Preliminary Study of Energy Absorbing Nose Structures for Pilot Protection in an Emergency Landing

Paolo Astori
Politecnico di Milano
20156 Milano, Italy
Paolo.Astori@Polimi.it

and

Vittorio Pajno
20077 Melegnano, Italy
Vittorio.Pajno@Fastwebnet.it

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Abstract

Glider accident survivability can be increased with proper crashworthy design criteria. This study starts by investigating possible ground crash scenarios to define some representative crash conditions for potentially survivable accidents. Then, two numerical multi-body models are set-up for a reference rigid glider structure and a crashworthy structure is obtained by modification of the previous one. The models, that include the occupant model, are used to analyze the potential reduction of injury parameters that can be obtained by using a collapsible, or energy absorbing, structure in the front part of the aircraft. Finally, a possible design solution is outlined to match the crashworthy mechanical properties indicated by the numerical analysis.

Introduction

For general aviation, transport and rotary wing aircraft, the corresponding regulations EASA-CS 23, 25, 27 and 29[1, 2, 3, 4] consider two dynamic tests on cabin, seat and restraint systems to assess the occupants' safety in case of an emergency landing. The test conditions are representative of crash landings and derive from years of accident investigations.

Analogous investigations for the definition of glider crashworthiness have been carried out in the last decades and the most significant result is a series of amendments to EASA-CS 22[5], in those sections concerning emergency landing conditions. EASA–CS 22 rules consider a static load applied to the front part of the glider fuselage, at the keel, inclined at 45° to the horizontal construction line. Of course, the indication of a static load to represent an emergency landing condition is drawn by the fact that dynamic experimental testing would exceed typical glider design and manufacturing costs.

Moreover, the updated rules define the necessity of constructing a forward collapsible part, and possibly energy absorbing seats, to reduce occupant loads, as well as a stiff protective structural shell in the cockpit area to maintain a livable volume around the occupants.

This preliminary research work at Politecnico di Milano is an effort to discuss possible solutions to increase glider crashworthiness following these guidelines.

The research can be divided into three sections: first the most significant impact conditions are estimated on the basis of a literature review and from considerations related to the aircraft aerodynamic characteristics; in the second section numerical models of the glider and occupant are set up for dynamic analysis of ground impacts; finally some structural considerations are proposed and verified by numerical analysis, leading theoretically to significant reductions of pilot's injury risks.

Crash scenarios

Actual glider cockpit construction techniques derive from the EASA–CS 22 rules and, in summary, can be described as a set of shell structures stiffened longitudinally in order to build up a relatively collapsible structure. Examinations of gliders wrecked by hitting mountainous soil are important in order to determine not only the possible causes of the accident but also to better define the impact angle with the soil[6].

The examination of the glider dynamics before and after the impact may help to define the physical consequences on the pilot and, therefore, suggest remedies to limit injuries. Two principal types of inadvertent maneuvers are frequently observed and may lead to severe impact conditions: the spiral dive and the spin, both consequences of a human error due to wrong actions on the controls. Based on a series of hypotheses and assumptions on typical performance characteristics of standard gliders at a flying weight of 380 kg, and confirmed by discussions with pilots, a representative impact condition may occur with a trajectory at an angle of 35° with respect to the ground, the glider being aligned with the trajectory and at a velocity of 60 km/h. Fig. 1 is a general representation of the scenario, where α is the trajectory angle with respect to the ground and β the aircraft attitude with respect to the ground.

Another important research work on this subject[7], in which crashworthy solutions are analyzed, leads to four significant impact conditions on the basis of accident investigations; these impact conditions are summarized in Table 1, cases 1 to 4, together with the reference case mentioned above and here indicated as case 0.

Case 4 was originally indicated by the author at 28 m/s, which appeared to be a too severe crash condition, with limited possibilities of survivability using conventional crashworthy solutions.

In case 3 the glider also had a 10° yaw angle that gave a non-symmetrical impact; a possible consequence of a wing-tip ground contact prior to impact.

The kinetic energy associated with the normal component of velocity with respect to ground, v_n, should be representative of the impact severity: this criterion is, in fact, commonly used to indicate the severity of vehicle impacts against road-side safety barriers[8]. For a 380 kg glider the results are reported in Table 1.

Case 2 has a relatively low impact severity; cases 0 and 3 are comparable from the energy point of view because their difference in speed is partially compensated by the difference in angle; case 4 has a very much higher severity level.

In this research, cases 0, 3 and 4 are studied. In all cases the glider is considered aligned with its trajectory ($\beta = -\alpha$) and has no yaw angle. This symmetry of case 3 simplifies the dynamics of both the aircraft and occupant, allowing a better understanding of the basic crash response at this first stage of the investigation. Case 4 is here considered with a 19.5 m/s impact velocity, as finally tested by Sperber[7].

Numerical models

A multi-body approach is used for the analysis of the crash scenarios, using VEDYAC[9], developed at Politecnico di Milano and used in a wide variety of crashworthiness analyses that include full-scale structures[10, 11], structural components[12] and cabin safety[13, 14].

As the reference glider, a V1/2 *Rondine* is considered, showed in Fig. 2 in picturesque flight.

The reference glider model is prepared starting from a detailed finite element model of the aircraft structure; a twin pilot version of this model has been developed as an MSc thesis[15] at Politecnico di Milano in 2006, but it was a completely linear model used for stress analysis under the EASA-CS 22 nose static-load condition.

The finite element model, then, was discretised into a lumped mass model (Fig. 3a) made of rigid bodies spread along the fuselage line and the wing span; masses and moments of inertia were derived from a mass distribution file provided by the designer. The rigid bodies are connected by flexional nodes whose stiffness has been computed as a function of the local characteristics of the structure cross-section, in terms of geometry and lamination of the composite layers. This model is usually referred to as *stick model*. Fig. 3b shows a detail of the modeling technique, where contiguous rigid bodies can be seen easily, together with their mutual connections and polyhedral volumes used for contact load calculation.

