Experimental Study of Impact Phenomena in the case of a Composite Glider

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Abstract

The subject of the study was a glider made of composites and subjected to high loads typical of glider crashes. The aim was to provide experimental data for validation of a numerical model of the cockpit-pilot system during impact. Two experimental tests with the composite glider cockpit were performed (for practical reasons and for these tests, a typical car-crash track was used with limited space and wings and tail were substituted by properly adjusted weights fixed onto the cockpit). During the first test the cockpit with a dummy inside was crashed onto the ground at an angle of 45 degrees with a speed of 55km/h. Accelerations and deformations at chosen points on the cockpit as well as signals coming from dummy sensors and forces in seat belts were recorded. Examination of the cockpit performed after the test (with an ultrasonic method) did not indicate any significant damage to the structure. The second test was much more severe. It was an impact into a rigid wall with a speed about 80 km/h. This time the cockpit was heavily damaged. The full-scale tests were accompanied by a number of quasi-static and dynamic laboratory tests with samples of the composite material. The experimental tests provided valuable results for parametrical identification of a simulation model developed using the MADYMO software.

Nomenclature

$\dot{D}$	damage state rate
D	current damage state
χ	elastic strain energy
$\dot{\chi}$	elastic strain rate
P_1	parameter in damage evolution law
P_2	parameter in damage evolution law
P_3	parameter in damage evolution law
DOF	Degrees of Freedom
HIC_{36}	Head Injury Criterion
CON3ms	Continuous 3ms Criterion

Introduction

The glider design satisfying the requirements of CS-22[1] (JAR-22) should prove the safety of the pilot during correct landing procedures (with the defined level of vertical speed) or during a "hard landing", when levels of acceleration and forces affecting the pilot do not exceed acceptable values. However, no rule can predict all accident situations. There are no crashworthiness requirements; therefore there are no established testing procedures for accidents.

Selected statistical data

In contrast to the automotive industry with its millions of cars and numerous research laboratories, glider manufacturers form a kind of niche in which the safety issues have not been investigated on a high level. There are a few reasons behind such a situation. The number of casualties, according to data collected from four countries, is not to alarming[4, 5, 6, 7, 8]. The data show the total number of fatalities has slightly exceeded 200. Relatively lower number of casualties in Poland (24 fatalities in the years 1987 – 2003) probably were caused by a lower population of pilots. On the other hand, it is impossible to calculate the total number of fatalities in glider accidents due to the lack of information from many countries where statistical data are either not published or published for the whole aircraft category.

As compared with the automotive industry, the number of glider accidents and the casualties is relatively low. That concerns also civil aircraft transportation, where 10,767 people died in the years 1991-2000[2].

Unlike the automotive industry where one can specify several typical car crash scenarios, the glider can crash in almost an unlimited number of ways. Therefore, based on the results obtained from investigations of accidents, some typical (the most frequent) accident scenarios have been formulated[3]. However, one should be aware that the scenarios presented here are connected with "in flight" situations, like stall or spin. Also, since there is a lack of publications devoted to the situations when the glider hits a barrier after landing, such a situation is reported here.

Research objectives

Nowadays, when the attention is focused (besides the airworthiness) on crashworthiness issues, the lack of experimental data, necessary for designing modern and safe gliders, has became an important problem. Present design process is still based on experience and professional ability of the constructors.

As mentioned above, a small number of accidents involving smaller casualties as well as relatively weak interest in the crashworthiness issues caused crash tests to be not obligatory and, as a consequence, no procedures associated with crash accidents have been established. Such a state leads to the lack of information necessary in the design process. On the other hand, a small production in the case of gliders (about few hundred per year) causes glider manufacturers to have insufficient funds for research and development.

The lack of glider crash data allows one to formulate the following research aims:

- Collect data on the loads acting upon the human body (accelerations and forces) during the impact process
- Collect data on the loads acting upon a glider cockpit structure, including such dynamical issues as load history, strain and damage propagation
- Produce measurements that allow for validation of a numerical model of the cockpit – pilot system during impact
- Formulate suggestions for Polish and international authorities that could be useful in the process of issuing regulations on crashworthiness of gliders

Experimental setup and data collecting system used in the crash tests

First test

The first test was performed in the Automotive Industry Institute (PIMOT) in Warsaw in March 2007. During the laboratory test, the original PW-5 cockpit with a dummy inside was crashed at the speed of 54.7 km/h onto the ground at the angle of 45 degrees. Such a configuration was selected as a result of preliminary studies and analyses (e.g. several years ago similar tests were performed at TÜV Rheinland[6]; the aim of the present study was to check behavior of the PW-5 glider and to collect data necessary for development of a simulation model of the glider). The test stand contained three important elements: the ground barrier, the model of a PW-5 glider and the model of a pilot's body.

