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IMPACT LOADS AND CRASH SAFETY OF THE COCKPIT OF A COMPOSITE GLIDER

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ABSTRACT

One major problem associated with gliding is the safety of the crew during landings in the country outside the airfield. The analysis of glider-accident statistics shows that such out-landings may significantly influence the safety. Therefore, of vital importance are the crashworthiness properties of the glider fuselage structure. The subject of the study was the PW-5 glider fuselage 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 using a typical car-crash track. During the first test the cockpit with a dummy inside was crashed onto the ground at the angle of 45 degrees at a speed of 55 km/h. Accelerations and deformations at chosen points in the cockpit as well as signals coming from the dummy sensors and forces in the seat belts were recorded. The second test was an impact into a concrete wall at a speed of about 80 km/h. The full-scale tests were accompanied by a number of quasi-static and dynamic laboratory tests on samples of composite material. The experimental tests provided valuable results for the parametrical identification of a simulation model developed using the MADYMO software.

Keywords: crash safety, composite glider, model experimental validation.

INTRODUCTION

The glider design satisfying the requirements of CS-22 [5] (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 the acceptable values. However, not all accident situations can be predicted. There are no crashworthiness requirements; therefore, there are no established testing procedures for accidents. The authors' motivation was to make a contribution to solving this important problem by research consisting of crash computer modelling and experimental verification. The object of investigation was a PW-5 glider, designed at the Warsaw University of Technology in 1993 and later manufactured in Poland in relatively large series (more than 300 planes). The PW-5 glider was recognized by the International Aeronautical Federation as a glider representing a new mono-type competition class named "World Class" (1993 – 2013), and was very popular outside Poland (especially in the USA and New Zeeland)

Figure 1. PW-5 glider in Bezmiechowa (photo M. Rodzewicz)

GLIDER ACCIDENTS – SELECTED STATISTICAL DATA & TYPICAL SCENARIOS

Research in the field of glider safety is very limited. There are a number of reasons behind this situation. The number of casualties, according to data collected from the UE and other countries, is not too alarming [1, 3-4, 6, 10, 12-13]. Figures 2a, 2b and 2c present the data for the EU. It is worth emphasizing, that the most glider accidents happened during the landing phase of flight (see Fig. 2c). Compared to the automotive industry, the number of glider accidents and casualties is relatively low.

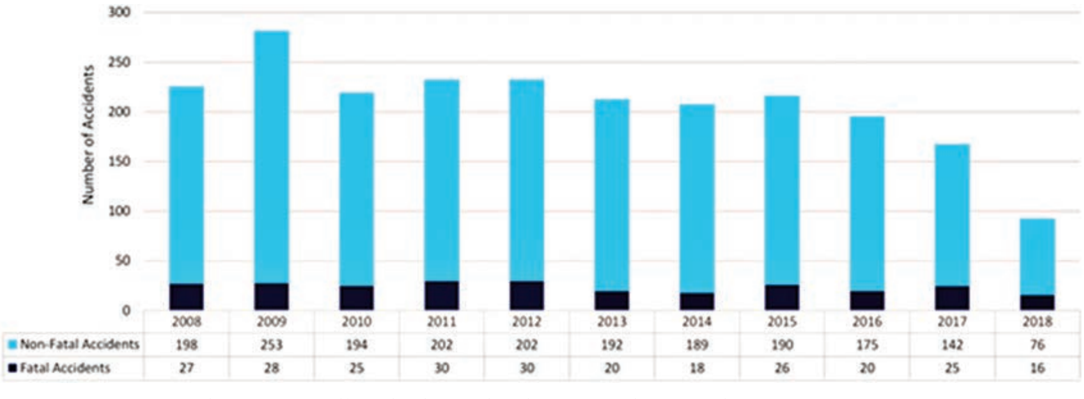


Figure 2a. Statistics of glider accidents in the EU [1]

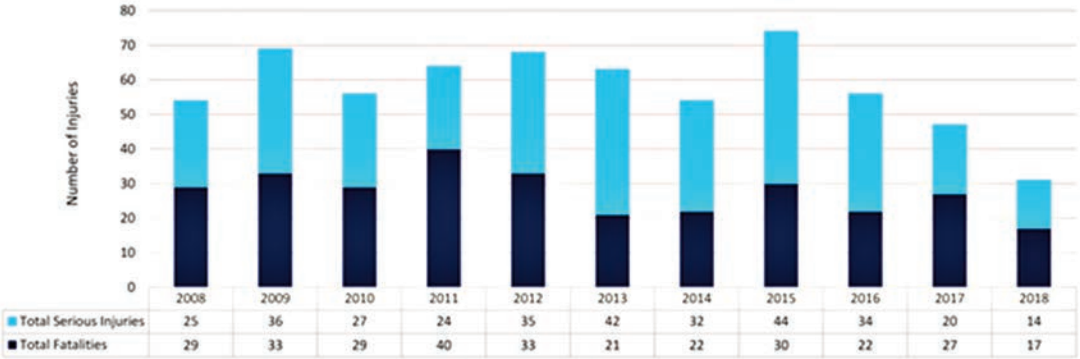


Figure 2b. Glider/Sailplane fatalities and serious injuries 2008-2018 [1]