This reference model, then, has a global mass matrix and a global stiffness matrix that approximately correspond to the glider matrices.

The crashworthy glider model is a stretched version of the previous one, with an energy absorbing structure integrated into the front areas (Figs. 4a and 4b). The complete nose is crashworthy for 300 mm: this should provide load attenuation during impacts at high angles with respect to the ground. The absorbing system, then, is extended in the lower section of the vehicle from the nose for about 850 mm aft, to provide load attenuation when impact angles with respect to the ground are smaller.

The front area of the crashworthy model is more detailed, in the sense that additional rigid bodies and connecting elements are locally spread to account for local deformation during ground contact. Nevertheless, in accordance with the crashworthiness guidelines[5, 18], the cabin area is stiff and capable of maintaining a survivable volume around the occupant.

The crash or energy absorbing structure is actually made of five sections, as indicated in Fig. 4b: two sections are located in the nose and three sections are located in the lower front area from the nose to the pedal area. This splitting of the crash structure into a set of different blocks is necessary to better characterize the collapsing structure with different local properties according to its location.

The occupant model represents a Hybrid II anthropomorphic test dummy, normally used for aircraft impact testing, and has been validated vs. experimental tests in past years. The forces acting on the occupant come from its interaction with all the cabin interiors and a four-point safety-belt system.

Each belt segment is a cable that connects one point fixed on the glider to one point fixed on the dummy. This is a rough representation of an actual safety-belt system, principally because the sliding of the belt on the body surfaces cannot be properly represented. Nevertheless, the choice of suitable attachment points on the glider structural model and the calibration of the force-extension function led to an acceptable belt model that includes the dummy flesh deflection and provides a low tensile response when sliding of the belt segment would occur on the body.

The ground is a flat surface with a contact load/unload function tuned to represent a relatively soft soil, with some ploughing effect. The normal and tangent contact forces, F_{CN} and F_{CT} respectively, are defined as follows:

$$F_{CN} = f(\Delta V) A_{CN}$$
$$F_{CT} = F_{CN}\mu + \xi A_{CT} v_t^2$$

where $f(\Delta V)$ describes a function of the glider penetration volume into the soil, A_{CN} the contact surface, μ the Coulomb friction coefficient, ξ the ploughing coefficient, A_{CT} the ploughing surface normal to the trajectory and v_t the tangent velocity. The normal force, then, is a function of the penetration and surface extension; the tangent force is a function of the Coulomb friction and ploughing effect, the latter being proportional to the front ploughing area and the square of the velocity; the ploughing force function derives its formulation from the exchange of momentum between the rigid airplane structure and the soft soil, that responds approximately like a fluid. The calibration of the parameters in the functions is based on experience of previous work by the authors and other VEDYAC users. As a matter of fact, the soil response changes with composition, humidity and compaction and, therefore, an average setting is used in the present model.

The multi-body technique is well consolidated to analyze the response of large structures under high-load conditions. Its main advantage is the computational cost: because the model is eventually made of a few tens of rigid bodies, a complete simulation takes minutes on a modern PC. This short time allows one to perform a relatively high number of analyses with different design variables and search for optimum solutions. On the other hand, the model is rough if compared to a finite-element model and does not provide the same detailed level of results: the complete model of glider, occupant and ground is made of 44 rigid bodies (of which 27 are for the glider), 70 connection elements and 95 contact volumes, described in total by 665 nodes.

Choice of significant measurements and limits

The analysis allows one to trace the global dynamics of the impact, including occupant's biomechanics, and to take some measurements of interest: the type of results that can be read are the complete dynamics of the rigid bodies, the internal reactions of the connecting elements and the contact forces.

Four measurements were considered as cabin injury parameters to assess the vehicle crashworthiness: lumbar spine load of the occupant, the resultant acceleration of the thorax, shoulder safety-belts load and aircraft centre of gravity acceleration.

The lumbar spine load is a parameter of utmost importance in an emergency landing condition. Its measurement is required by the regulations during seat and restraint system certification tests[1, 2, 3, 4]. The limit is fixed at 6670 N for a 50th percentile male dummy. As a matter of fact, this measurement is important because an injury at the lumbar level may result in difficulties to abandon the vehicle after a crash, which is an important requirement in the above mentioned regulations to reduce the risk of burn injuries from a post-crash fire. Fire is not the case for a glider but, in any case, a vertebral fracture at lumbar level is likely to produce a permanent disability and has high social costs.

The thorax resultant acceleration is a measurement of interest in automotive crash tests, where accelerations have important components along the vehicle longitudinal axis: this well represents the load condition considered for this research. High accelerations result in internal organ lacerations and death. The limit was fixed at 60g for a duration of 3ms[16, 17] even if, at present, more sophisticated criteria are used for the evaluation of automotive chest injuries.

Shoulder belt tensile loads are still a measurement required by the regulations[1, 2, 3, 4], being correlated to chest injuries. The limit in one segment is 7.7kN but the total load of the dual shoulder strap system must not exceed 8.8 kN.

Finally, the aircraft center of gravity acceleration is reported. This is not directly an injury criterion but, nevertheless, the occupant dynamics are correlated to the aircraft dynamics and, then, the vehicle acceleration can be considered a rough indicator of the level of protection.

Comparisons of the measurements are made between the original version of the glider, considered rigid, and the version equipped with the crash energy-absorption system.

Results of the numerical analyses

The reference rigid model and the crashworthy version are analyzed under the three above mentioned impact conditions. All the calculations were done for a time of 0.5s, so that the main transients are ended, the secondary ground impacts have occurred and the overall dynamics of the glider were clearly determined.

