Improvement of Sailplane Crashworthiness through Keel Beams with Silicone Cores

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Abstract

Occupant safety is a major concern in the development of modern sailplanes. Particularly, the crashworthiness of cockpit structures is an important design consideration. In this paper a structural concept for a forward fuselage is presented which has been developed to improve the crash performance of sailplanes. The proposed design solution primarily addresses the issues of survival space integrity as well as occupant acceleration. It is based on the use of composite box beams filled by silicone rubber as crash elements in the lower cockpit structure. The elastomeric material was selected owing to its remarkable properties in terms of shock absorption and damping. The crash performance of this design concept was evaluated through numerical simulation using an explicit transient dynamic code. For this purpose a detailed finite element model of a generic glider fuselage was established comprising all relevant structural elements. Additionally, the model was equipped with occupant dummies which provided high fidelity acceleration data. A comprehensive parametric study was conducted which demonstrated the capability of the proposed keel beam concept to improve the crashworthiness of glider cockpit structures.

Introduction

The crashworthiness of sailplanes is essentially influenced by the fuselage and cockpit structural design. With regard to an aircraft ground impact, occupant safety primarily requires survival space integrity and, secondly, rather smooth accelerations instead of distinct peaks. Therefore, a variety of so-called crash elements have been developed in order to dissipate a significant portion of the kinetic energy of the aircraft through crushing or material failure [1–3]. A combination of a stiff cockpit and one or more dedicated crash elements can be considered the state of the art in terms of crashworthy glider design [1, 3–6]. Usually, their integration into the aircraft requires additional space. Also, extensive structural tailoring of the fuselage is necessary in order to support these crash elements and to prevent the cockpit from collapsing. These shortcomings as well as the recently tightened EASA CS-22 crashworthiness requirements [4] clearly indicate a demand for new design solutions in order to enhance occupant safety. This issue has been tackled in a research project which will be presented in the following. The research was particularly focused on exploring the capability of silicone rubber with regard to crashworthiness improvements of the cockpit structure.

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Silicone energy absorbing material

Based on the results of a screening programme conducted on silicone rubber materials [7] the so called θ-6-Gel was selected as the most promising candidate for aircraft crash applications. It belongs to a family of materials known by the trade name α-Gel. Apart from θ-6 this family comprises five other silicone materials that primarily differ in stiffness and strength due to a specific production processing. Currently, α-Gel materials are exclusively offered by the Japanese Taica Corporation and are being utilized in a wide spectrum of applications, primarily for shock absorption and vibration damping [8, 9]. The term "gel" might be misleading in this context, because all members of the α-Gel group are elastomers exhibiting the constitutive behavior of rubber.

Table 1 summarizes the basic physical properties of θ-6. Regarding aircraft operation θ-6 offers superior resistance to ultraviolet light, humidity and ozone. Also epoxide-, phenol- and polyester resins do not impair the material which is an important feature when used in composite structures. Furthermore, contact with the human skin is harmless and the material does not emit toxic gases when burned [8]. More detailed information on the material characterization of θ-6 as well as on the development of a calibrated material model for the crash simulations can be found in [7].

Table 1: Physical properties of θ-6-Gel [8]

Property	Value
Density [g/cm^3]	1.06
Tensile strength [kPa]	1580
Young's modulus [kPa]	670.3
Max. tensile strain [%]	480
Application temperature [°C]	$-40 \sim 200$

Parametric crash model for numerical simulations

A parametric finite element model of a glider fuselage was established, which comprises occupant dummies in order to allow for a reliable investigation of the crash behavior. The model permits an arbitrary initial aircraft attitude prior to impact as well as different laminate thicknesses of major structural elements. Figure 1 gives a general view of the baseline model which is derived from the two-seat glider D-B11, designed by the university gliding club *Akaflieg Dresden*. The fuselage structure of this aircraft is entirely made of carbon fibre reinforced plastics (CFRP). In the forward part of the fuselage foam core sandwich is applied whereas the tail boom is monolithic. To maintain a generic character all laminates have a stacking sequence resulting in quasi-isotropic properties. The view of the cockpit in Fig. 2 shows distinct upper longerons where CFRP laminates cover a foam core. The load bearing structure also includes a front frame, two stick bulkheads, consoles, a crossbar and the seat shells. Hip belts and shoulder straps fasten two 50th percentile dummies. To keep the simulation model simple and robust items such as canopy and instrument panels have been neglected. In view of an aircraft crash the masses located behind the occupants must be considered. Thus, wing, horizontal tail plane and main landing gear are modeled by point masses. Table 2 defines the laminate data of the baseline fuselage. The layer angles denoted by the index

