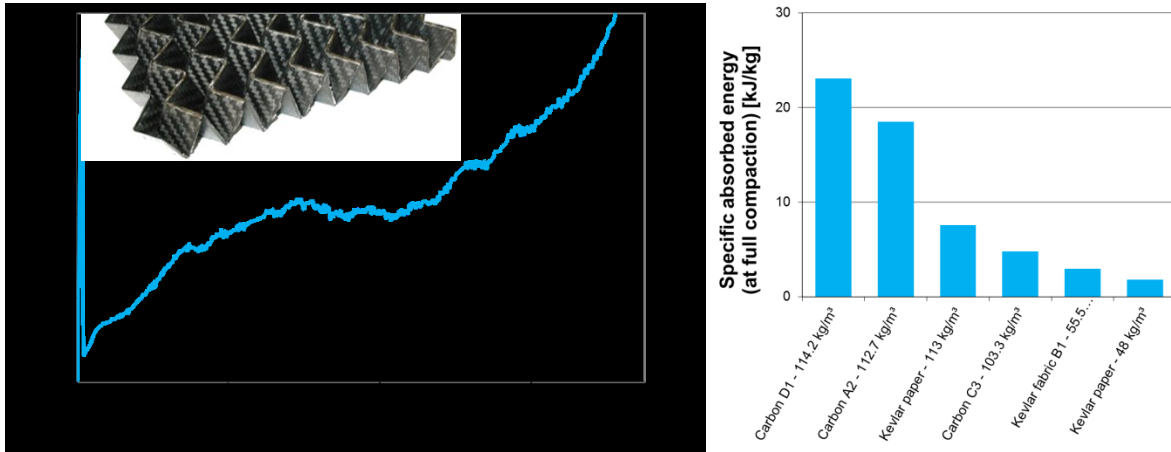


Fig. 4: Typical stress-strain curve of carbon foldcore (114 kg/m<sup>3</sup>) and comparison of specific absorbed energy at full compaction of different foldcores

#### *Other cellular structures:*

Plenty of other cellular structures for energy-absorption purposes exist and are under current development. Lately, the EU project CELPACT [5] focused on the development of innovative cellular structures for energy absorption purposes in the aircraft environment and concepts e.g. based on metallic hollow spheres, metallic lattice core structures or folded cores were investigated.

#### **4. Testing vs. simulation**

The research of new energy-absorbing structures typically involves a large amount of specimen manufacturing and testing to investigate the influence of certain parameters on the mechanical performance. This is both a time- and cost-intensive procedure. Nowadays, numerical simulations based on the finite element (FE) method have become a standard tool in the development process in aircraft industry – from the material level over the component level up to the full aircraft (Fig. 5).

Therefore, it is reasonable to use this technique also for the characterisation of energy absorbers. Instead of manufacturing expensive prototypes e.g. of innovative cellular structures, FE models on a parametric basis are generated and dynamic simulations of compressive and shear tests are performed in order to evaluate the cell wall deformation behaviour and the effective mechanical properties of different core geometries. This method of virtual testing, which can be combined with a core geometry optimisation for certain requirements, can be a very time- and cost-efficient approach [6].

The tendency in aircraft industry is clear: the amount of testing shall drastically be reduced and mainly be limited to essential coupon tests and few validation tests of components. The majority of development efforts shall be performed on the numerical side, using the test data only for necessary model validations.

As a matter of fact, it is more and more possible to substitute the aircraft structure's certification tests, which were requested to be real physical tests in the past, by validated simulations. The acceptance of certification just by simulation requires the demonstration of complete model validation with test data on similar structures and was, for instance, successfully shown for the certification of the Airbus A380 upper cap zone against bird strike [7].

#### **5. High velocity impact load cases and energy absorption**

In the following paragraph, some specific examples of foreign object impact load cases in aircraft operation and respective energy absorption mechanisms and solutions are given.

##### *Bird strike:*

Bird strike is a major threat to aircraft structures and can lead to serious structural damage. Besides other threats like hail, runway debris or tire rubber impact, about 90% of all impact incidences today are reported to be caused by bird strike [8].