The ground barrier was represented by a special cage, full of compacted soil and covered with grass. The glider was represented by the original PW-5 cockpit with elements of the fuselage. The wings and tail cone were modeled by elements of proper weights fixed onto the cockpit. Such a simplification in glider modeling and the application of a relatively low impact speed resulted from some limitations imposed on the experiment namely:

- The test stand was constructed for testing cars, therefore, there was no space for testing the whole glider.
- The Hybrid II dummy, applied in the test (anthropometrical manikin made for modeling the human body behavior during the frontal impact), is quite expensive and the authors were not allowed to damage it, therefore the speed limit was 55 km/h. Further, to prevent damage to the manikin the canopy was removed during the test (moreover, the canopy would make the cinematographic analysis impossible).

In the course of the experiment, signals from 34 channels of measurement gauges were recorded. Additionally, the whole process was filmed using three high-speed cameras.

The equipment used to measure the loads acting on the cockpit structure was as follows:

- 12 strain gauges registering deformations at selected points of the cockpit sill (see Fig. 1)
- 3 accelerometers (3 DOF each) situated at selected points on the structure: on the rear part of the cockpit, in the cockpit mass center and at the point in the vicinity of seat pan and pilot's pelvis location

The equipment used to measure the loads acting upon the human body was as follows:

- 2 accelerometers (3 DOF each) registering acceleration on the dummy head (mass center) and torso (sternum area)
- sensors registering the forces acting upon the lumbar section of spine, femur and in safety belts, respectively (lap belt as well as the shoulder one) – 7 channels

Second test

The second test was performed in a different way. Based on the results from the first test, the authors decided to change the configuration as well as the experimental stand arrangement. The glider speed was increased to 77 km/h to observe accident consequence at a speed higher (10%) than the standard landing speed (about 70 km/h). Also the barrier was changed to simulate a rigid one (e.g. a wall).

Such impact conditions are not observed during real world accidents. Consequently, the main aim of the test was collection of time histories of strains at chosen points of the cockpit during the first phase of a severe crash. Such data are necessary for the identification of parameters of the FEM simulation model of the glider that is currently under development and will be used for future studies.

Since the authors did not have the anthropometrical dummy at their disposal, the biomechanical measurements could not be performed (a simplified manikin was used).

The equipment used to measure the loads acting on the cockpit structure was the same as for the first test. The experimental stand arrangement for both tests is shown in Figs. 2 and 3, respectively.

All acceleration and force signals were subjected to filtration according to standard SAE J211[9].

Crash experiments

First test

This test allowed the simulation of a slight aircraft (glider) accident. Figure 4 presents some selected movie frames from the experiments.

In the course of the test, the soil with grass was too deformable. As a result, the glider moved quite gently and the fuselage nose softly penetrated the ground (because such deep penetration is not observed during real impacts on grass airfields, the problem should be thoroughly investigated to find appropriate surface models, satisfying for example AVSCOM recommendation CBR=25[12], before similar tests are performed in the future). As a result, the loads acting upon the pilot as well as the structure of the cockpit occurred to be relatively low (the details are given below). However, cinematographic analysis shows that there are some other potential hazards, e.g. serious risk of the pilot being injured after hitting his head and arms on the canopy.

During the experiment one can distinguish three stages (see Fig. 5) of the crash. The first stage is the time between the moment when glider hit the ground barrier (t = 0.892s after starting the registration) and the time when the frontal wheels of the sled contacted the ground (t = 0.966s). In this phase, the largest increase (and obtained values) of structure deformation (the sled structure did not influence the cockpit structure behavior) was measured because the whole load was transmitted by the composite cockpit. In this period, the glider nose cone penetrated the soil softly which caused the loads affecting the pilot to be relatively small. This phase of the motion was the most important from the cockpit structure point of view.

The second stage lasted until the moment the rear wheels of sled impacted the rigid track of the experimental stand (at 1.4247s). In this phase, as a result of contact between the front wheels of the sled and the ground, accelerations were increasing. This was a reason for the significantly increasing loads acting upon the pilot. In next part of this period, the glider nose cone continued further penetration, but the large level of soil energy absorption caused the acceleration values to decrease. Beside the penetration along the direction of motion, the whole structure was falling (under the action of gravity) and nose cone rotation was observed. Such glider behavior is typical during accident situations, when the glider hits the ground at some angle (not perpendicular to the surface).