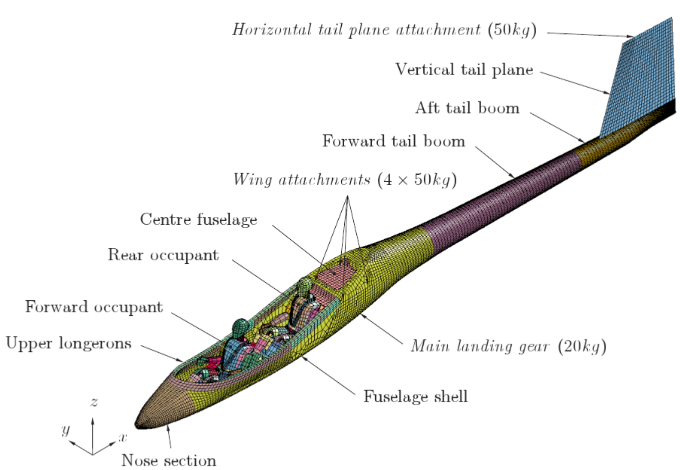


Fig. 1: Crash model baseline layout

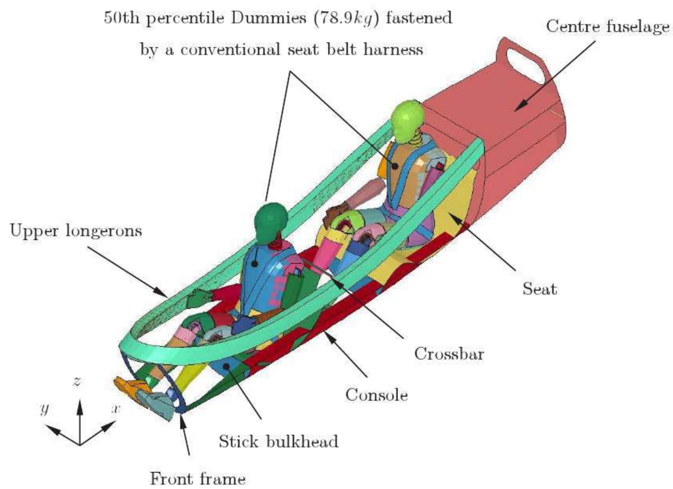


Fig. 2: Cockpit view of the baseline model (fuselage shell and nose section are not shown)

Table 2: Laminate data of the fuselage structure

Structural element	laminate stacking sequence	thickness [mm] laminate	core	total
Fuselage shell	$[0_f/45_f/CORE/45_f/0_f]$	2×0.5	6.0	7.0
Nose section	$[0_f/45_f/CORE/45_f/0_f]$	2×2.0	5.0	9.0
Centre fuselage	$[0_f/45_f/CORE/45_f/0_f]$	2×2.0	4.0	8.0
Consoles	$[0_f/45_f/CORE/45_f/0_f]$	2×1.0	2.0	4.0
Stick bulkhead	$[0_f/45_f/CORE/45_f/0_f]$	2×1.0	2.0	4.0
Front frame	$[0_f/45_f/CORE/45_f/0_f]$	2×2.0	4.0	8.0
Seats	$[0_f/45_f/CORE/45_f/0_f]$	2×2.0	6.0	10.0
Forward tail boom	$[0_f/45_f]_s$	2.0	—	2.0
Aft tail boom	$[0_f/45_f]_s$	2.6	—	2.6
Upper longeron	$[0_f/45_f]_s$	2.0	—	2.0

f refer to fabric plies. Core thickness values apply to sandwich structures. Based on the mechanical properties from [10] a gross mass of 528.5 kg has been determined for baseline model.

All crash simulations have been conducted using the explicit finite element code LS-DYNA. During the crash, accelerations are recorded at the respective centre hip nodes of the forward and rear dummy in order to get information on the spinal loads of the occupants. These dummy models have been provided by the LS-PREPOST software.

The model incorporates numerous parameters which influence the crash behavior. This is especially true for friction coefficients, material properties and failure criteria as well as the

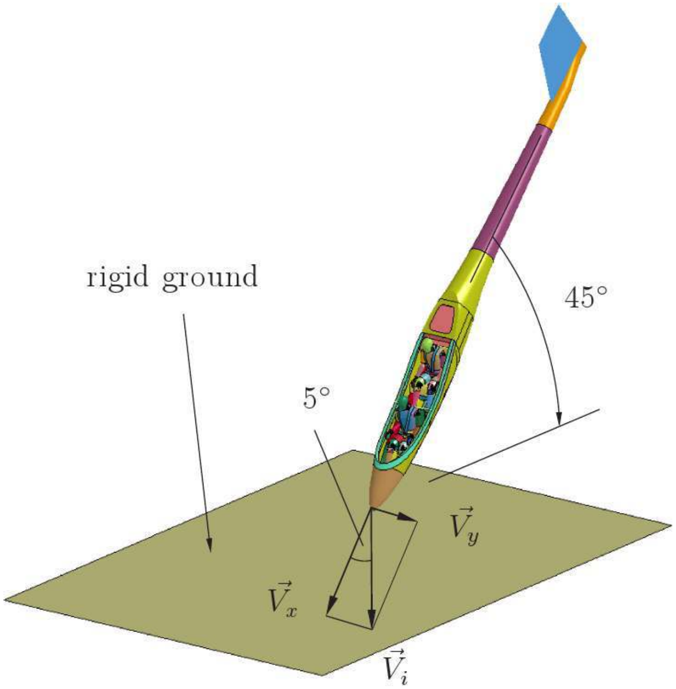


Fig. 3: Initial aircraft attitude

unknown reaction of the soil. Hence, it is virtually impossible to calibrate the crash model by means of existing experimental data. However, this does not impair the utilization for comparative analyses. Particularly, the model is very well suited to investigate the effect of design changes on the crashworthiness compared to the baseline aircraft.

Crash behavior of the baseline model

In a first step the crash model has been employed to get an understanding of the basic crash characteristics. The initial aircraft attitude considered in this investigation is shown in Fig. 3. The aircraft has a flight path angle of $-45°$ and zero angle of attack, i.e. the velocity vector points towards the fuselage longitudinal axis. As shown in [1] approximately 50% of all glider accidents exhibit this attitude prior to impact. Usually, this is initiated by a stall at low altitude (e.g. through a failed winch launch or at final approach) which causes the glider to spin until ground impact. This kind of accident occurs most frequently and usually results in severe or fatal injuries.

For the present study an additional side slip angle of 5° has been introduced in order to perturb the symmetry. This approach is believed to be more conservative and closer to reality than the symmetrical case. The aircraft impacts the rigid ground at time step $t = 0$ having a total velocity $\vec{V}_i = 80$ km/h and 130 kJ kinetic energy. Additionally, gravity forces act throughout the entire crash simulation. The friction between the aircraft and the ground has been considered by a friction coefficient of $\mu_g = 0.4$.