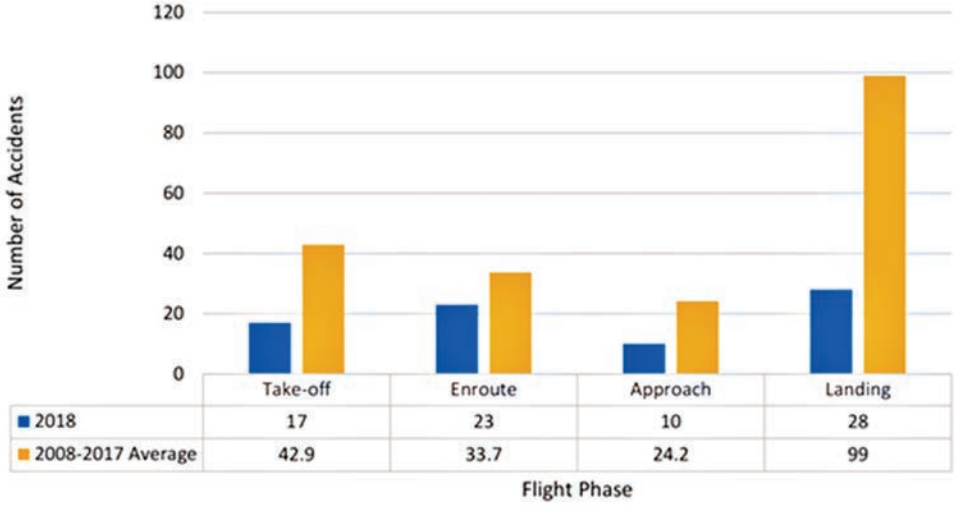


Figure 2c. Events of accidents and serious injureies vs phase of flight [1]

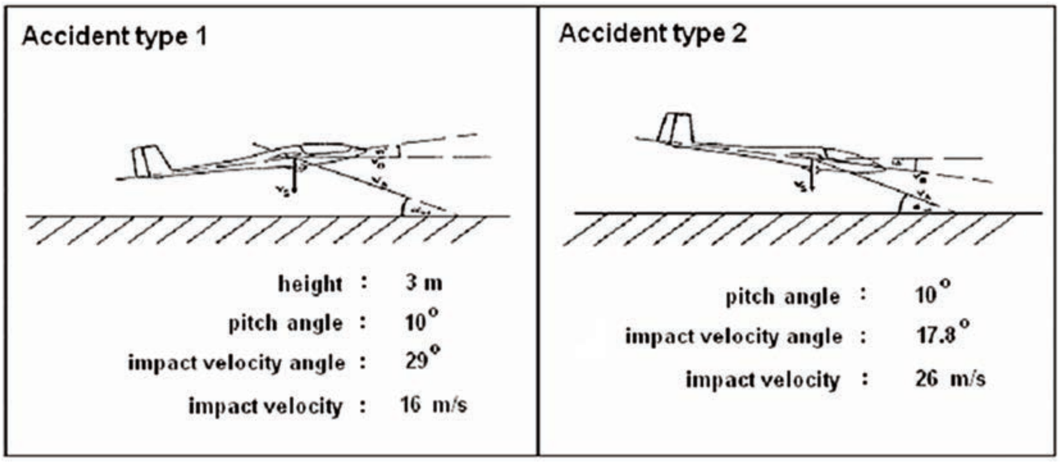


Figure 3a. Typical scenarious of glider accidents – part 1 [9]

Unlike in the automotive industry, where one can identifi several typical car crash scenarios, a glider can crash in an almost unlimited number of ways. Therefore, based on the results obtained from accidents investigations, some typical (the most frequent) accident scenarios have been formulated [9]. However, one should be aware that the scenarios presented here are associated with “in flight” situations, like stall or spin (Fig. 3a and 3b). Also, since there is a lack of publications devoted to the situations when a glider hits a barrier after landing, such a situation is reported here.