Second test

During the test, the authors focused on the cockpit structure damage and deformation. The higher speed and different barrier allowed for observation of interesting phenomena associated with deformation and damage processes during the crash.

In the course of test, one can distinguish two stages. The first stage is the time between the moment when glider hit the rigid wall barrier (t = 0.067s after starting the registration) and the time when the cockpit starts to rotate (t = 0.095s) (Fig. 6). During this phase of the crash, one can observe the rapidly increasing structure deformation which led to damage of the frontal part of the cockpit. The structure was heavily damaged. From the experiment point of view, this 30ms is decisive. After this time (the motion of the failed structure), registration of deformations and accelerations have no practical meaning considering the later validation problems and safety issues.

Results – loads acting upon the pilot

As a result of the tests, results were obtained from 13 registration channels, which contained the information about loads acting upon the pilot's body. The following data were obtained: acceleration in the dummy head (mass center, 3 DOF), acceleration in sternum (3 DOF), force (axial and shearing, 2 DOF) and moment (in the sagital plane) in the lumbar section of the spine, axial force in the femur bones (left and right, 2 DOF) as well as forces in the safety belts (lap and shoulder, 2 DOF).

The registered time histories allowed for definition of the maximum loads the pilot was subjected to. The results are shown in the Table 1.

Generally, obtained values were far below the tolerance limits of the human body. However, one of the loads is worth considering. In Table 1, one can find that the force in the lumbar section of spine exceeds 3.2kN. It is a "safe" value for the pilot up to an age of 60, but for older persons it could be potentially dangerous.

Moreover, the measurement results allowed for the determination of some injury criteria and evaluation of the risk of serious injuries. The longitudinal force in the femur bone reached the value of 1.31kN for the left leg and 1.71kN for the right one. Based on Fig. 7 (from Ref. 11), one can conclude that the legs are part of pilot's body subject to a relatively small load.

For evaluating the risk of head injuries, the *Head Injury Criterion (HIC)* as well as the *Continuous3ms (CON3ms)* criteria (common) were applied. The later criterion was applied also to the thorax. The results of analysis and the tolerance limits are shown in Table 2.

As one can see, the calculated values of the HIC_{36} were small. Also, the *CON3ms*, determined for the head and thorax, were significantly smaller than their tolerance limits (the values were about a half of the limits).

Results – the loads acting upon the glider structure

The second part of the research was determination of the loads acting upon the glider structure and observation of structure damage. In order to achieve these aims, accelerations were measured at three points on fuselage as well as deformations at 12 points on the cockpit sill. The measurement results will be briefly discussed.

The following results were obtained during the first crash-test:

- maximum acceleration of the glider mass centre: 21.4g in the moving direction and 12.5g in the vertical direction,
- maximum accelerations under the pilot seat: 23g and 15g, respectively,
- deformations observed on the cockpit side at two points slightly exceeded 6‰ (operational limit)

and at one point reached 8‰ (close to strength limit).

Figure 8 shows the time history of the strain at the cockpit sill point subjected to the highest load.

There was no serious damage observed. Nevertheless, at a few points, small cracks appeared (see Fig. 9).

After cleaning the glider cockpit of soil and dust, the structure was examined using the ultrasonographic method. The main aim of the examination was to check all places and points on the surface which could not be examined by simple visual assessment but could be damaged (e.g. thick layers of glued joints). The simplified ultrasonographic method (Y/N) was used (Fig. 10). Based on expert opinions, about 100 points were selected for close examination.

In the course of the examination, no serious faults were observed. This means, that the structure of cockpit at selected points withstood the imposed loads.

The following results were obtained during the second crash-test:

- maximum acceleration under the pilot seat: 53.8g in the moving direction and 93.6g in the vertical direction,
- deformations observed on the cockpit at the most of the point exceeded 20 ‰ (registration limit) and the cockpit was heavily damaged

In the course of the examinations, complete damage of nose cone, cockpit sill and frontal part of the fuselage were observed. This means that the structure of the cockpit failed under the imposed loads.