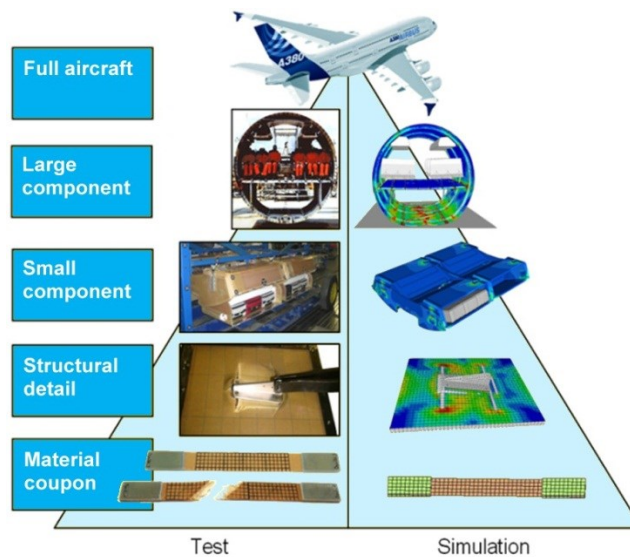


Fig. 5: Testing/simulation pyramid in aircraft development

Specified bird impactor masses of 4 lb. and 8 lb. and typical velocities of approx. 180 m/s lead to kinetic energies of 30 – 60 kJ. During the bird impact on the leading edge of wing or empennage, the energy is mainly absorbed by structural deformation of the metallic, composite or hybrid leading edge skin (Fig. 6). An additional absorber concept has been developed in the EU project CRAHVI, which was called ‘tensor skin concept’ and is based on the unfolding and stretching of Dyneema plies, which initially are folded as loops and embedded between carrying laminates [9].

Another example is the bird impact on the radome shield behind the nose of the aircraft. This shield is a non-structural energy absorber panel, which protects the cockpit from penetration and is currently designed as an aluminium honeycomb sandwich panel. Different other energy-absorbing cellular cores were investigated in order to find a lighter solution, including aluminium foam [10] and polymeric hollow spheres [11].

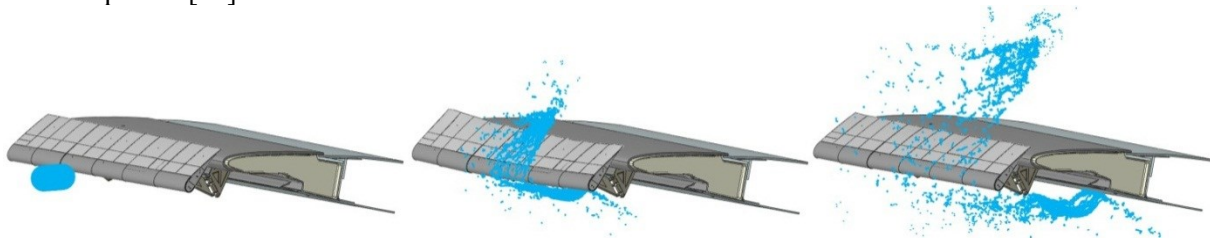


Fig. 6: Bird strike simulation on wing leading edge components

*Hail/ice impact:*

Hail on ground is typically a low velocity impact load case and does not require any specific energy absorbers. Hail impact during flight, however, can occur with impact velocities up to 300 m/s and lead to serious damage. Still, specific energy absorbers against hail impact are typically not implemented, but the structural design needs to be impact-resistant against hail impact to prevent from major damage. The same is true for impact resulting from ice fragments that are released from propeller blades [12].

*Runway debris, stones:*

Runway debris and stones are small particles that are propelled by the tires during take-off or landing and that can hit the lower fuselage panels with velocities of approx. 50 – 170 m/s. Typical projectile masses of 10 – 15 g lead to impact energies of 17 – 194 J. While this impact energy typically needs to be absorbed by an impact-resistant structural design of the skin, additional energy-absorbing foam layers were also investigated at EADS, especially for sandwich skins with thin face sheets that need to be protected [13].



#### *Hydrodynamic ram:*

Hydrodynamic ram is the pressure pulse in a fluid-filled tank after external excitation e.g. by a penetrating projectile of e.g. 45 g with 560 m/s, leading to an energy of 7 kJ. This pressure pulse can lead to serious damage of the tank structure [14]. Additional internal energy absorbers on the tank walls were investigated to prevent from any structural damage, e.g. based on volume-filling foam, self-sealing liners or energy-absorbing foam.

#### *Tire rubber impact:*

Impact of tire rubber after wheel failure can involve projectile masses of e.g. 2.45 kg, velocities of 64 m/s and a resulting kinetic energy of 5 kJ. Because of the hyperelastic behaviour of rubber, a significant amount of strain energy is stored as elastic deformation of the projectile during impact [15], making an impact-proof design with significant structural deformation typically sufficient, without the use of additional energy absorbers against tire impact.

#### *Rim release:*

Rim release is referred to as the impact of a wheel rim fragment after fracture of the aircraft wheel during take-off or landing. Aircraft wheels are typically made from forged aluminium alloy, such as 2014-T6, 2040-T6 or 7050-T74. During service they are exposed to harsh operating conditions, like high take-off and landing loads, high-energy and high-temperature braking events or corrosion from runway and aircraft fluids. The main cause of rim fracture is high-cycle fatigue loading with the weakest area at the flange of the wheels. When wheel failure occurs, the fragments are often propelled with high energy of e.g. 8 kJ, resulting from a mass of 1.68 kg and a velocity of 100 m/s. The use of a PMI foam energy absorber concept to protect a composite linkage structure of a wing flap mechanism against rim release impact was investigated in [16] (Fig. 7).