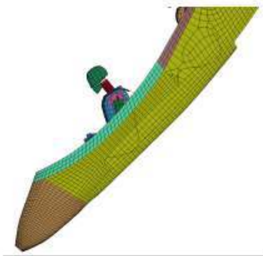
Figure 4 shows the resulting crash behavior. At $t = 36$ ms the upper longerons start to fail, resulting in a decrease of the fuselage bending stiffness. Due to this, the nose section loses part of the supporting structure and no longer contributes to the energy absorption. This shows, that a crash element mounted at the fuselage nose would be rather ineffective. At $t = 65$ ms the fuselage bottom shell fails due to increasing bending stresses. As a result, the cockpit stops collapsing at the front seat position. However, the survival space of the rear occupant begins to shrink which is further driven by the failure of the aft longerons at $t = 105$ ms. The occupant in the rear seat experiences a very high vertical acceleration which will probably result in severe spinal injuries upon ground impact. Figure 5 shows the significant increase in acceleration at the hip centre node between 90 and 180 ms.

For comparison, Ref. 11 describes a similar crash behavior of an airshow accident, where the glider experienced a stall at the downwind leg. This aircraft had the same initial attitude before impact as discussed above and also exhibited a premature failure of the forward fuselage in a very similar fashion. According to Ref. 1 crashed glider cockpits generally show the most severe structural damage in the area of the occupant seats. Particularly, in the case of composite gliders the majority of these spinning accidents cause fatal injuries, namely more than 70%. Reference 1 also shows that the overall safety of metal or wooden glider designs is superior to CFRP airframes, because the brittle failure modes of carbon fibre composites generally result in a poor energy absorption.

Integration concept for θ-6-Gel

The deficiencies of the baseline design reveal the need for an increased stiffness of the cockpit section which provides the survival space. This can be efficiently addressed by distinct upper and lower longerons. While most gliders have a canopy frame which can be referred to as upper longerons, there are generally no lower longerons. Consequently, the basic design idea has been to introduce keel beams in order to increase the fuselage bending stiffness about the lateral axis of the aircraft.

Figure 6 shows the general arrangement of the final design with two keel beams integrated in the baseline fuselage. They extend from the nose wheel to the main landing gear. Two keel beams in parallel have been chosen to provide a centre channel that can accommodate rods or wires of the control system. As shown in Fig. 7 both beams have a box cross-section with a height of 60 mm and a width of 50 mm throughout their length. They are made from 2 mm thick laminates of aramid fibre reinforced plastic (AFRP) which enclose a θ-6-Gel core. Again, for simplicity, a quasi-isotropic layup has been applied. AFRP has been chosen as skin material due to its high toughness and energy absorption capability. As the silicone material is incompressible this kind of design is expected to improve pre- and post-failure stability and thus postpone or prevent a complete collapse of the cockpit structure. Moreover, the keel beams are positioned underneath the seats in order to provide additional protection to the occupants similar to the design concepts presented in [2] and [12]. The only modifications necessary for the

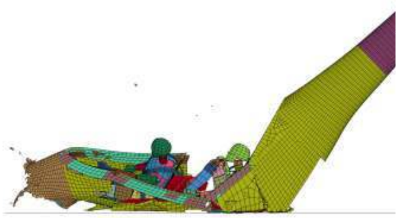


(a) $t = 0$ ms

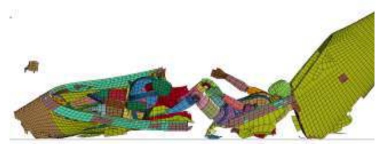
(b) $t = 36$ ms

(c) $t = 65$ ms

(d) $t = 105$ ms



(e) $t = 160$ ms



(f) $t = 250$ ms

Fig. 4: Crash sequence of the baseline model

keel beam integration are cut-outs in the two stick bulkheads. The gross mass of one keel beam including the AFRP shell as well as the θ-6 core is 6.85kg. For the θ-6-Gel the LS-DYNA material constitutive model MAT 181 is used in the simulation. It specifically accounts for the nonlinear stress-strain behavior and damping properties which have been determined by static and dynamic tests [7].

Crashworthiness improvements through θ-6-Gel keel beams

Parametric study

In order to assess the feasibility of the keel beam approach the influence on the crash behavior has been investigated for a number of different fuselage structures. These were established by varying three design parameters of the baseline model, which are shown in Table 3. The idea behind the skin thickness variation of the fuselage shell and the upper longerons is to cover various structural design concepts. The aim of altering the laminate thickness of the forward tail boom has been to examine the effect of preventing or triggering a premature tail boom failure on the crash behavior of the forward fuselage. Except for these modifications the fuselage remains the same and complies with

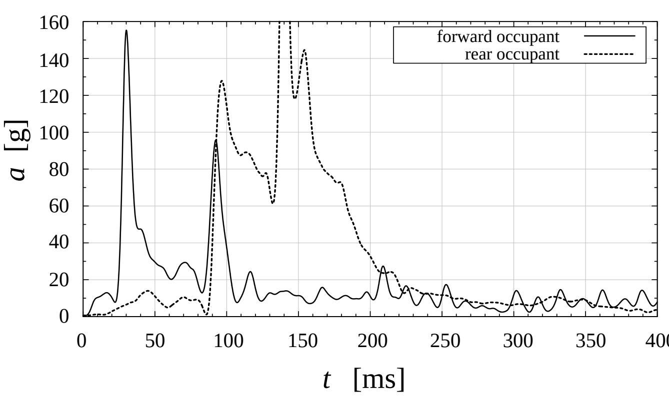


Fig. 5: Total hip accelerations at the forward and the rear occupant (baseline structure)

Table 3: Varied laminate thickness

Structural element	t_1 [mm]	t_2 [mm]	t_3 [mm]
Fuselage shell sandwich skin	0.5	1.0	2.0
Upper longeron sandwich skin	0.5	1.0	2.0
Forward tail boom laminate	2.0	4.0	—

the baseline structure according to Table 2.