Crash phenomenon modeling with MADYMO software

One of the aims of the experimental investigations was collecting the data necessary to validate a numerical model of crash phenomena which could, then, be applied to further research into glider crashworthiness and pilot safety. It was found that is possible to make the model which simulates a crash phenomena in realistically (including damage of the structure). However, making a simulation in full-scale requires appropriate definitions of parameters in the model of a damage process. The model, using MADYMO software, is based on the following damage evolution law[11]

$$\dot{D} = \frac{P_1 \chi^{P_2}}{(1-D)^{P_3}} \dot{\chi}$$

where the P_1, P_2 and P_3 are the parameters in the damage evolution law. The parameters only could be defined by experimental studies (usually tests on simple samples). The problem is that those parameters do not have strictly physical meaning.

In order to define the P_1, P_2 and P_3 values, additional experiments were performed with a special impact test stand (Fig. 11) similar to the Charpy hammer.

The specimens that were used in the experiments were composite cones made from 2 layers (4 layers together with the overlaps at the nose cone) of a glass fabric (300 g/m^2) and epoxy resin (0.36 vol. fraction). The cones were fixed into the ring-fastening which was positioned at the end of a pendulum arm together with the adjustable weights. The angle of pendulum and the signal from accelerometer placed in the centre of the cone-fastening were recorded. On this basis, we estimated the energy of impact and its dissipation. The signal from the accelerometer allowed calculation of the impact force. An example of results obtained from the experiments is shown in Fig. 12. The specimens after impact are shown in Fig. 13.

Time histories of some quantities (pendulum angle and acceleration) allow for validation of a numerical model by proper choosing the values of the model parameters. Figure 14 shows the first and the last animation frames.

One can observe that values as well as time histories obtained from the computation (Fig. 15) are in quite good accordance with results of the experimental test. Such results allow the conclusion that, using the damage model available in MADYMO software, one can simulate a glider crash in a quite realistic way. The numerical model of a full scale crash test of the PW-5 glider (cockpit structure) is being prepared.

Conclusions

The experimental investigation reported here led to the following conclusions which are important from a scientific point of view.

The simulated glider accident can be considered a minor one in view of both the glider and the pilot. Crash at the limited speed (54.7km/h) does not cause any serious damage in the glider cockpit structure which ensures an adequate safety level. Also, the pilot would have survived the accident without any serious injuries based on load time histories and the injury criteria. It should be emphasized that high deformability of soil (due to high energy absorption) was decisive in the obtained results. In case of a crash onto a real airfield, an outcome could be much worse!

In view of the level of safety ensured by the cockpit structure and risk assessment, it was found that the head, chest and upper legs were subject to lowest loads. The highest loads were acting upon the spine, which is commonly observed in glider accidents. This was due to the pilot's body location and orientation relative to the cockpit (close to direction of loads) as well as the fact that pelvis and spinal column are situated in the vicinity of the impact area (lack of a deformable zone).

The forces acting in the safety belts seem to be relatively small (especially, as compared to the limits defined in automotive industry). However, direct comparison between the results presented here and data taken from regulations on cars is impossible due to different designs and arrangements. In the future, it seems necessary to formulate some criteria for the loads in the glider safety belts. There was no canopy in the crash test. However, the movie proves that the dummy should have definitely hit the canopy, which could generate additional loads acting upon the head and arms.

Some shortages in the experimental equipment forced the necessity for neglecting the forces acting upon the neck and pelvis, the injuries of which are commonly observed in practice.

The second crash test, as expected, showed that hitting a rigid barrier with speed about 80 km/h caused severe damage to the cockpit structure. The resulting large values of accelerations and collapsing structure, which do not protect the human body, illustrate a pilot has no chance to survive.

The results of the second crash indicate the importance of gaining some valuable experience from Formula 1 racing where appropriate design (and manufacturing) of a structure give good protection of the human body even in case of a crash at the speed exceeding 200 km/h. It should by a strong recommendation for all glider constructors to increase the crashworthiness efforts during the design process.

The results of computation made with MADYMO software allow the expectation that, in the near future, simulating of the crash in realistic way will come true. Use of a numerical model of crash phenomenon allows the saving of experimental research funds as well as the time necessary for the investigations. Numerical modeling of the crash will be a great advantage from a researchers point of view.

