RESTRAINT SYSTEM IN GLIDERS UNDER BIOMECHANICAL ASPECT

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In earlier times, the focus in developing gliders was above all the optimization of flight performances. Man (the occupant) was in the background when a solution for this technological challenge was looked for, and, quite deplorably, the aspect of passive safety was paid too little attention. Passive safety includes all measures inside and outside the glider which contribute to reducing the consequences of an accident.

However, in recent years people became more aware of safety standards and, inspired by a series of accidents with gliders where passengers were injured fatally or severely, although the plane was not damaged notably, research was initiated to increase passive safety in gliders.

In its first research, the TÜV Rheinland Aviation Engineering Ltd. first investigated belt systems (Reference 1). In its second research the TÜV Rheinland is now examining general restraint systems in a glider. Both research orders were initiated by the LBA (Luftfahrt Bundesamt) and carried out by order of the Federal Transport Ministry, Aviation department.

2. Analysis of accidents with gliders and definition of typical accident situations

A prerequisite for the investigation of glider belt systems is the knowledge of the forces acting the passenger during an accident according to size, direction and duration.

Glider accidents are very complex, three-dimensional processes; every accident is more or less an individual case. Thus, we have a vast variety of accident situations which as a whole could not be imitated in the simulation phase. Therefore, it was the first step to attempt to extract a limited number of representative accident situations from real accidents. For this purpose, all accidents with gliders in the Federal Republic were evaluated, which were registered within the period of 1983 to 1986.

Of the total of 911 accidents; 64 were fatal and 133 involved serious injuries. For the present investigation only those accidents were relevant where the ground was touched as primary contact; the number of these was 129.

Four representative accident types are illustrated in Figure 1. Speeds and attitudes are shown in Table 1. The ground surface was grass or soil. They are based on the accident reports and on discussion of the results with representatives of the Luftfahrt-Bundesamt (LBA), the DAeC (German Aero Club) and leading manufacturers of gliders:

TABLE 1

Accident type	1	2	3	4
Horizontal speed V_B m/s	14	25	18	20
Vertical Speed V_S m/s	7.6	4.3	10.5	20
Resultant speed V_A m/s	15.9	25	21	28
Longitudinal tilt	+10°	-10°	-30°	-45°
Vertical tilt	0°	0°	0°	0°
Angle of yaw	0°	0°	8°	0°
Impact direction αV_A	29°	10°	30°	45°

Negative angle are nose down.

Type 1 – Stall from up to 3 metres.
Type 2 – Late or insufficient flatten out
Type 3 – Outlanding with turn, or stall from low altitude.
Type 4 – Stall and spin from high altitude, or landing against obstacle.

In most cases, the impact speed after spinning from major altitudes exceeds 100 km/h, and even when the restraint system is perfectly designed, injuries are still most likely to be fatal. Thus, it does not make much sense to examine the glider belt system for higher impact speeds. A second accident analysis for the period of 1987 to 1989 backs the above mentioned 4 typical accident situations. Within this period, there was a total of