A series of analyses were first performed with the crashworthy glider to find a suitable characterization of the mechanical properties of the energy-absorbing structure, and to obtain a significant reduction of the cabin injury parameters. As design variables of this parameter study, the plastic responses or constant load levels of the five energy-absorbing areas were chosen, their elastic domain being limited and of secondary importance for energy absorption.

Figures 5 and 6 show the dynamics of the glider and occupant during the cases 3 (angle = 30° / speed = 21 m/s) and 4 (angle = 45° / speed = 19.5 m/s) impact conditions. In case 4 the aircraft is modeled in its initial conditions leveled with respect to the horizon and impacting a ground at a slope of 45°.

The overall dynamics are not very different from the visual point of view. The local deformation of the energy-absorbing nose structure can be noticed in both cases 3 and 4. In case 0, which is not reported here because it is less relevant than the others, the deformation also was noticed but to a lesser extent.

Comparison of the numerical results

The target functions are, of course, the four measurements described in a previous section, i.e. the occupant lumbar spine load, chest resultant acceleration, total shoulder belt tension and glider resultant acceleration. They are shown, respectively, for the three impact cases in Figs. 7 to 18.

In all cases, a considerable reduction of the injury parameters is observed for the crashworthy glider with respect to the rigid version taken as the reference configuration, with the exception of the aircraft centre of gravity resultant acceleration shown in Fig. 18 and related to case 4. Here a 37g peak is measured in the crashworthy glider analysis, compared to a more regular 30g acceleration measured in the reference configuration. One possibility to explain this deviation is some irregularity in the contact algorithm due to the important deformation and twisting of some faces of the polyhedrons describing the collapsible sections under the front area. This may lead to spikes in the contact forces and, then, to an increase of the measured aircraft acceleration. Nevertheless, because they have a limited time duration, they do not lead to a significant increase in the other parameters, i.e. lumbar spine load, thorax acceleration and shoulder-belt tension.

The load levels of the five different collapsible sections in the front area have been calibrated to obtain an extended deformation in the most severe impact condition, or case 4, so that in this case a more important reduction of the cabin injury parameters is obtained.

Each collapsible section has a maximum allowable deformation before bottoming; after this limit an increase of overall accelerations is expected. In general the best load attenuation in the cabin is obtained by allowing the complete deformation of the crashworthy volumes with no bottoming.

In all the graphs, the limits indicated by the regulations are plotted, with exception of the vehicle acceleration because no limits were prescribed.

The lumbar spine limit of 6.67kN is exceeded in the rigid glider for cases 3 and 4 (in the last condition a peak higher than 9kN is reached). The introduction of the crash structure is able to reduce the peak within the limit in case 3, but still in case 4 a value of 7.2 kN is reached.

The chest resultant acceleration limit of 60g is never exceeded and, in all cases, the effect of the deformable structure is to reduce the peaks.

The tensile load limit of 8.8kN of the two shoulder belts is exceeded in the analyses with both the rigid and, marginally, the crashworthy glider in impact case 4.

A delay may be noticed between the chest acceleration and the belt tensile load: this is due to the fact that the chest acceleration is first due to the contact force between the occupant and the seat and later on, when the upper body starts leaning forward, to the shoulder belt tensioning.

In cases 0 and 3 the aircraft cg and dummy chest acceleration show secondary peaks between 0.28 and 0.5s. They are due to the impact of the rear fuselage with the ground and do not introduce a significant increase of the lumbar spine load and seat belt tensions because their resultant is mainly directed along the yaw axis direction. Their role from the injury point of view, then, will be considered of minor interest in this paper.

Conceptual design of the crashworthy area

The introduction of a crash structure in the front part of the aircraft may be obtained by inserting collapsible volumes of material, softening the lamination where the collapsible volumes are inserted and reinforcing the lamination in the adjacent areas.

There are different solutions for collapsible or crushable volumes. The most effective, from the cost/efficiency point of view, is honeycomb of a suitable density. Use of low density aluminum foams may be more efficient but more expensive.

A solution is outlined in Fig. 19. The collapsible area is located in the front lower section of the structure. The lower volumes are involved principally during low-angle impacts with the ground, because the contact is localized in this area. The nose is principally involved in high-angle impacts. The energy-absorbing area is extended for approximately 850 mm from the nose to the lower pedal area. Here the capability to absorb energy with a relatively constant load should be extended for 100 – 150 mm along the aircraft yaw axis to provide enough protection during low-angle impacts. According to the numerical results obtained so far, this might be accomplished by a 25kg/m^3 density honeycomb structure with cells size around 13mm, oriented along the yaw axis. The complete nose, including its upper section, should be crashworthy for an extension of around 300mm along the aircraft roll axis, to reduce the longitudinal accelerations during impacts at high angles. In this case, a higher density honeycomb is suggested by the numerical analyses, e.g. a 35kg/m^3 system, same cells size as before, but oriented along the roll axis. Of course, the indicated length of 300mm is only a *first suggestion* and may be increased for higher energy-absorbing capabilities.

Note, Epoxy resin should be used with all the following laminations.

The area where the collapsible volumes are inserted should have a skin with a thin lamination, for instance five layers of glass fiber (E) balanced fabric as follows:

- 1st 160g/m^2 +45°/-45°;
- 2nd 290g/m^2 0°/90°;
- 3rd 290g/m^2 +45°/-45°;
- 4th 290g/m^2 0°/90°;
- 5th 290g/m^2 +45°/-45°.

In this way, it will scarcely contribute to the strength, and energy absorption will be mainly accomplished by the honeycomb.