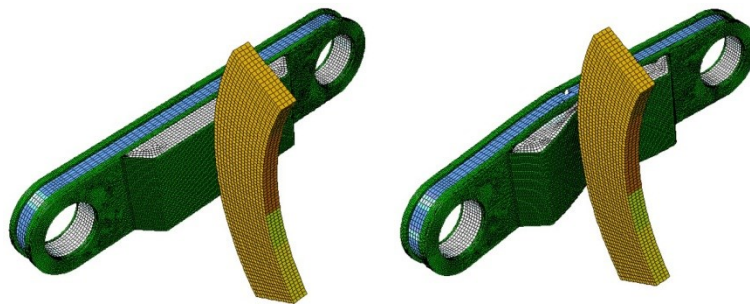


Fig. 7: Impact of rim flange fragment on linkage structure with foam energy absorber

#### *Blade-off:*

The release of an engine fan blade is the most severe impact load case with a typical mass of 2.72 kg, a velocity of 366 m/s and resulting impact energy of 180 kJ. The certification regulation in CFR §33.94 requires to prove no penetration of the engine containment and a safe shutdown of the engine. In order to achieve this goal, typical engine containments consist of several energy-absorbing layers made of aluminium or Kevlar to slow down and stop the projectile from penetration. New threats arise from open rotor engines without any protective containment, mounted at the rear end of the fuselage [17]. As armouring of the fuselage might be too heavy, concepts are developed for structural design that allows for possible penetration while maintaining structural integrity and system redundancy.

## **6. Blast load cases and energy absorption**

Explosive blast is a load case which is not only relevant for military aircraft, but also for commercial aircraft. Therefore, aircraft manufacturers have to face such threats and develop hardening and blast mitigation approaches. During blast loading a considerable amount of energy is released in a relatively short time period. A blast wave is generated when the atmosphere surrounding the explosion is pushed back by hot gases produced from the explosion source. The front of the wave, called the shock front, is like a wall of highly compressed air and has an overpressure much greater than that in the region behind it. The peak overpressure decreases rapidly as the shock is propagated outward [18].

For the aircraft manufacturer, the following blast load cases are relevant:

*External blast by explosive warhead:*

Mainly relevant for military aircraft, the direct attack by a rocket with explosive warhead has disastrous consequences. Air-to-air missiles, man-portable air-defence systems (MANPADS) and rocket-propelled grenades (RPG) are the main threats, using warheads with blast charges, hollow charges or fragment charges. It is virtually impossible to develop an energy absorbing concept or armour to withstand all of these attacks, the additional weight would make it impossible for the aircraft to fly. Therefore, more efforts are put into hit avoidance like warning systems, flares, defensive jammers or rapid flight manoeuvres.

*Rocket motor blast:*

This blast load is generated when a missile is launched from a helicopter or fighter aircraft and the blast pressure from the igniting rocket motor hits the aircraft surface. Since this event typically occurs regularly after each missile launch, no typical single-use absorbers are utilised but the structural design needs to be strong enough to withstand this pressure loading.

*Internal blast by improvised explosive device:*

In times of terrorist attacks, bombing in commercial aircraft is a present threat that first occurred in the 1950s. Plastic explosives like C-4 or PETN were often used and hidden in luggage, parcels, carry-on baggage, shoe soles, etc. In the last decades, significant progress was achieved to implement blast-mitigating structures against such attacks. Blast-resistant luggage containers either based on aluminium/glass fibre hybrid structures or high-performance textiles were developed in [19, 20]. Hardening measures and protective linings against explosive loading for the main fuselage are also under investigation, with concepts e.g. based on blast-resistant sandwich panels [21, 22], elastomeric polyurea coating or aluminium/glass fibre hybrid lay-ups with layers of Kevlar-reinforced elastomers [23].

## 7. Crash load cases and energy absorption

Survivable crash landing scenarios on solid ground (besides water ditching [12]) are among the most challenging topics taken into account in the design of aircraft structures. Modern civil aircraft are designed for crashworthiness with the fuselage structure's crash behaviour typically being evaluated in vertical drop tests on solid ground, as illustrated in Fig. 8. Such a drop test scenario shall represent the maximum decelerations at the passenger seats, which are defined in the Federal Aviation Regulations §25.562, in order to obtain a survivable crash landing. The kinetic energy at the moment of impact is supposed to be absorbed by the lower part of the fuselage, while the passenger cabin shall remain intact to ensure a safe evacuation of all passengers. In case of metallic materials, the impact energy is normally absorbed by plastic deformation (e.g. Airbus A320), while it is crushing and fracture for composite structures. Besides the deformation of the primary fuselage structure itself, additional energy absorbers can be incorporated to improve the crash behaviour and limit the g-forces acting on the passenger floor, which can be based on different concepts.