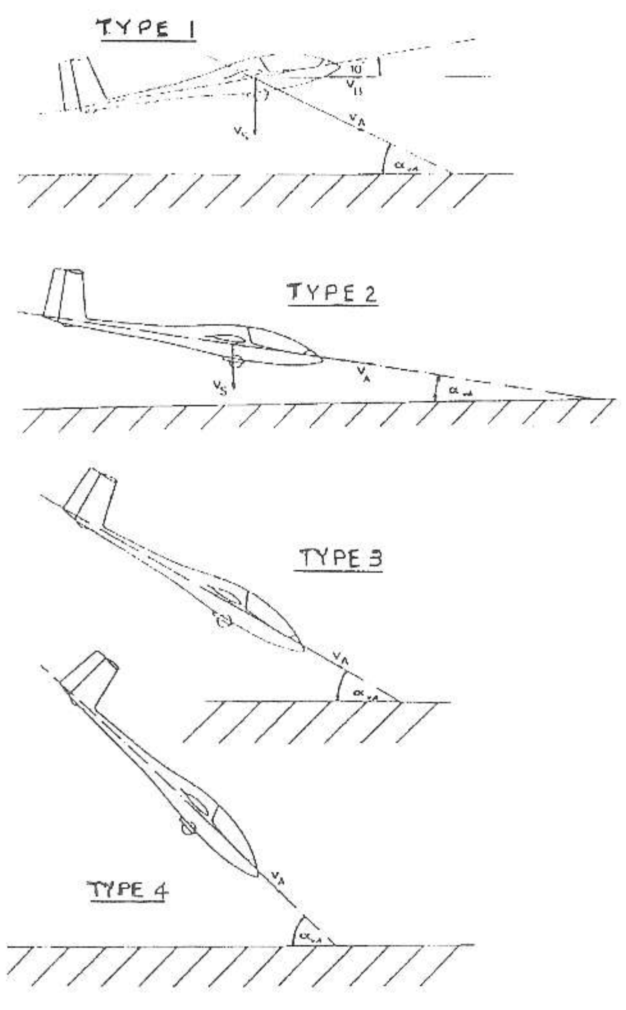

FIGURE 1. Representation of Accident types.

558 accidents; 28 of which were fatal and 90 with serious injuries. Ninety per cent of the 72 accidents which could be evaluated are related to these 4 accident types.

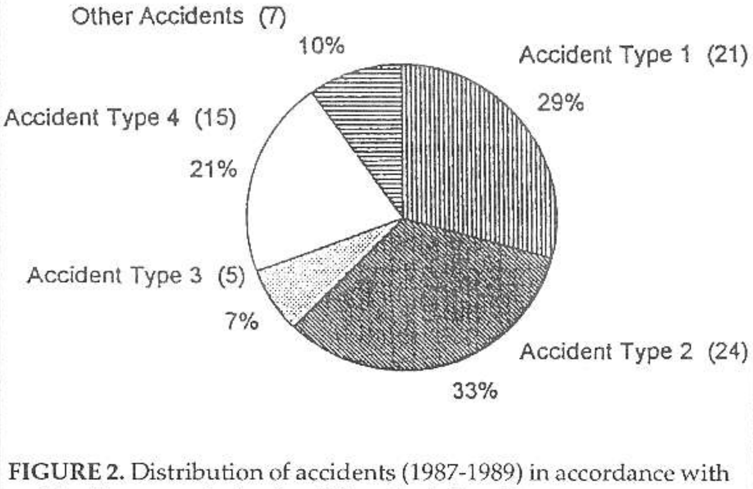

FIGURE 2. Distribution of accidents (1987-1989) in accordance with accident types on the basis of 72 evaluated accidents.

3. Field tests to determine the forces acting during accidents

With the definition of these typical accident situations, the crash impact parameters were widely known, however not the size and duration of the forces in the cockpit during the accident, necessary for the nondestructive simulation of these accidents by way of slide impact tests. These values were determined in so-called field tests with two front fuselage glider components. Since a loss of the components was very likely in these tests, only accident types 1 and 4 were simulated for cost reasons. Figure 3 shows the set-up of the field tests.

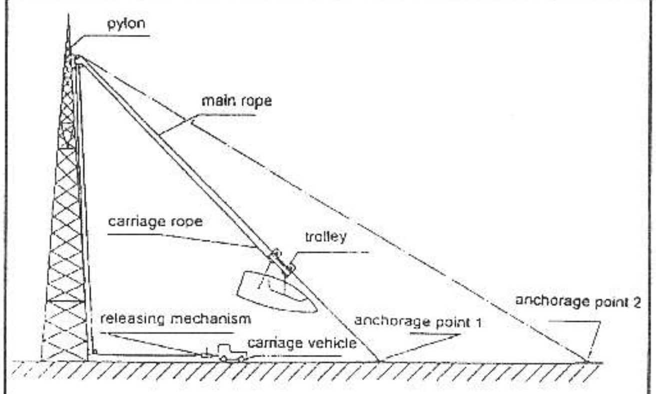

FIGURE 3. Scheme of the set-up of the field tests.

In the field tests, the decelerations acting on the total system: glider / passenger, were measured as a function of time. An example is shown in Figure 4. For further data see Reference 1.