The other area, next to the collapsible area and around the cockpit, should have a skin with a reinforced sandwich lamination, suggested as follows:

- 5 external layers as previously indicated;
- 6 mm 360g/m^2 closed cell foam core material;
- 6th 290g/m^2 0°/90°;
- 7th 290g/m^2 +45°/-45°;
- 8th 290g/m^2 0°/90°;
- 9th 290g/m^2 +45°/-45°.

This should take over the load coming from the impacted area and transfer it without collapsing, thereby maintaining the integrity of the cockpit and protecting the occupant from a volume reduction.

A possible alternative solution, in place of the collapsible volume elements, is a more suitable and crash oriented lamination. This is an efficient solution adopted in racing car energy-absorbing noses, where actually the impact condition is only frontal and, then, the nose failure pattern and response are more predictable. An application of this solution to the glider case may require some longer experimental testing for a final calibration, if compared to the honeycomb insertion whose mechanical characteristics and response are better determined.

Conclusions and future developments

This preliminary research suggests that the introduction of energy-absorbing materials and structures in the front part of a glider may improve considerably the structural crashworthiness. Table 2 summarizes the results achieved, showing the percent of reductions (and, in one case, of increase) of the injury parameters that have been chosen for this research. In the table, the calculation of the variation in the centre of gravity acceleration is done before 0.2s, i.e. before the acceleration peaks occurring during tail boom ground impact.

The introduction of an energy-absorbing structure does not seem to be a difficult challenge for the designer: a suitable lamination of the composite layers and the insertion of collapsible volumes (e.g. honeycomb), followed by a reinforcement of the surrounding areas, should be dimensioned easily to match the failure and strength requirements.

Of course, the results obtained so far must be considered preliminary and indicative only: even if the anthropomorphic dummy model and safety-belt system are well validated, further experimental activity is needed for validation of the aircraft structural part. Both analytical and experimental activities are planned for future development of this research. Therefore, the fabric layers and honeycomb characteristics previously indicated should be considered as rough indications and not as guidelines.

The analytical development in the program is, first of all, a refinement of the model in the impacting area. This should give better indications of the load levels required to properly tune the collapsible volumes. Additional energy-absorbing strategies can be analyzed: the seat pan can be modified to include a deformable system to provide further lumbar spine protection (whose load in case 4 impact conditions could not be brought under the limit indicated by the regulations) and the shoulder safety-belts can be equipped with load limiters, to reduce the tensile loads (that also exceeded the limits in case 4).

As an example, in Fig. 20, the further load attenuation in lumbar spine is shown when an energy absorbing seat is installed, with a stroke of 100 mm (along the aircraft roll axis) activated at a constant load of 11 kN. In Fig. 21 the effect of a shoulder belt load limiter is shown with a stroke of 50 mm and activation load of 3.7 kN for each strap. Both results have been obtained for the case 4 impact condition.

Future experimental activity should consist of static and dynamic testing on specimens of representative cross sections of the structure, aimed at calibrating the collapsible volume and laminations to better match with the indications outlined by the numerical analysis parameter study.

Eventually an impact test of an extended section of the structure, including the cockpit area, seat and anthropomorphic dummy, should be programmed for final validation of the numerical model.

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Table 1
Most significant impact conditions

	Case 0	Case 1	Case 2	Case 3	Case 4
Trajectory angle with resp. to ground α, °, + downward	35	29	10	30	45
Glider attitude with resp. to ground β, °, + nose up	-35	10	-10	-30	-45
Velocity along trajectory, m/s	16.7	16	25	21	19.5
Kinetic energy associated to total velocity, kJ	53	48.6	118.7	83.8	72.2
Kinetic energy associated to normal velocity v_n, kJ	17.4	11.4	3.6	20.9	36.1

Table 2
Benefit of a crash structure introduction: percent of reduction (-) and increase (+) of injury parameters

	Lumbar spine load	Chest accel.	Shoulder belt load	Aircraft CoG accel.
Case 0	-18 %	-19 %	-16 %	0 %
Case 3	-15 %	-16 %	-14 %	-6 %
Case 4	-19 %	-26 %	-9 %	+23 %

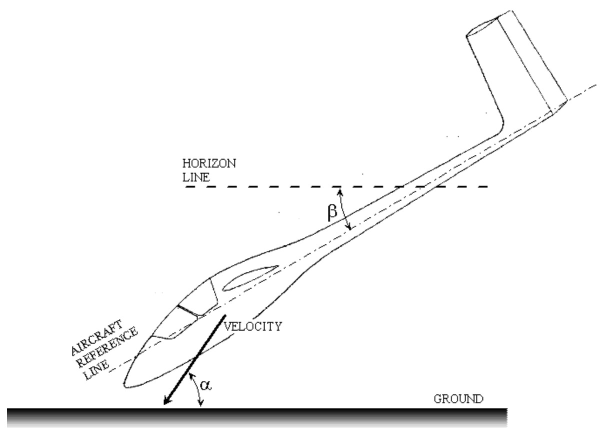


Figure 1 Reference crash scenario

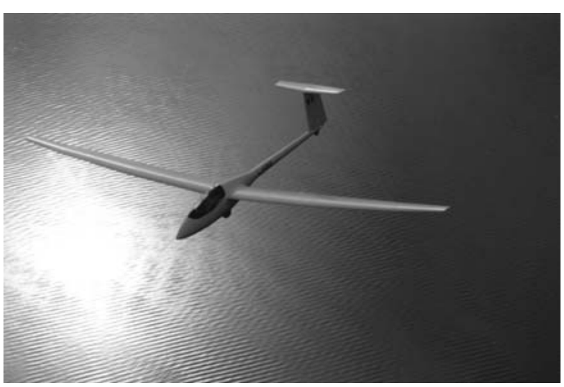
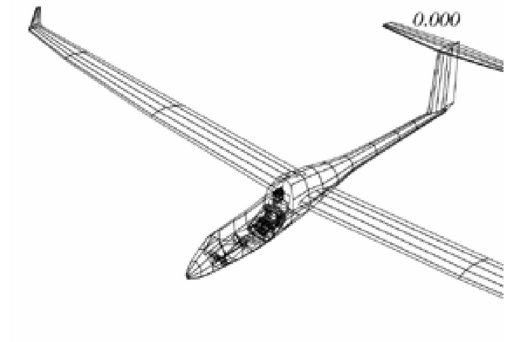