The parameter variation results in 18 different structures, each of which has been investigated with and without keel beams, respectively. For clarity each model is labeled as follows:

M[klm]	model variant without keel beam
M[klm]KB	model variant with keel beam

The indices k, l and m denote the three laminate thicknesses t_i considered in the study and given in Table 3. They refer to the following structural elements:

$k \rightarrow$ index of the fuselage skin thickness
$l \rightarrow$ index of the upper longeron skin thickness
$m \rightarrow$ index of the forward tail boom thickness

For example, "M321KB" indicates a crash model with keel beam, having a fuselage skin thickness $t_3 = 2.0$ mm, an upper longeron skin thickness $t_2 = 1.0$ mm and a tail boom thickness $t_1 = 2.0$ mm. Depending on the variant, the total mass thus ranges from 528.5 kg (M111) to 592.63 kg (M332KB).

Assessment

The assessment of occupant safety is essentially based on the total acceleration

$$\begin{aligned} a(t) &= |\vec{a}(t)| \\ &= \sqrt{a_x(t)^2 + a_y(t)^2 + a_z(t)^2} \end{aligned}$$

at the centre hip node of the respective dummy. The severity of injuries is rated by an anthropological measure that expresses

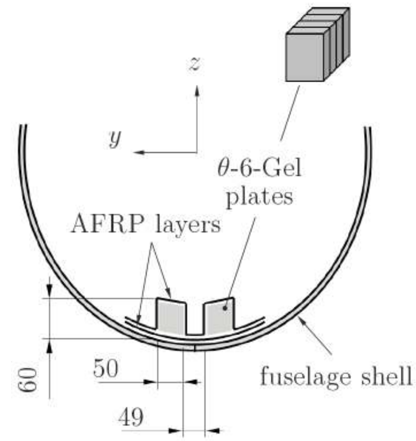


Fig. 7: Cockpit cross-section showing the keel beam integration concept (dimensions in mm**)**

the nodal acceleration history in terms of a scalar value. A typical example for such a measure is the so-called *Head Injury Criterion* (*HIC*) [13]:

$$HIC = \max\left[(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)^{\text{head}} dt\right)^{2.5}\right] \quad (1)$$

This index is determined by integrating the actual nodal acceleration $a(t)$ between time t_1 and t_2 which must be chosen to yield the maximum value. While equation (1) assumes certain units, namely acceleration in g and time in ms, the *HIC* itself has no units. It comprises not only the acceleration magnitude but also the duration, i.e. a short impulsive peak is not necessarily more severe than a moderate but long lasting acceleration. With regard to crash applications the time interval $(t_2 - t_1)$ is usually limited to 36 ms, which is denoted by HIC_{36}.

A similar methodology was chosen in this study to assess the spinal loading of the occupants. This proved to be necessary due to the lack of well established specific criteria. The applied criterion is designated IC_{36}^{hip} in order to show that it refers to the

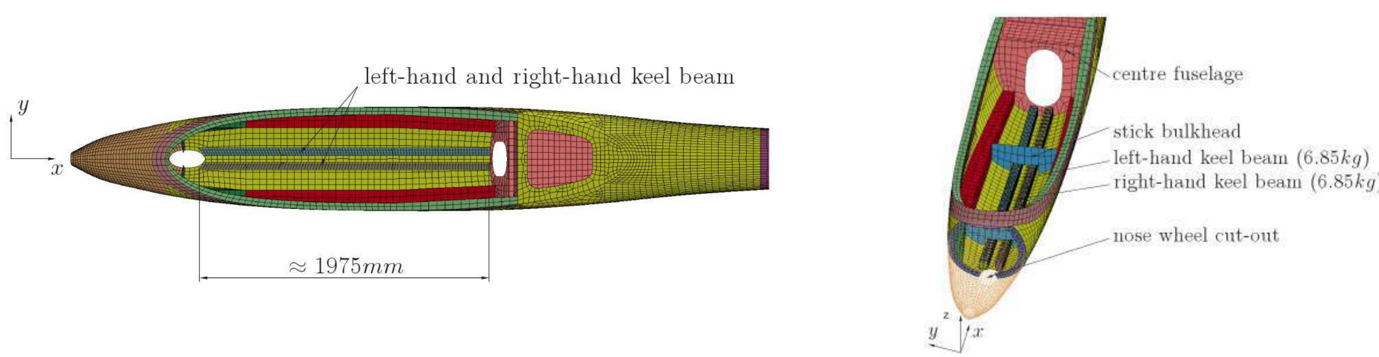


Fig. 6: Integration of two keel beams (seat shells are not shown)