4. Simulation of accidents with gliders in slide impact tests to optimize belt systems

The impulses determined in the field tests were simulated without destruction by tests on a glider cockpit mounted on a carriage vehicle (slide) using a fully instrumented Hybrid II Dummy.

The evaluation of more than 40 slide impact tests gave the typical motion course for accident type 4 shown in Figure 5.

In the first phase of the deceleration impulse, the dummy slips forward to the thigh contact area. Thus, the kneecaps strike against the instrument panel. The upper part of the body whips forward as far as the shoulder belts allow, and the head moves like a whiplash. Thus, the shoulder belts tighten. So the belt lock and thus the pelvic belt are pulled over the belt system of the parachute to the abdominal area of the dummy. The following mechanisms can lead to injuries of the passenger.

Submarining

Submarining is the clear slipping of the body under the pelvic belt. Thus, almost the entire force during an impact acts on the soft parts and may lead to critical injuries of the internal organs. For this reason the pelvic belt must not move over the hipbone.

To solve this problem requires correct belt

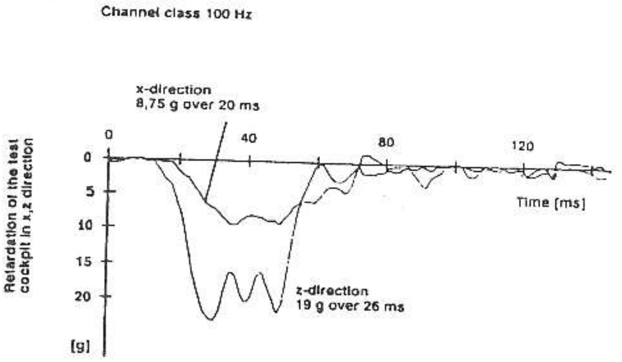

FIGURE 4. The typical acceleration at the center of gravity for accident type 1.

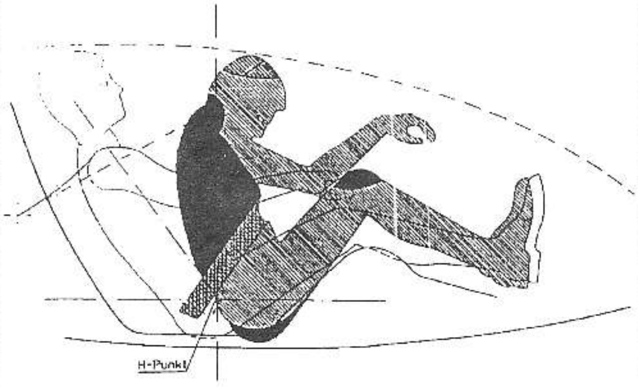

FIGURE 5. Typical motion course of the dummy in accident type 4.

geometry as well as an adequate seat construction (ramp seat). For this to be achieved the anchorage points of the lap belt should be located well below and behind the H-Point at the angle between 80° ±10° to the datum line through the H-Point parallel to the longitudinal axis of the sailplane (see Figure 6). Slide impact tests proved that submarining is significantly reduced or even avoided completely where the pelvic belt anchorage points are fixed within the optimum range.

The H-point is the point in a person, sitting in a cockpit, which marks the theoretical axis of revolution between the legs and the trunk.

A device for determining the H- point is described in Appendix 1.

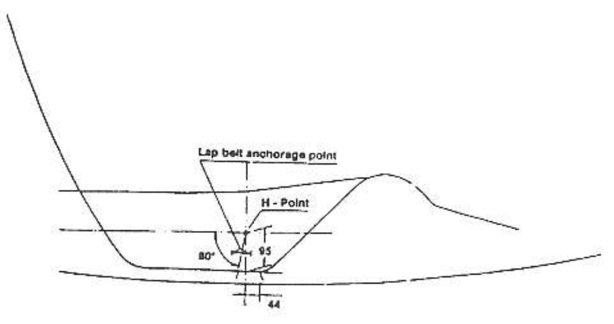

FIGURE 6. Optimum area to fix the belt anchorage points.

TABLE 2

Period	1983-1986	1987-1989
Spinal injuries	41%	63%
Fatal Injuries	12%	10%
Serious Injuries	3%	1%
Other Injuries	34%	18%
No Injuries	3%	8%
Injuries Not Known	7%	

Whiplash movement of the head.