Figure 2 V1/2 Rondine



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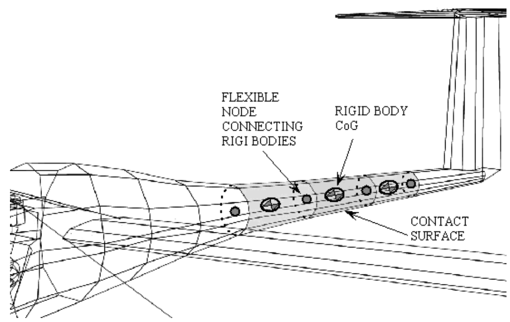
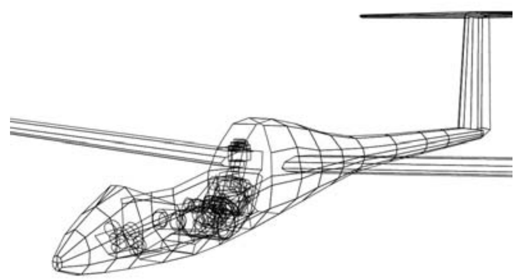


b

Figure 3 **a** Multi-body model obtained from the finite element model, **b** detail.



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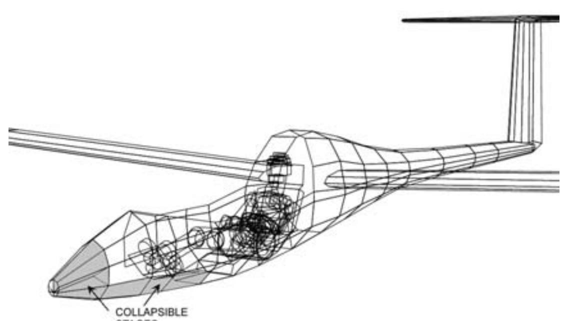

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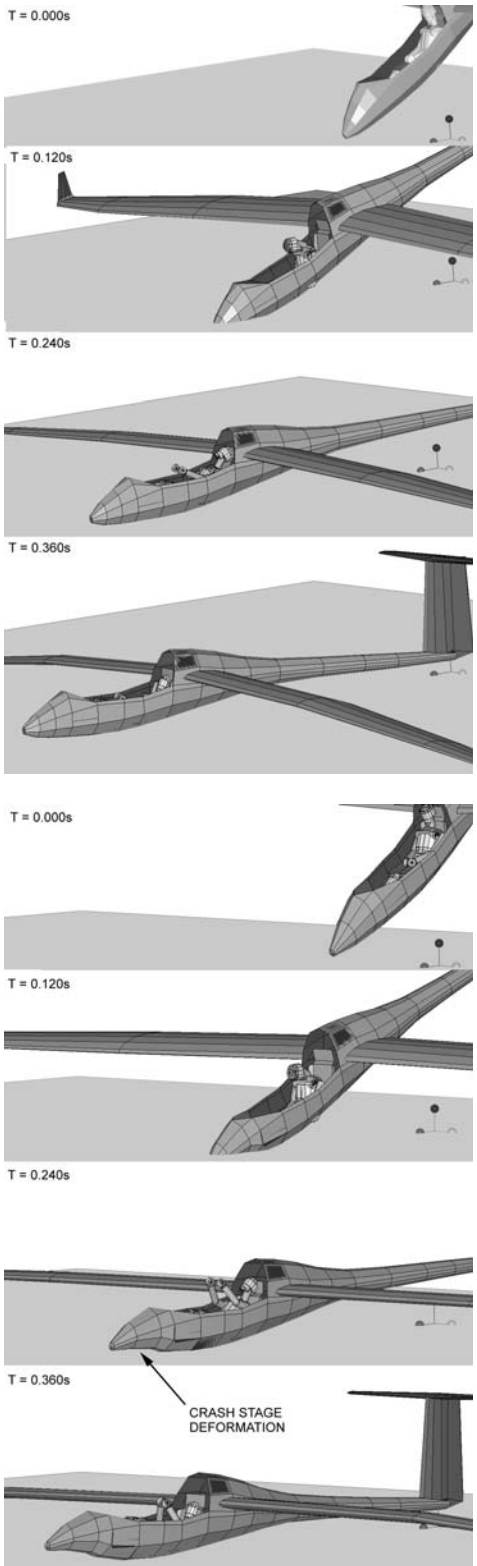
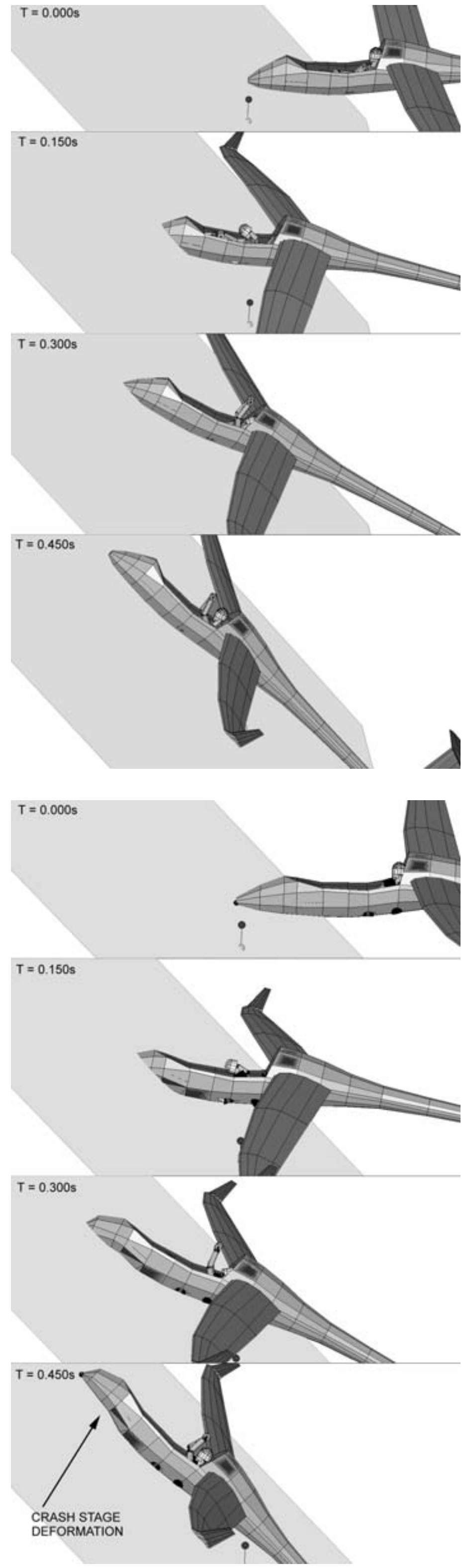
Figure 4 **a** Reference rigid glider, **b** crashworthy glider



