Abstract

A crash absorber element integrated in composite vertical (z-) struts of commercial aircraft fuselage structures was developed, which absorbs energy under crash loads by cutting the composite strut into stripes and crushing the material under bending. The design concept of this absorber element is described and the performance is evaluated experimentally in static, crash and fatigue test series on component and structural level under normal and oblique impact conditions. These tests highlight the robustness of the absorber design as this system worked under various conditions and angles with an impressively high reproducibility. The physics of the energy absorption by high rate material fragmentation are explained and numerical modelling methods in explicit finite element codes for the simulation of the crash absorber are assessed.

Introduction

Survivable crash landing scenarios are among the most challenging topics taken into account in the design of an aircraft structure. 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. 1 [1, 2]. 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, 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, which can be based on different concepts. In the chain of energy absorption, the subfloor area of the lower fuselage is loaded first as it first comes into contact with the ground. A lot of research was conducted with respect to energy absorbers in the subfloor structure [3-5]. Additional absorbers or plastic hinges can also be integrated in the circumferential frames of the fuselage [6].
A new approach, presented in this paper, includes energy absorbers in the z-struts of the fuselage (Fig. 1) [7]. 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 [8, 9]. In this study, a lightweight composite crash absorber element was developed, which absorbs energy under compression loads and meets at the same time design criteria like stiffness, buckling stability, trigger load or fatigue performance. Besides the design and experimental testing of this absorber device, approaches for numerical modelling are also addressed.

**Design Concept of Crash Absorber**

When it comes to the weight-specific energy absorption (SEA) of crash elements it is known that composite materials are superior compared to metallic absorbers. The fragmentation of fibre-reinforced composites happens under a nearly ideal constant crush load level, while the folding pattern of metallic crash boxes under compression typically leads to severe load amplitudes for each fold. The characteristics of composite crash absorbers and the influence of various geometrical shapes, fibre architectures or trigger mechanisms have been investigated extensively in the past [10-12].

The idea behind the following study was to use the z-strut – made from a circular profile of composite material – as the crash element that is being crushed in its supporting device, allowing for a very long energy absorption length, basically the whole length of the strut (Fig. 2). The absorber element and its components are shown in detail in Fig. 3, their materials and functions are explained as follows:

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**Figure 2: Composite z-strut with integrated energy absorber (before/after crash test)**

**Figure 3: Energy absorber device and components**
Composite strut:
The composite strut is made from a carbon fibre/epoxy prepreg laminate with 50% fibres in 0° (axial) and ±45° direction, which was most suitable for the crush load requirements and constraints of this study, defined by the aircraft manufacturer. Of course, the lay-up can be adjusted for other requirements. Although braided struts were also tested, prepreg material led to higher reproducibility. To avoid corrosion problems with the aluminium supports, an outside layer of glass fibres was used (Fig. 4a).

Inlet radius:
The inlet radius at the upper end of the support device ensures the functionality under oblique impact conditions up to an angle of about 10°. It is important to ensure that the absorber also works in the oblique configuration, as there is some rotation of the struts to be expected in the crash load case of the fuselage (Fig. 1). These design constraints were derived from a global fuselage crash analysis using a kinematics model [2].

Shear pins:
All static loads are transferred from the composite strut to the metallic absorber device through shear pins (Fig. 4b). In case of the crash load, they are supposed to fail at a specific limit by shear failure, so that the crushing of the composite strut begins. Titanium pins were found to be superior compared to aluminium pins, as their yield and ultimate strength values are closer, leading to a more brittle failure without undesired nonlinearities. Composite CF/PEEK pins were also tested as an alternative but showed no improvement. Since solid pins led to bearing failure of the composite laminate, hollow titanium pins were used. The final geometry of the pins and their fillet radii were optimised with respect to fatigue demands. Initial trials with bonded surfaces instead of shear pins appeared to be less promising and posed the ageing problem of the adhesive and were therefore rejected.

Figure 4: Post-test view of composite crash absorber (a) and shear pin failure (b)

Deflection ring:
The 7075-T651 aluminium inner ring inside the absorber element acts as a deflection device. Once the shear pins fail, the composite strut hits the inner ring and the composite material is deflected outwards. The angle of this deflection device primarily influences the crush load of the whole absorber system.