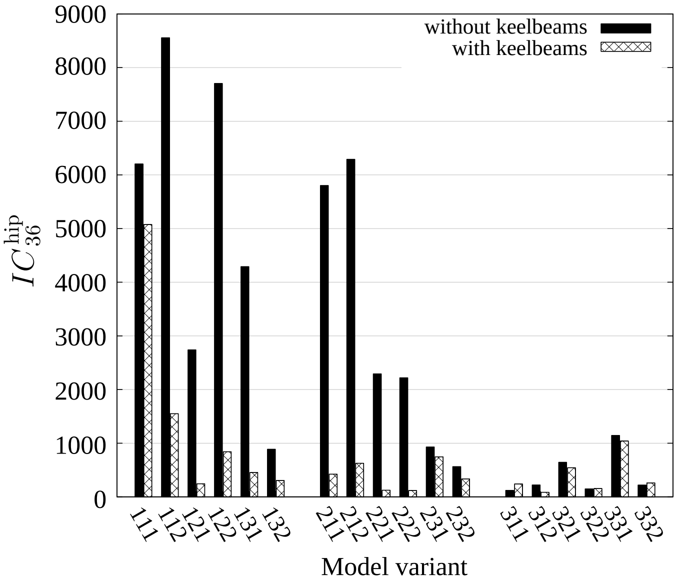


Fig. 8: Comparison of the rear occupant's IC_{36}^{hip}

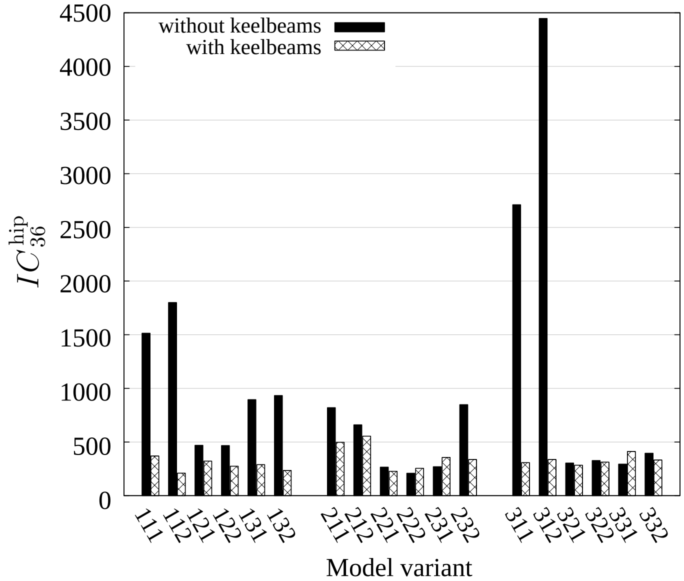


Fig. 9: Comparison of the forward occupant's IC_{36}^{hip}

hip acceleration. It is determined by:

$$IC_{36}^{\text{hip}} = \max\left[(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)^{\text{hip}} dt\right)^{2.5}\right]$$

$$\text{with } \; t_2 - t_1 \leq 36 \text{ ms} \tag{2}$$

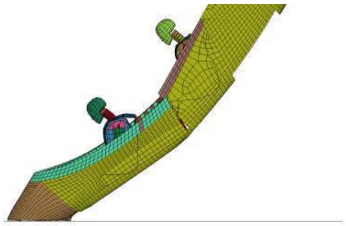
This approach has been assumed feasible, because the included weighting of acceleration and duration provides an adequate measure of the occupant injuries. In order to reduce numerical noise the acceleration history $a(t)$ has been low-pass filtered prior to the calculation of the IC_{36}^{hip}.

Figures 8 and 9 summarize the resulting values at the respective occupant for all variants investigated. As a major finding, the θ-6-Gel keel beams reduce the IC_{36}^{hip} in most cases. This is especially true for less stiff fuselage structures, represented by the models M1*xx* and M2*xx*. In 5 out of 18 cases the IC_{36}^{hip} decreases only for one occupant, whereas the other is exposed to higher accelerations. However, the IC_{36}^{hip} reduction gained is always of greater magnitude than any increase of this parameter. Also it affects the occupant with the higher load. Obviously, the proposed keel beam concept improves occupant safety considerably, at least within the scope of this study. In the following section two crucial structural variants, M112 and M312, are discussed in more detail in order to thoroughly examine the specific crash mechanisms of the keel beams.

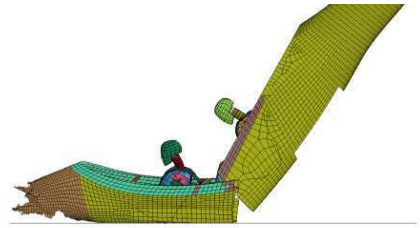
Model variant M112

This variant has relatively thin sandwich skins in the fuselage shell and the upper longerons but a relatively thick tail boom laminate. Figure 10 shows the crash behavior of this structure without keel beams. At $t = 38.5$ ms the fuselage shell as well as the upper longerons start to fail due to increasing bending loads. Damage growth separates the forward from the rear cockpit section. The forward part starts rotating and the crash front reaches the forward seat at $t = 90$ ms. The acceleration-time history of Fig. 11 indicates a distinct acceleration peak at this point. During the further course the energy absorption is almost entirely limited to the aft cockpit structure. Due to the loss of structural integrity the rear occupant hits the ground severely at $t = 130$ ms. Figure 12 reveals a rather high acceleration with a maximum IC_{36}^{hip} of 8555 which is the highest value within the scope of the parameter study.

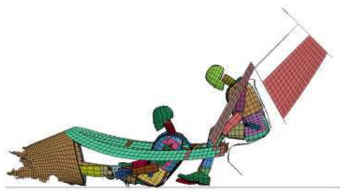
The crash sequence of this fuselage variant with keel beams (M112KB) is shown in Fig. 13. When the crash front approaches the keel beams at $t = 30$ ms the increased fuselage stiffness causes a more distinct rotation about the aircraft lateral axis compared to the version without keel beams. As a result the forward occupant experiences an increased acceleration as shown in Fig 11. After a similar fuselage failure at $t = 38.5$ ms the tough keel beams prevent the breakup of the cockpit section. At $t = 90$ ms they are being bent at the aft stick bulkhead. Since the θ-6-Gel is entirely encased the keel beam stiffness is maintained to some extent. This effect decreases the front seat accelerations observed at $t = 105$ ms. In the further course the keel beams delay the collapse of the aft survival space until they finally separate from the bottom fuselage shell. At $t = 135$ ms the rear occupant additionally benefits from the damping of the seat, owing to the θ-6-Gel material. The diagrams in Figs. 11 and 12 clearly show that the total acceleration of both occupants is significantly reduced by adding the keel beams.