a

b

Figure 5 Crash sequence in Case 3 for **a** rigid glider and **b** reference glider



a

b

Figure 6 Crash sequence in Case 4 for **a** rigid glider and **b** reference glider

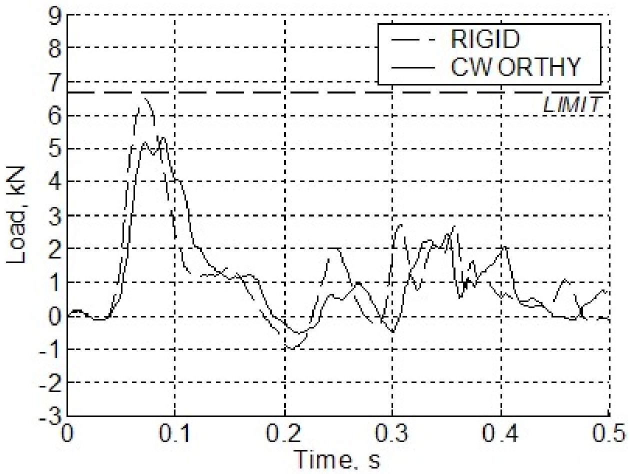


Figure 7 Case 0, lumbar spine load

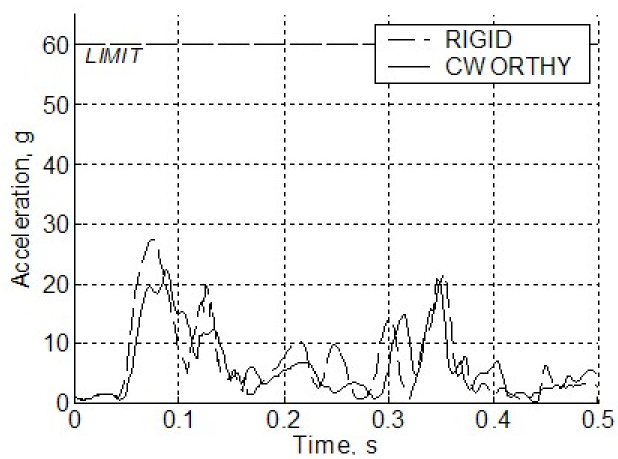


Figure 8 Case 0, chest resultant acceleration

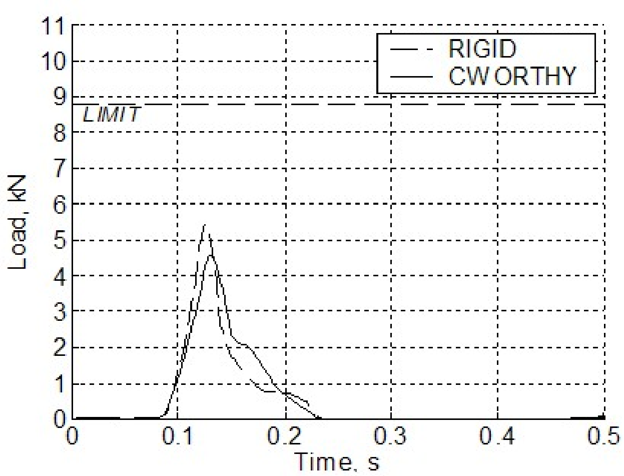


Figure 9 Case 0, total shoulder belt load

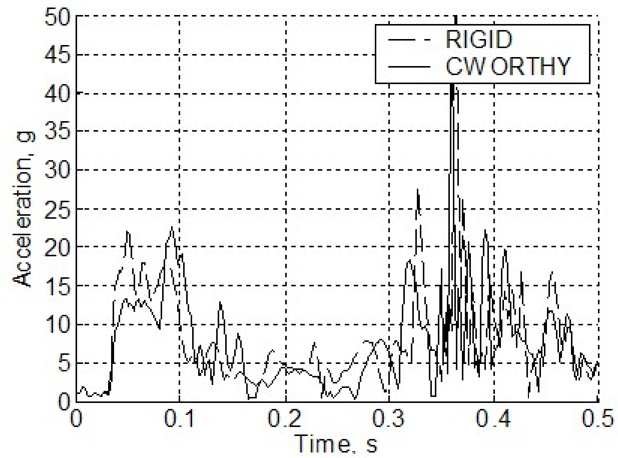


Figure 10 Case 0, aircraft CG resultant acceleration

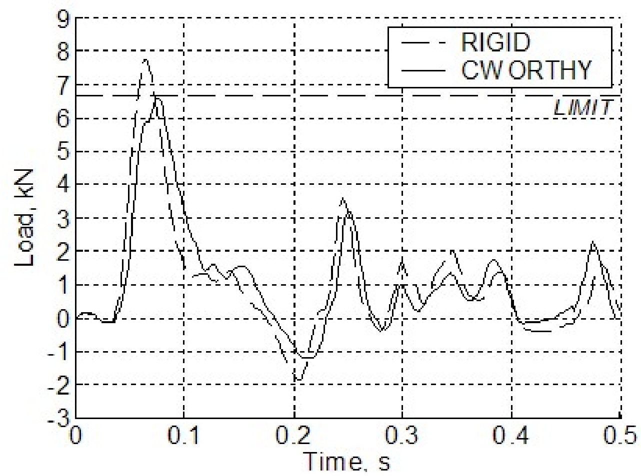