When the head moves forward like a whip, this may lead to injuries of the cervical vertebrae, ranging from "simple" whiplash trauma to fractures with torn ligaments. In the rebound phase, in which the head falls back, the head accelerates in x-direction to approx. 40 g.

According to size, shape and material of the head rest, serious injuries of the head may be caused. The head rest should be designed as a rigid part of the back rest. And in addition, it should be upholstered with a so-called energy-absorbing material (foam).

5. Injury types

The two analyses of glider accidents show a high percentage of vertebral spine injuries compared to other injuries of the passengers (see Table 2).

The analyses were made according to the injury descriptions given in the accident reports. It is possible that some of the injuries described as fatal, serious, etc. were also spinal.

6. Biomechanics

The human body can support a limited physical load only. Many examinations have been made to determine biomechanical load limits: e.g. animal tests, corpse tests, tests with volunteers and tests at preparations. The extent of such loads is defined by the acceleration as a physical value, the unit being the acceleration due to gravity 9 (9,81 m/s^2).

Another important physical value is the time of effect t. The form of the impulse $a = f(t)$ must also be considered. Data for the body as a whole, and for individual body segments (head, thorax, vertebral spine, etc.) have been determined.

One tolerance criterion for the load-bearing capacity of the total body are the tolerance curves established by Eiband (Reference 2) which were published as early as in 1959, and the self-tests by John P. Stapp.

In Figure 7, the load-bearing capacity is indicated for different increase rates of acceleration in the z-direction (vertically downward in direction of the vertebral spine) in which the capacity is least.

Figure 8 shows the maximum acceleration as a function of time.

The Eiband curves indicate a z-direction limit of acceleration 16 g for < 40 ms; there is no clear limit for the increase-rate of acceleration.

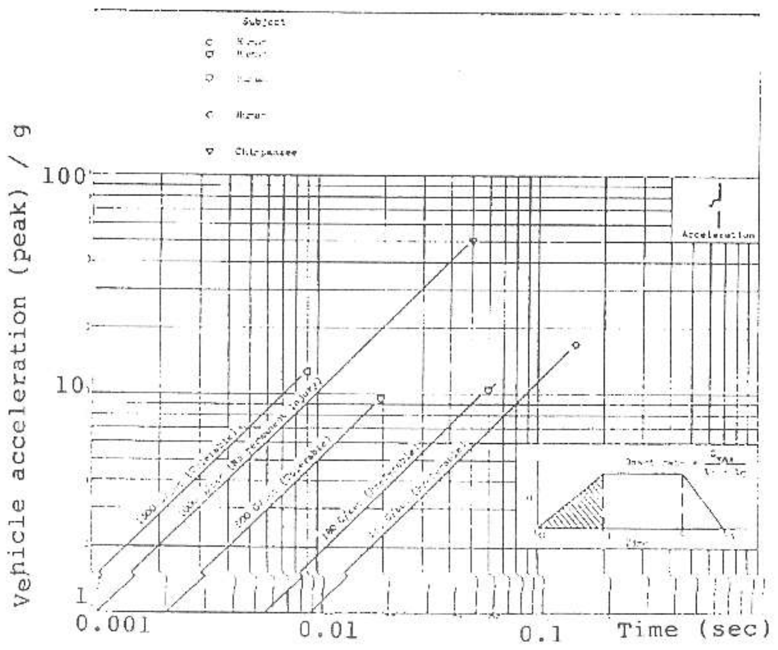

FIGURE 7. Increase of deceleration in z-direction.