Absorber device:
The aluminium absorber device is basically the support for the z-strut and the connection to the fuselage structure. It consists of several circumferential holes, through which the composite strut is pushed after being deflected by the inner ring. Due to the sharp edges of the holes, the strut is cut into stripes. Through these holes the outflow of the material is ensured so that no blockage can occur, assuring the absorber functionality. Some trials were also performed with titanium absorber devices, leading to a slightly lower SEA, which may be attributed to the higher wear resistance and hence sharper cutting edges.
In summary, the energy is absorbed by cutting the z-strut into stripes and bending the material outward via the deflection device. During this process it delaminates and is crushed and fragmented to a large extent (Fig. 2, Fig. 4a). For this application, this process turned out to be the optimum to meet the targeted crush load level, which is illustrated in Fig. 5. The first peak in the force-displacement diagram is the trigger load, when the shear pins fail and the absorber starts to work. It was specified to be 20% higher than the ultimate load of the static design and is therefore only reached in the crash case. After shear failure of the pins, the load level drops to zero, due to free displacement of the composite tube up to contact with the deflection ring, which is supposed to avoid the addition with the following peak load when the crushing begins. After this second peak a stable crush load plateau develops that lasts until all energy is absorbed. For sure, the crush load level can be increased by crushing the whole tube instead of cutting it into stripes, but if the SEA increases the wall thickness of the tube would have to be reduced to meet the targeted load level, leading to buckling and bearing failure issues. Also the continuous material outflow would be more problematic and the initial peak load is much higher for the full tube crushing.

Figure 5: Absorber characteristics in force-displacement diagram

Testing of Crash Absorber

The development of this crash absorber is based on a step by step testing approach from cylinder crush tests to absorber component tests to full-scale crash tests and fatigue tests:

The crash absorber development started with cylinder crush tests to identify the SEA of various laminates and materials with different trigger geometries, covering braided tubes made of HTS fibres and RTM6 epoxy resin and prepreg tubes made of HTA fibres and MTM28 epoxy resin. The crush tests were performed on a Myrenne drop tower with pneumatic acceleration with an impact energy of 750 J (Fig. 6). The SEA of the full composite cylinders was in the range of 80-100 kJ/kg.

Static compression tests of the absorber element were performed on an Instron universal testing machine to evaluate the shear pin failure load without crushing of the tube. The influence of different pin geometries and materials as well as the number of pins could also be investigated in these tests.

Dynamic compression tests of the absorber component with a relatively short composite tube were performed on the same Myrenne drop tower test rig as mentioned before with an impact energy of 750 J (Fig. 6). The aim was to assess the shear pin failure under dynamic loads and the overall energy absorber performance. The shear pin failure was proven not to be influenced by strain rate with comparable failure loads for impact velocities of 3 x 10^{-5} m/s, 4 x 10^{-2} m/s and 8 m/s. The SEA of the tube being cut into stripes and crushed under bending was in the range of 40-45 kJ/kg.

Full-scale crash tests of complete z-struts were performed at the horizontal crash test facility of the Institute of Composite Materials (IVW), Kaiserslautern. The velocity of the sledge in both test cases
was 6.8 m/s and the sampling frequency of the data acquisition was 250 kHz. Despite this high frequency, the shear pin failure loads could not exactly be identified in the force curves due to oscillations. The final force-displacement curves that are shown in the modelling and simulation chapter of this paper were filtered with a CFC 600 filter to reduce oscillations. The full-scale crash tests were performed successfully both under normal and 7° oblique impact conditions (Fig. 7). The main conclusion from this test spectrum was the robustness of the absorber design. While other absorber concepts often show their full performance only under a narrow range of ideal conditions, this system worked under various conditions and angles with an impressively high reproducibility.

The testing spectrum was finalised with fatigue tests under tension-compression loads. This is of special importance to qualify the absorber for its intended use, as a premature fatigue failure has to be excluded. A rather conservative fatigue load spectrum was defined based on a hard landing load case for each cycle, which was successfully passed.

**Modelling & Simulation**

In aircraft engineering there is a strong interest in reliable numerical methods for structural design to reduce testing expenses and development time. For this reason, numerical analyses were also performed in the framework of the development of the crash absorber. The aim was to assess the accuracy of state-of-the-art numerical methods and to verify if it is possible to develop a simulation model that can assist the absorber development.