Figure 11 Case 3, lumbar spine load

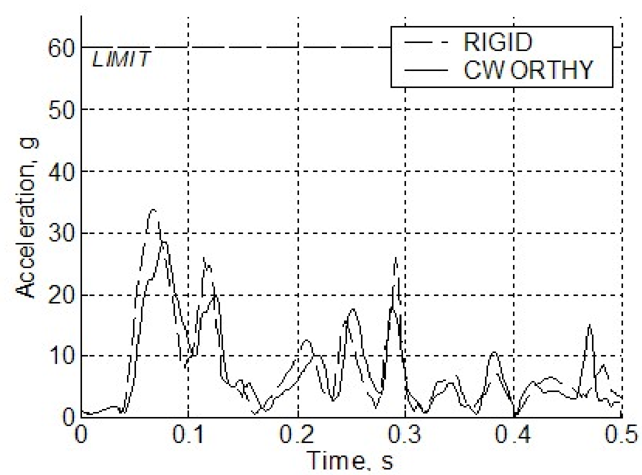


Figure 12 Case 3, chest resultant acceleration

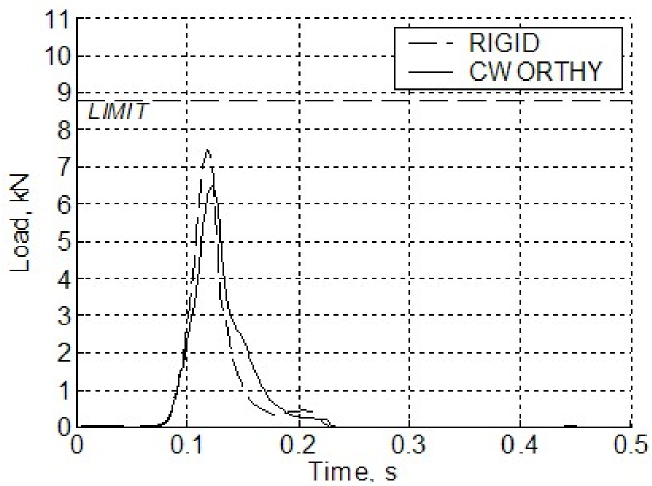


Figure 13 Case 3, total shoulder belt load

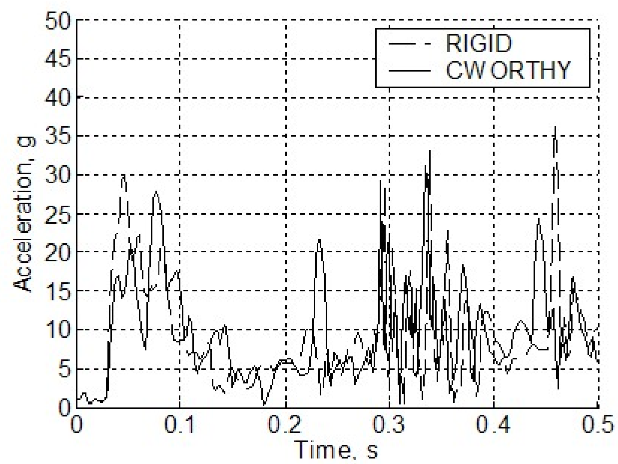


Figure 14 Case 3, aircraft CG resultant acceleration

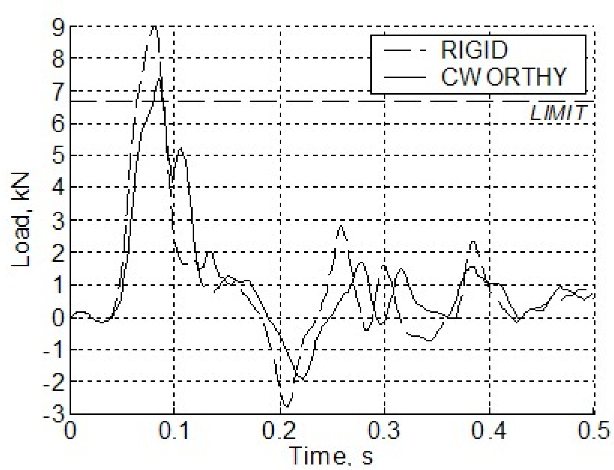


Figure 15 Case 4, lumbar spine load

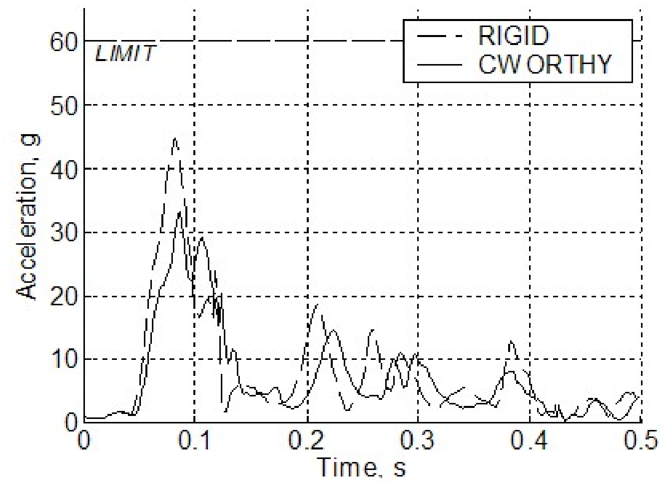


Figure 16 Case 4, chest resultant acceleration

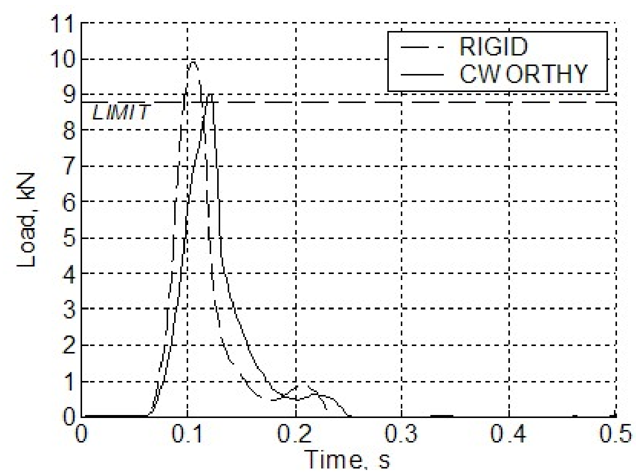


Figure 17 Case 4, total shoulder belt load