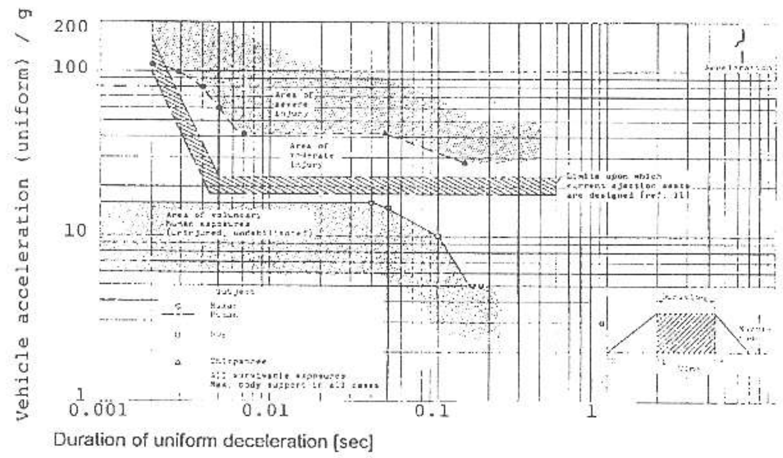

FIGURE 8 Deceleration in z-direction (Eiband).

Minor injuries (e.g. petty vertebral fractures) resulted from an acceleration of 22 g up to 45 g with t = 10 ms. These limits were established with strong persons correctly harnessed. For this reason, they can be related to a representative group of glider pilots to a limited extent only. Such factors as advanced age, earlier injuries of the vertebral spine or an unfavorable sitting position may cause a significant shift of the tolerance limits. Furthermore, the tolerable acceleration reduces to 5 g within the range of 5 Hz (200 ms).

In the Eiband tests, the test person did not faint. Also the glider occupants experiencing their vertebral injuries remained conscious. This backs the assumption that the vertebral spine is the first to be injured in a z-load.

Injury mechanisms of the vertebral spine are:

Injuries of the cervical vertebrae The cervical vertebrae are injured predominantly by head movements in x-direction caused by impacts.

Injuries of the thoracic and lumbar vertebrae There are two typical forms of injuries for high z-loads and for combined z-/x-types of load (x direction is perpendicular to the vertebral spine).

a) Wedge breaks in the front vertebral area, caused by compression and flexion and frequently appear in glider accidents despite a fourpoint belt with non-optimum sitting position and the belt system allowing a movement of the vertebral spine in x-direction.

b) Bursting fractures. These fractures are caused by a very high compression load on the vertebrae and very often lead to lesions of the spinal cord (paraplegia).

Load limits of individual vertebral preparations The load limits of individual vertebral preparations have been determined in a series of experimental investigations, mostly with isolated preparations. The most important results for pressure forces are listed in Table 3 (Reference 3).

TABLE 3

MEAN BREAKING LOAD (kN) OF SPINAL ELEMENTS IN COMPRESSION BY AGE GROUP
(Yamada 1970)

Spinal Element	20 - 39 Yr.	40 - 59 Yr.	60 - 79 Yr.
Cervical Vertebrae	4.09	3.30	1.86
Cervical Disc		3.13	
Upper Thoracic Vertebrae	3.62	3.13	2.31
Upper Thoracic Disc		4.40	
Middle Thoracic Vertebrae	4.22	3.65	2.27
Lower Thoracic Vertebrae	6.30	4.51	2.63
Lower Thoracic Disk		11.25	
Lumbar Vertebrae	7.14	4.67	3.01
Lumbar Disc		14.66	

7. Seat pan in gliders

In modern glider constructions, the seat pan itself and the small space between the seat pan and the lower part of the trunk are not designed to absorb energy. This deficiency leads to a deceleration in the z-direction undamped at ground contact, in some cases causing serious vertebral injuries.

The typical sitting position in a glider cockpit was evaluated by a test series with different persons (size) and a dummy. The insufficient support of the lumbar vertebrae is the focus of criticism. The load limits stated above were reached only in those cases where the vertebral spine can preserve its normal curve. As shown in Figure 9, there is no support for the lumbar disc at all. During long flights the lumbar vertebrae go slack, and if there is a push in the vertebral direction, even with little load can fracture.

8. Seat pan with energy-absorbing element

In accidents of type 1, the main push component is in vertical direction. The main part, which is the kinetic energy acting on the pilot, must be absorbed by the seat pan. Modern seat pans, having a rigid construction, do not meet this requirement, resulting in a considerable number of vertebral injuries.