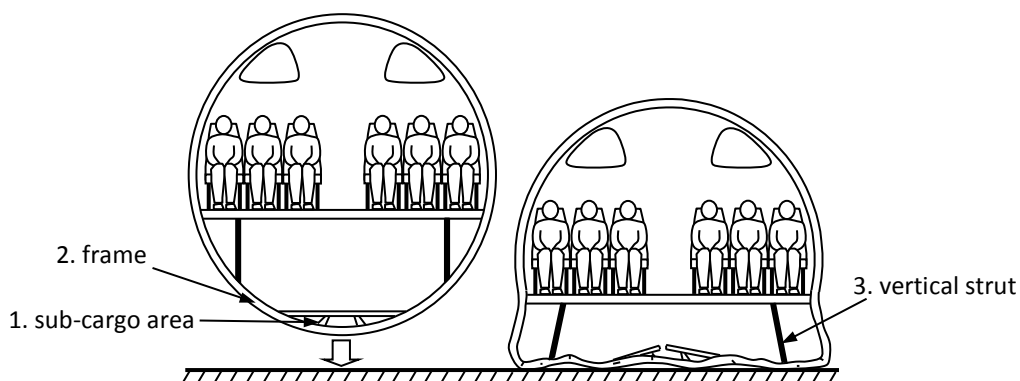


Fig. 8: Illustration of aircraft fuselage drop test for crashworthiness evaluation



#### *Energy absorber in sub-cargo area:*

In the chain of energy absorption, the sub-cargo area in the lower fuselage part is loaded first as it first comes into contact with the ground. A lot of research was conducted e.g. in the EU project CRASURV with respect to composite sine wave beams in the subfloor structure that are crushed under vertical crash loads [24, 25]. Further concepts are based on foam [26] or honeycomb absorbers in the subfloor structure [27].

#### *Energy absorber in frame:*

Additional energy absorbers or plastic hinges can also be integrated in the circumferential frames of the fuselage [28], as the frame typically breaks at a location close to the attachment of the vertical struts.

#### *Energy absorber in vertical strut:*

The third option includes energy absorbers in the vertical z-struts of the fuselage. Z-struts are the connection of passenger floor and lower frames, acting as the support in vertical (z-) direction. In the crash case, they are loaded in axial compression as soon as the lower fuselage part is flattened. In [29], a lightweight composite crash absorber element was developed for integration into the vertical struts, which absorbs energy under compression loads by cutting the composite strut into stripes and crushing the material under bending.

#### *Energy absorber in overhead compartments:*

In order to increase safety for the passengers during turbulence or survivable crash landing, energy absorbers have also been integrated in the support structures of the overhead baggage compartments to prevent their detachment from the primary aircraft structure and to ensure their structural integrity [30, 31]. These conceptual energy absorbers were based on metallic bending deformation, composite cylinder crushing and composite bearing failure (Fig. 9).

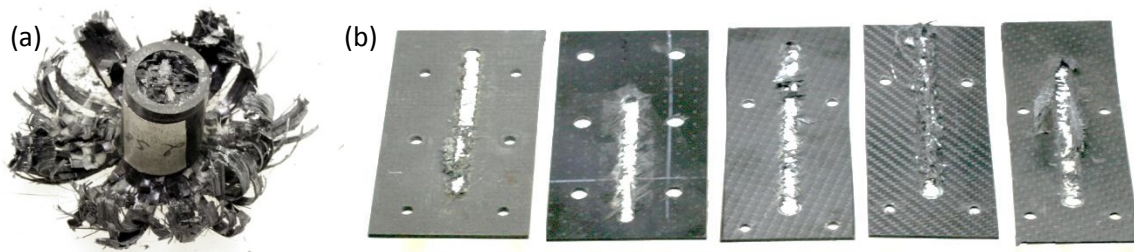


Fig. 9: Conceptual energy absorbers based on composite cylinder crushing (a) and pin-bearing (b) for use in overhead compartments

## 8. Conclusions

It was shown that many different dynamic load cases are important for the aerospace industry, where energy absorption is an important issue. These are mainly categorised as foreign object impact, explosive blast and crash load cases. Strict regulations and requirements by the aviation authorities have an influence on structural design. After many decades of experience with energy absorbers and energy-absorbing materials in aviation, most absorbing mechanisms today are based on metal plasticity, composite fragmentation or cellular core crushing. The main drivers in energy absorber development, besides their intrinsic performance, are cost and weight. To further improve these factors, much active research work is continuously conducted in order to meet the many waiting challenges for new energy absorbers or energy-absorbing materials.

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