Besides in-plane failure under bending, two degradation modes are dominating in this energy absorption process that need to be covered by the model: fragmentation and delamination [13]. In this context, fragmentation can be seen as the last step of degradation, where the material is reduced to small particles. The initiation of fragmentation takes place at the microscale, where microscopic buckling of fibres occurs, leading to kink band generation. Besides ply fragmentation, delamination as the interlaminar separation of two plies of the composite laminate is also a key mechanism in energy absorption. Delamination modelling on the mesoscale typically involves interface models between separate plies or sublaminates represented with shell, continuum shell or solid elements. These interface models may e.g. be contact definitions or cohesive elements, with their failure behaviour classically being based on the cohesive zone model with a defined traction-separation law. On this basis, it was investigated if the features available in today’s commercial explicit FE codes are able and accurate enough to predict the crush load level of the z-strut absorber. In this study the commercial code Abaqus/Explicit was used (Fig. 8).
All aluminium parts of the absorber, i.e. the absorber device, the inner ring and the support on the other side of the strut were modelled with C3D6 and C3D8R solid elements and an elastic-plastic material law with isotropic hardening. The composite strut was modelled with two layers of S4R shell elements and one interface layer of COH3D8 cohesive elements in-between for delamination. Intralaminar failure in the multi-layered composite shell elements is covered by the Hashin criteria for damage initiation and a fracture energy-based formulation for damage evolution. The first row of elements in the strut was weakened to act as a trigger and initiate stable contact behaviour and crushing. It has to be mentioned that the cutting seams in the composite tube had to be predefined in the model like in [14] by lines of cohesive elements in order to achieve stable simulations and crack propagation. Although the shear pins were included in some first calculations on component level, they were excluded in the final crash simulation of the complete z-strut because the high loading rate in the crash test in combination with the limited sampling frequency and superimposed oscillations led to the fact that the shear pin failure could not be evaluated in the experimental force plots and therefore no comparison with the simulation was possible. A general contact definition was used to avoid penetration of the individual parts. The boundary conditions were defined corresponding to the experimental crash tests with an impact velocity of 6.8 m/s and an initial kinetic energy of 1911 J.

The force-displacement diagrams of crash test and Abaqus/Explicit simulation are shown in Fig. 9, both being recorded with the same frequency and filtered with a CFC 600 filter. The simulation was stopped earlier after the stable crush load level was clearly identified.
It can be seen that the load peaks in the beginning cannot be covered by this model, as they are the result of the crack initiation. The initiation, however, is predefined in the model by the cohesive interface seams, the simulation only covers failure propagation. It can be seen that the experimental curve is slightly progressive in the crushing zone, which is a result of wear at the cutting edges. This effect is not covered by the model. Although stress concentrations appear in the aluminium material, the yield stress of the elements is not reached. The metallic cutting edges would have had to be modelled with a very fine mesh for this purpose, making the explicit calculation inefficient. However, besides these drawbacks, the most important characteristic – the crush load level – can be predicted quite satisfactorily with a mean deviation of only 4%. This indicates that the main contributors to the energy absorption are represented by the model: the cutting of the tube into stripes by the cohesive elements and the damage and delamination modes under bending. The evaluation of the damage output variables for the composite material model shows that matrix failure and fibre compressive failure are the dominating intralaminar failure modes. The robustness of the model was proven to be very good for different impact angles, but limited for different wall thicknesses of the composite strut or different angles of the deflection device, which may be due to the simplified damage or delamination modelling [15]. Again, it has to be recalled that the real physical process of fragmentation cannot be represented by this mesomodel, it is just approximated. This study highlights that the accurate simulation of composite crushing is one of the biggest challenges in finite element analyses and further improvements are necessary for industrial application.
Conclusions

A lightweight composite crash absorber was developed, which is integrated in the z-struts of a commercial aircraft to improve the crashworthiness behaviour. Component tests and complete z-strut crash tests under normal and oblique loading conditions provided consistent results within all requirements and showed a very high degree of robustness and reproducibility of the results. Although the absorber in this study was designed for specific load requirements, it can be adjusted to individual trigger and crush load levels by an appropriate choice of:

- Composite tube material, lay-up and thickness.
- Shear pin material and design.
- Angle of the deflection device.
- Number of cutting holes.

The use of explicit FE simulations with the commercial code Abaqus/Explicit was shown to be successful to a certain extent for an overall prediction of the crush load level. However, specific peaks in the load curve could not be represented, this would require a much more detailed and at the same time less efficient modelling approach. The real physical fragmentation phenomena can just be approximated, highlighting that the numerical prediction of composite energy absorption for industrial use cases is still a big challenge and currently under further investigations.

References