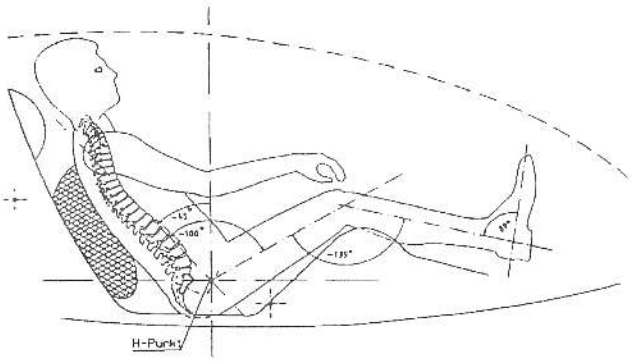

FIGURE 9. Typical sitting position in a modern glider cockpit.

The seat pan must be designed to dampen the impact. It is necessary to transform the kinetic impact into deformation work. The following factors must be considered for the construction of a glider seat pan with energy-absorbing element:

- limited space in the glider cockpit
- smooth functioning during an accident
- little maintenance work
- low manufacturing costs.

Based on these considerations, the function principle of Figures 10 and 11 was developed.

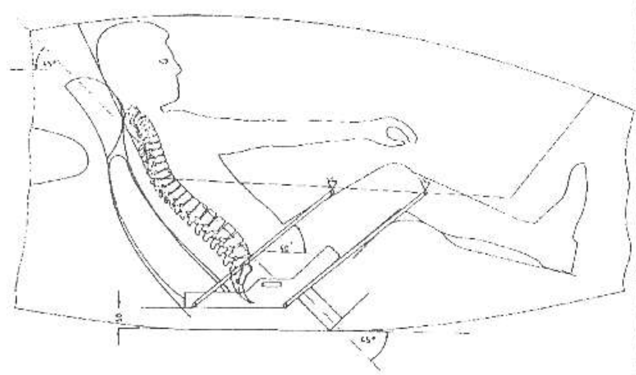

FIGURE 10. Functioning principle of an energy-absorbing seat pan (before crash).

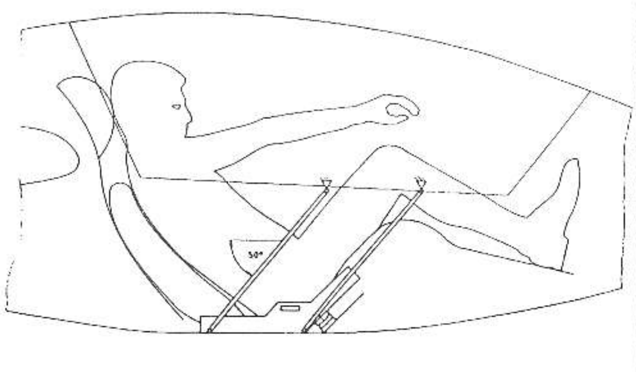

FIGURE 11. Functioning principle of an energy-absorbing seat pan (after crash).

The vertebral spine has an angle of approx. 45° to the fuselage axis. The vertebral direction is defined as tangent line at the 8th thoracic vertebra. The energy-absorbing element acts in this direction.

The maximum distance between the seat bottom and the cockpit skin is 60 mm. It is not possible to place an element with sufficient energy-absorbing capacity within this space. The only space is below the front part of the seat pan, inclined at about 45° (thigh contact area). The seat pan is separated from the upper part of the thigh contact area and the back rest. It is fixed on four parallel swing rods and is supported by the energy-absorbing element. The swing rods are attached to the (reinforced) canopy frame of the cockpit.

In an accident with impact components in vertebral direction the damping element should deform when reaching the given force to start such mechanism. The geometry allows the seat pan to move almost linearly in the direction of the axis of the energy-absorbing element. Practically no maintenance work is necessary. If the energy-absorbing element has deformed a little after a hard landing, a mark on one side of the seat pan could indicate whether replacement is necessary. Replacement is no problem.

9. Simulation of accidents with gliders in accordance with accident type 1

A suitable set-up was designed and built to fix the seat pan with energy-absorbing element (see Figures 10 and 11). This was tested as described in paragraph 4, being subjected to the deceleration impulses under accident type 1 as determined in the field tests, using a fully equipped Dummy Hybrid 11.