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Table 1
Results – loads acting upon the pilot

Maximum loads the pilot was subjected to

Acceleration [g]		Force in lumbar spine [kN]		Moment in saggital plane [Nm]	Longitudinal force in femur [kN]		Force in safety belts [kN]	
head mass centre	sternum	axial	sharing		left leg	right leg	shoulder belt	lap belt
35	31	3.22	1.59	46.8	1.31	1.71	2.81	2.05

Ultimate destruction force for lumbar spine [kN] (after H.Yamada)		
age 20-39	age 40-59	age 60-79
7.14	4.67	3.01

Table 2
Results – loads acting upon the pilot

Injury criteria determined basing on measurement results

Head		Thorax
Head Injury Criterion (HIC_{36})	CON3ms [g]	CON3ms [g]
178,6	34,07	29,67

Tolerance levels

Head		Thorax
Head Injury Criterion (HIC_{36})	CON3ms [g]	CON3ms [g]
1000	75	60

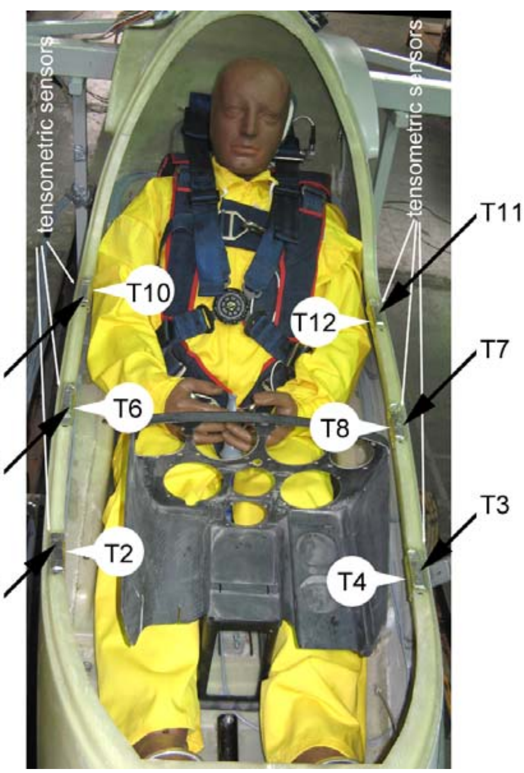


Figure 1 Strain gauges situated on the cockpit sill.

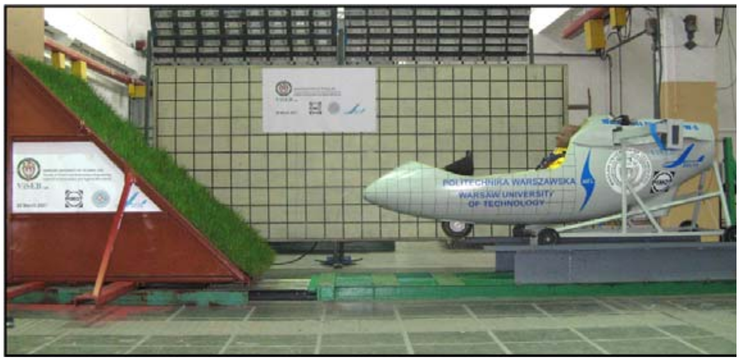


Figure 2 Experimental stand arrangement (the first test).

Figure 3 Experimental stand arrangement (the second test).