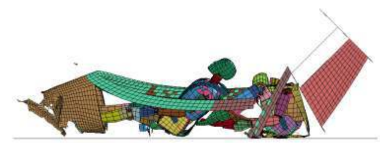
(a) $t = 38.5$ ms



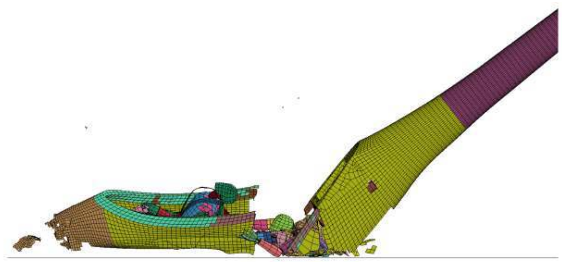
(b) $t = 90$ ms



(c) $t = 90$ ms



(d) $t = 130$ ms



(e) $t = 190$ ms

Fig. 10: Crash sequence of variant M112. Fuselage shell and consoles are not shown in (c) and (d).

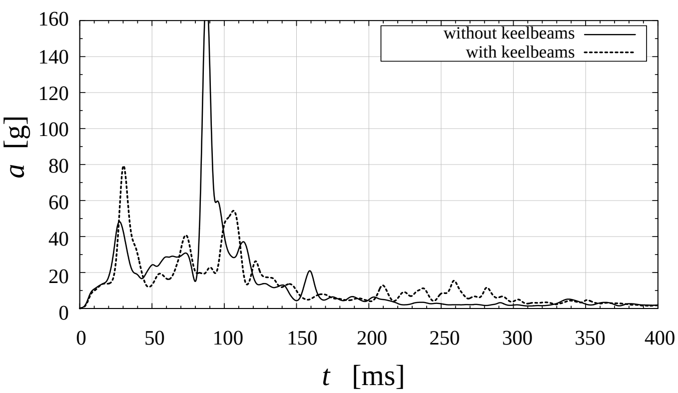


Fig. 11: Forward occupant acceleration (variant M112)

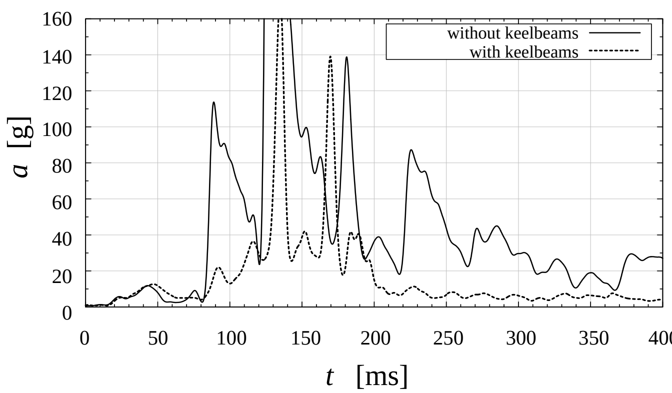
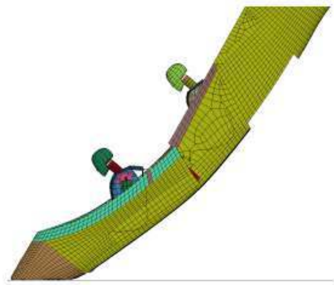


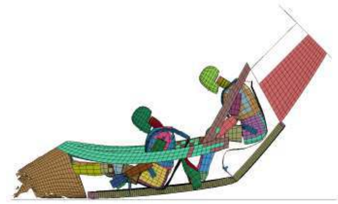
Fig. 12: Rear occupant acceleration (variant M112)

Model variant M312

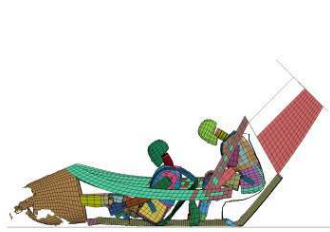
The second model to be discussed has a stiff fuselage shell, thin upper longerons and a stiff tail boom. Within the parameter study this variant yields the highest IC_{36}^{hip} for the forward occupant. Through the introduction of keel beams this parameter can be reduced considerably from 4447 to 336. Figure 14 depicts the crash sequence of the fuselage without keel beams. At $t = 42$ ms the upper longerons start to fail close to the front seat position. Due to the early collapse of the nose section the forward occupant experiences high accelerations when his seat impacts the ground at $t = 78$ ms. The acceleration-time history in Fig. 15 reaches a peak of 275 g at this point. Due to the load direction



(a) $t = 38.5$ ms

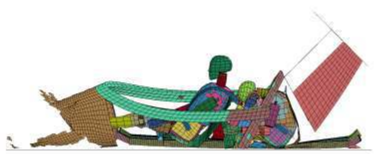


(b) $t = 90$ ms

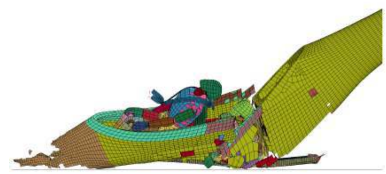


(c) $t = 105$ ms

(d) $t = 111$ ms



(e) $t = 135$ ms



(f) $t = 230$ ms

Fig. 13: Crash sequence of variant M112KB. Fuselage shell and consoles are not shown in (b), (c) and (e).

severe spinal injuries are most likely to occur in this case. In contrast to the variant *M112*, the cockpit structure collapses at the front seat position, even though the fuselage is stiffer. The acceleration of the occupant in the rear seat is relatively low, because the stiff tail boom maintains its integrity and thus retards the fuselage rotation.