The following energy-absorbing elements were used:

1. 2 aluminum honeycomb elements (right, left)
2. 2 tubes (hybrid tissue dynema/carbon) (right, left)
3. 1 corrugated spar (hybrid tissue aramid/carbon) (centre)
4. 1 element of distance tissue (glass fibre) (centre)

Further tests were carried out with a rigid seat pan having no energy-absorbing element and with a rigid seat pan with energy-absorbing foam inlet.

This is the preliminary result:

Aluminum honeycomb element: Good suitability as energy-absorbing element in glider seat pans. Exact choice and dimensioning of the energy-absorbing element possible using existing data sheets. The load in the lumbar vertebrae was reduced by 16% and the resulting pelvic acceleration in the dummy by 26%.

Corrugated spar: Limited suitability as energy-absorbing element in glider seat pans since it breaks at the edges of its fibres.

Tubelets: Generally very suitable as energy-absorbing element in glider seat pans. The tubelets used in the test were underdimensioned.

Distance tissue: In the tested version not very suitable as energy-absorbing element in glider seat pans. No optimum deformation behavior. Energy cannot be absorbed even after approx. 50% of the original length.

10. Summary

The tests showed that the belt systems can only fulfil their purpose as a passive safety element if an optimum belt geometry is maintained. This is achieved predominantly by a correct position of the pelvic belt anchorage points. In addition, the seat pan must have a clearly defined thigh contact area. The head rest should be designed to cope with the rebound effect (rigidity, energy absorbing foam).

The biomechanical tests showed that man is least capable of load in vertebral direction (z-direction). This result has also been obtained from the accident analysis which showed a high proportion of vertebral injuries.

In order to reduce the load on the occupants during a glider accident, the seat pan must be designed to absorb energy. Slide impact tests on an energy-absorbing seat pan showed that if the energy-absorbing element is chosen well, the load on the occupants during a glider accident can be reduced considerably.

In addition, it is important for the occupant of a glider to take a correct sitting position (lumbar vertebral support).

References

1) Pusch and Sperber, Investigation of Glider Safety Belt Behavior Under Accident Conditions. *Technical Soaring*, Volume 15, Number 3.
2) Eiband, Martin, NASA Memorandum, Human Tolerance to rapidly applied accelarations.
3) Yamada, H., Strength of biological materials, 1970.

Appendix I

Process of H-point determination

For the H-point determination, the thigh contact area and the seat level are the two reference areas in a cockpit.

a) Adjusting the glider
The even part of the seat area is to be adjusted with a bubble level or a protractor. A horizontal adjustment of the seat level is to be made in longitudinal and bank direction.

b) Placing and adjusting of the device
With the thighs some centimetres below the transitional area between seat level and thigh contact area, the device is placed in the centre of the thigh contact area and slowly pushed down to touch the seat pan at the same time. In this process, it is to be guaranteed that the thighs fully touch the thigh contact area.
If both thighs have optimum contact with the thigh contact area or optimum contact with the seat level, the device is, aided by the bubble level, adjusted horizontally on the connecting part and fixed in this position.

c) Marking of H-point and looking-up of optimum area of lap belt anchorage points.
When the device is adjusted, the H-point axis first is axially pushed to one side until the felt-tip pen, attached to the axis, touches the side wall of the seat pan. At this spot the H-point is marked. The same procedure is repeated for the other side.
Repeat the adjusting of the device and marking the H-point manifold.
Around all H-points marked on the side wall of the seat pan, a rectangle is to be drawn which should be as small as possible. The intersecting point of the rectangle's diagonal shows the "determined H-point."
For the determination of optimum area for the anchorage point of the lap belts, the device is placed on the seat pan in such a way that the H-point of the device corresponds to the "determined H-point" of the seat pan.
Now, the stencil is to be adjusted with the bubble level attached on it. Thereupon, the H-point axis is to be fixed with the locking device in the connecting part. Now, the area required for the anchorage point of the lap belt can be looked up on the stencil.

H-Point Device

The device is basically composed of the two thighs, the connecting part, and the H-Point axis (see drawing).

The original constructional drawings of the H-Point Device can be ordered from:
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