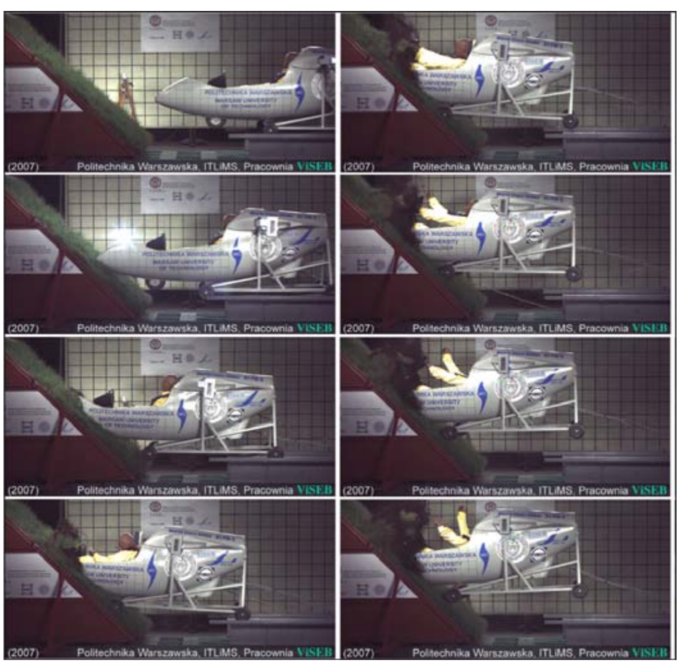
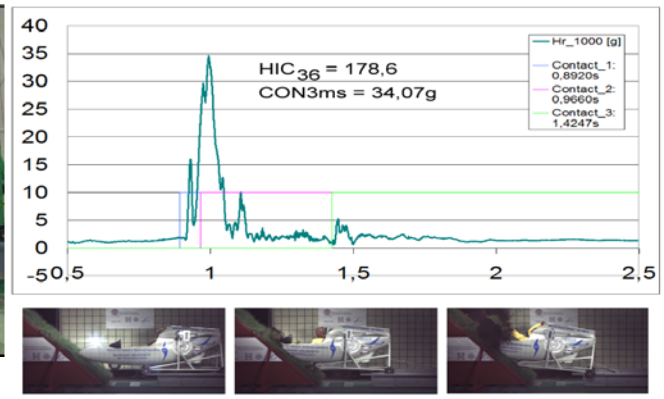
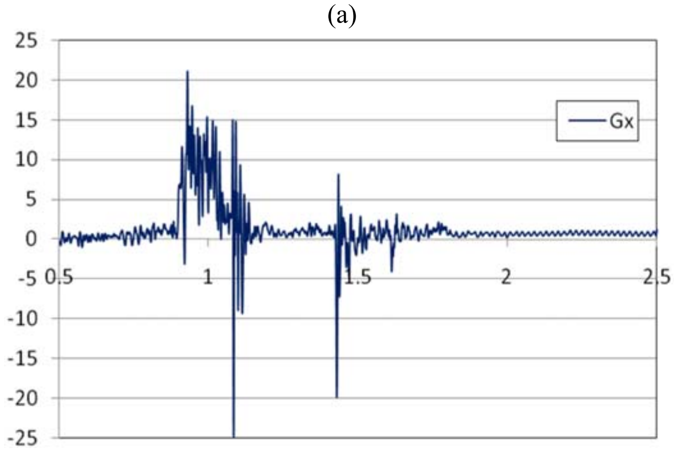


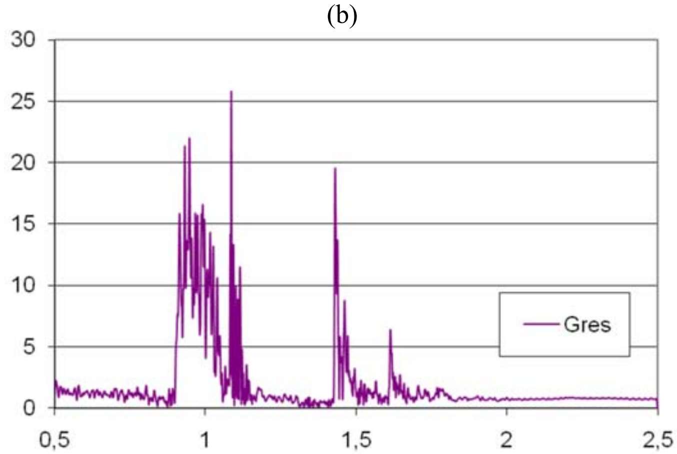
Figure 4 Selected movie frames illustrating the course of test one (Δt = 50 ms).



(a)



(b)



(c)

Figure 5 Time histories (test one) of: (a)—the resultant head mass center acceleration with corresponded test phases, (b)—impact direction component (Gx) of the deceleration measured close to C.G. of the pilot-glider system, (c)—resultant deceleration (Gres) measured close to the C.G. Peak values at 1.4-1.5s resulted from the rear wheels of sled impact onto the rigid track of the experimental stand and should not be taken into account.

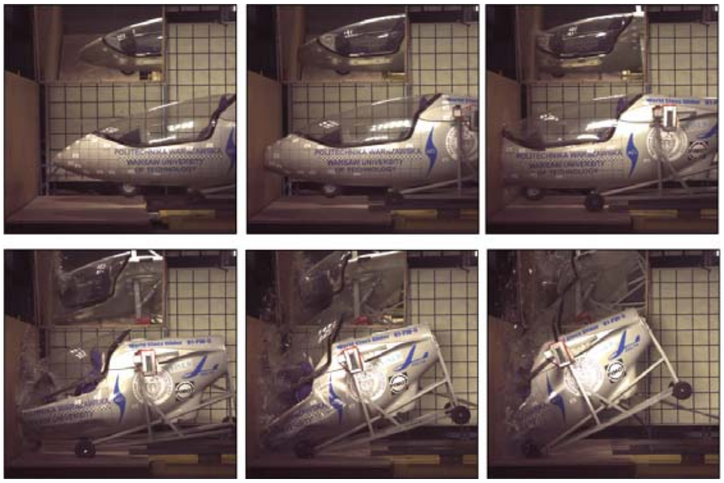


Figure 6 Selected movie frames illustrating the course of test two (Δt = 10 ms).