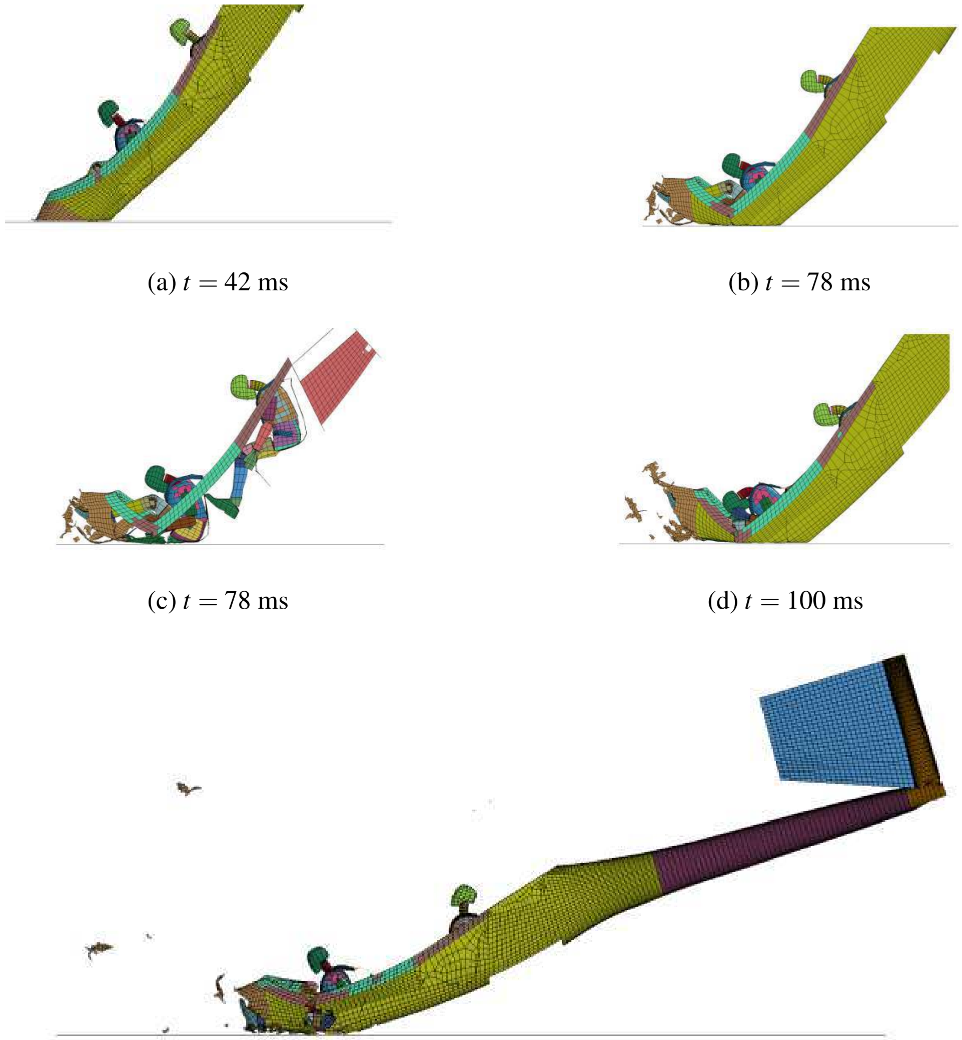
Figure 16 depicts the crash scenario with keel beams installed (M312KB). To provide a better view on the occupants the fuselage shell as well as the consoles are not shown. The acceleration-time history presented in Fig. 15 reveals an almost identical crash behavior until the crash front reaches the keel beams at $t = 38$ ms. The first peak in acceleration is caused by the ground impact of the pilot's feet. At time $t = 60$ ms the fuselage structure starts to fail at the forward stick bulkhead. Compared to the version without keel beams the cockpit does not collapse completely. The keel beams support the forward seat and delay its ultimate impact until $t \approx 83$ ms. Also, the maximum occupant acceleration is reduced from 275 g to approximately 60 g.

These significant improvements of the crash behavior are caused by the following effects:

- enhanced energy absorption of the fuselage nose section due to an increased cockpit stiffness
- early beginning of seat acceleration prior to its ultimate ground impact
- additional seat damping through the θ-6-Gel core when the fuselage bottom hits the ground

Discussion of the general feasibility

The 36 different fuselage structures investigated may only represent a small fraction of possible crash scenarios. Depending on soil properties, impact velocities, material properties etc., crash sequences are manifold in reality. However, in this first approach it could be shown that the keel beams considered here improve occupant safety in every case examined which substantiates the general feasibility to some extent. Due to the reinforcement of the entire survival space this design approach is expected to improve crashworthiness throughout a wide variety of crash situations. The keel beams are particularly considered suitable for those glider types having a rather short nose section where dedicated crash elements can not be applied. However, there are also shortcomings. For example, the keel beams have to follow the fuselage contour and are thus type-specific. Also,



(a) $t = 42$ ms (b) $t = 78$ ms

(c) $t = 78$ ms (d) $t = 100$ ms

(e) $t = 230$ ms

Fig. 14: Crash sequence of variant M312. Fuselage shell and consoles are not shown in (c).