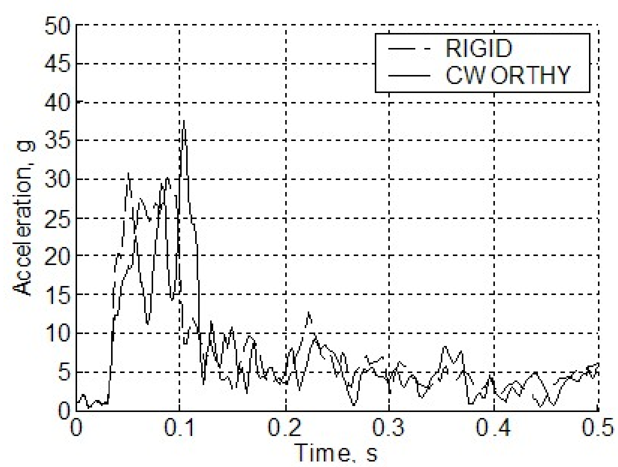
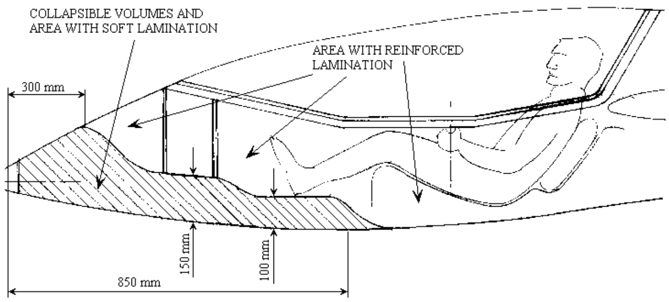
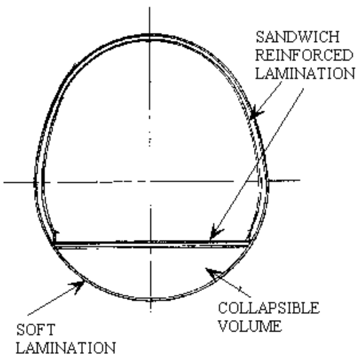


Figure 18 Case 4, aircraft CG resultant acceleration



side view



front view

Figure 19 Side and front cross section views of the solution outlined for the crashworthy area

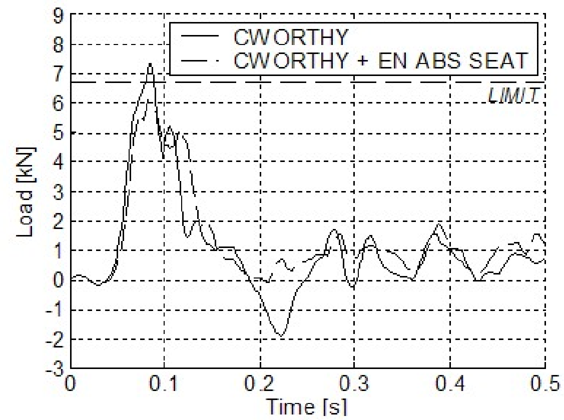


Figure 20 Spine load attenuation with a 11 kN / 100 mm energy absorbing seat system

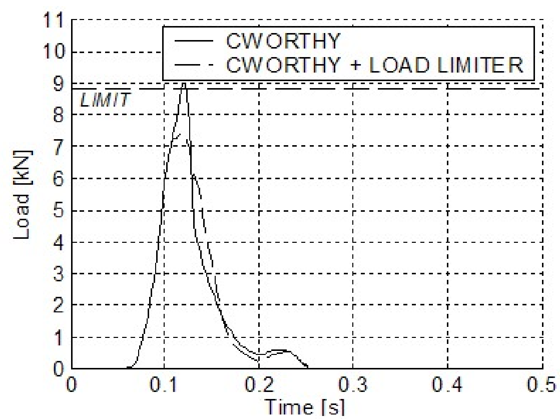


Figure 21 Total shoulder belt system load attenuation with a couple of 3.7 kN / 50 mm load limiters