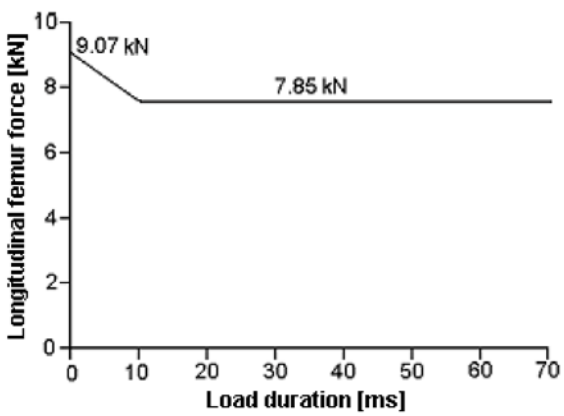


Figure 7 Femur Force Citerion.

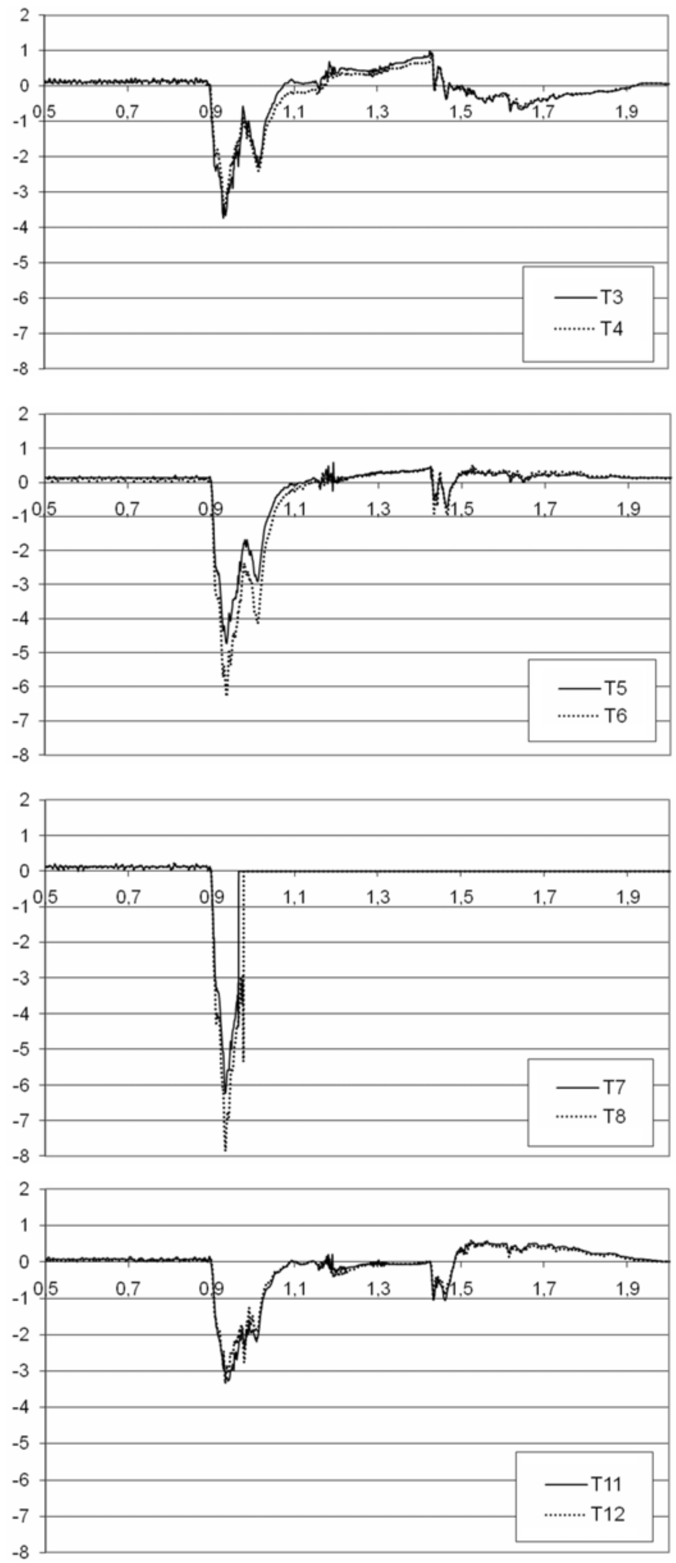


Figure 8 Time histories of strain at chosen points (shown in Fig 1) of the cockpit. Cables from sensors T7 and T8 were broken at 0.97s but the maximum strains were recorded earlier.