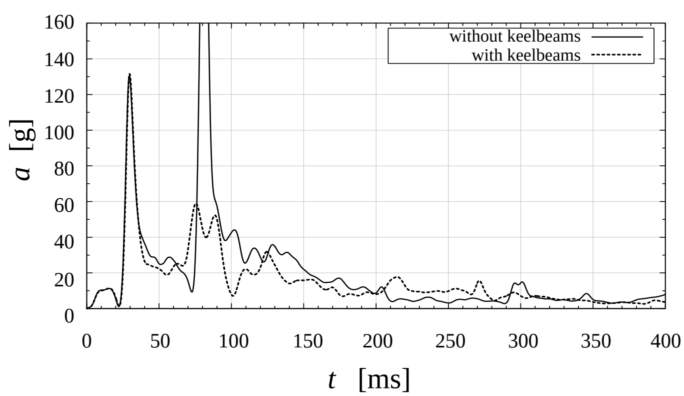


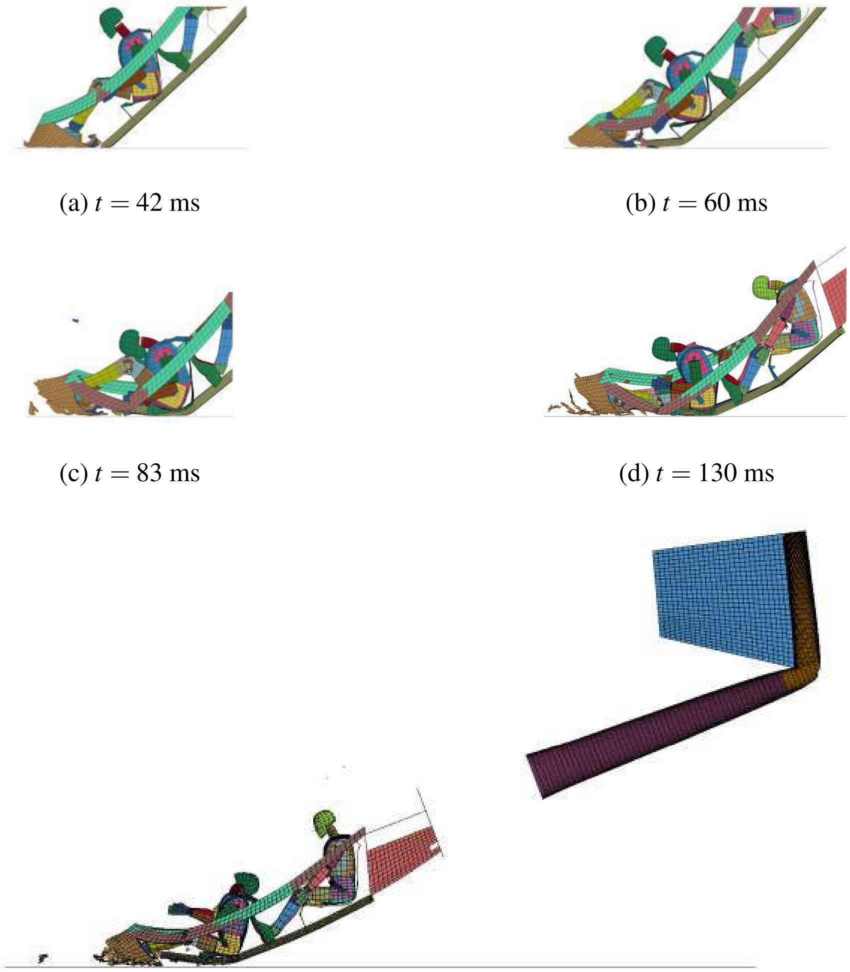
Fig. 15: Forward occupant acceleration (variant M312)

modern sailplanes usually offer very little space for the integration of distinct keel beams under the seats. Hence, the proposed design is not applicable as a retrofit solution.

Summary

A study was conducted to find new structural design solutions that improve occupant safety in sailplanes constructed of carbon fiber composites. The study was motivated by the tightened crashworthiness requirements released with the latest revision of EASA CS-22 in 2008.

The fundamental idea of the research was to exploit the excellent shock absorbing and damping characteristics of silicone rubber materials. Therefore, a screening has been carried out in order to identify the most appropriate material for the particular requirements. Based on the obtained results a silicone rubber



(a) $t = 42$ ms

(b) $t = 60$ ms

(c) $t = 83$ ms

(d) $t = 130$ ms

(e) $t = 213$ ms

Fig. 16: Crash sequence of variant M312KB. Fuselage shell and consoles are not shown.

called θ-6-Gel has been chosen as the basic energy absorbing material.

The primary tool used to evaluate the effect of different fuselage design concepts on the crashworthiness of sailplanes has been a parametric finite element model for numerical crash simulations. This model comprises the load-bearing structural parts of a generic sailplane fuselage as well as two 50th percentile dummies in the cockpit. These dummies allow for a decent investigation of ground impact effects on the occupants. Evaluation criteria have been the total acceleration at the hip of the pilots as well as the survival space left for the occupants after the crash.

A feasibility study revealed that the most promising structural design concept is to reinforce the lower cockpit shell by keel beams filled with the θ-6-Gel material. These structural elements have a quadrilateral cross-section and are made by wrapping the silicone core in layers of AFRP fabric. Thus, the enclosed incompressible core material enhances the bending stiffness of the beams which results in an improved survival space integrity. Since the keel beams are positioned underneath the seats, they also provide direct suspension and damping when the crash front reaches positions of the occupants. For the further investigation two parallel keel beams have been adopted in order to provide a central channel to accommodate rods and wires of the control system.

The selected structural concept has been evaluated regarding its capability to improve occupant safety by numerous crash simulations. As crash scenario a ground impact with a flight path angle of -45° and a side slip of 5° has been assumed. Several configurations of the reinforced fuselage designs have been investigated and compared to the crash behavior of the respective fuselage without keel beams. The effect of the design modifications on occupant safety has been assessed by using an average acceleration index. This factor characterizes the forces occurring at the hip of the dummies and can be regarded as a measure for the severity of the injuries suffered.

The numerical study proved that occupant safety can be enhanced by reinforcing the forward fuselage by keel beams with silicone cores. Particularly, for the most severe crash cases the application of keel beams offers a considerable reduction of the impact loads acting on the occupants. Due to these findings it can be concluded that the proposed structural design concept of the forward fuselage is a feasible and promising approach to improve the crashworthiness of sailplanes.

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