Figure 9 Small cracks observed after the first crash test.

Figure 10 Locations of selected examination points.

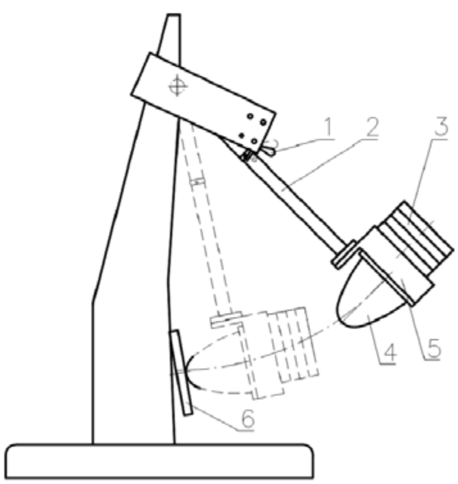


Figure 11 Sketch of the impact test stand.

1 –release hack
2 – pendulum arm
3 – adjustable weights
4 – specimen (composite cone)
5 – plate with the ring fastening
6 – steel wall

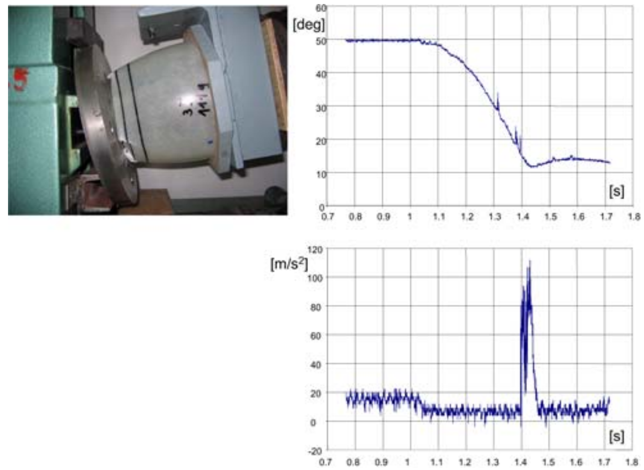


Figure 12 Results of an impact test stand experiment.

Figure 13 Specimens after impact.

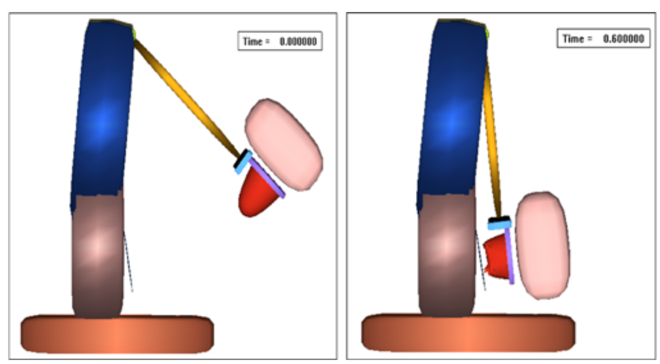


Figure 14 Animation frames (before/after impact) – MADYMO.

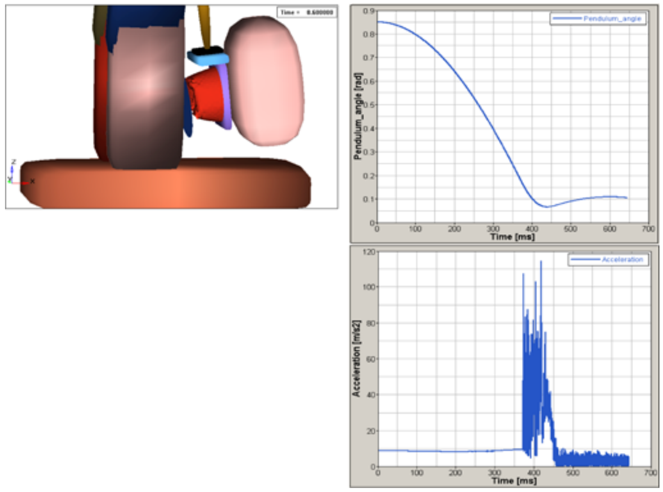


Figure 15 Results of numerical simulation (MADYMO).