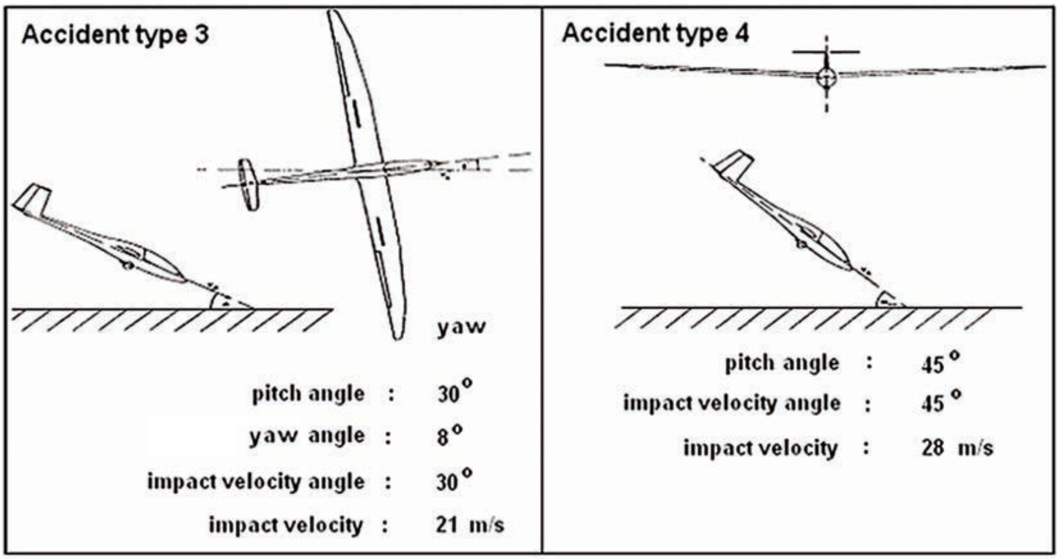


Figure 3b. Typical scenarious of glider accidents – part 2 [9]

RESEARCH OBJECTIVES

Nowadays, when the attention is focused (besides on the airworthiness) on crashworthiness issues, the lack of experimental data necessary for designing modern and safe gliders, has become an important problem. The present design process is still based on the experience and professional ability of constructors. As mentioned above, a small number of accidents causing severe casualties as well as a 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 for the design process. On the other hand, a small-scale production of gliders (about a few hundred per year) causes glider manufacturers to have insufficient funds for research and development.

The lack of data on glider crashes motivated the following research aims:

- to collect data on the loads acting upon the human body (accelerations and forces) during the impact process;
- to collect data on the loads acting upon a glider cockpit structure, including such dynamical issues as load history, strain and damage propagation;
- to produce measurements that allow for validation of a numerical model of the cockpit – pilot system during impact;
- to formulate suggestions for the 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

Two crash tests were prepared [7]. Both of them were performed at the Automotive Industry Institute (PIMOT) in Warsaw.

During Test 1, 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 based on the preliminary studies and analyses (e.g. several years ago similar tests were performed at TÜV Rheinland [12]); the aim of the present study was to verify the behavior of the PW-5 glider and to collect data necessary for the 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 the elements of adequate weights fixed onto the fuselage. Such a simplification in modeling as well as 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, employed in the test (anthropometrical manikin made for modeling the human body behavior during the frontal impact (Fig. 4)), was quite expensive and the authors were not permitted to damage it, therefore the speed limit was set at 55 km/h. The canopy was removed during the test (the canopy would have made the recording by cameras impossible).

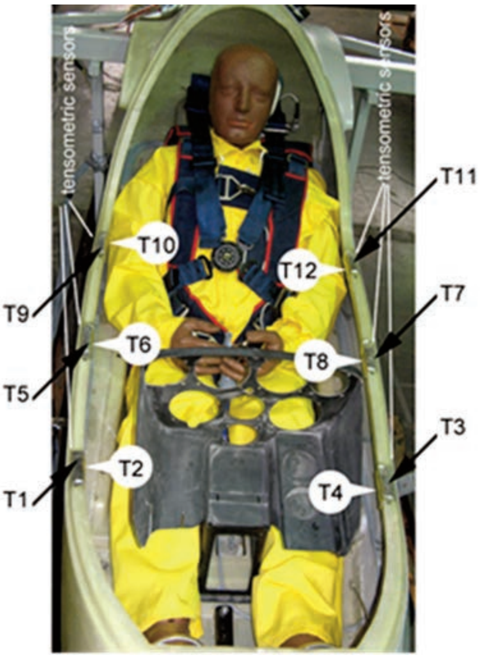


Figure 4. View of the dummy and location of the strain gauges glued on the cockpit sill

In the course of the experiment, signals from 34 channels of the 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 included:

- 12 strain gauges registering deformations at selected points of the cockpit sill (see Fig. 4),
- 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 the seat pan and the pilot's pelvis.

The equipment used to measure the loads acting upon the human body included:

- 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 the spine, femur and in safety belts, respectively (lap belt as well as the shoulder one) – 7 channels.

Test 2 was performed in a different way. Based on the results obtained 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 the consequences of the accident at a speed higher by (10%) than the standard landing speed (about 70 km/h). Also, the barrier was changed to simulate a rigid one (e.g. a concrete wall). Such impact conditions are not observed during real life accidents. Consequently, the main aim of the test was to collect time histories of strains at chosen points of the cockpit during the first phase of a severe crash. Such data were needed to identify the parameters of the FEM simulation model of the glider that was developed later [8] and to be used for future studies. Because of a very high risk of completly damaging the dummy representing the pilot body, instead of the anthropometric crash test dummy (used in the first test) a simplified manikin of similar geometry and mass was used. The equipment used to measure the loads acting on the cockpit structure was the same as the one used for the first test.

The experimental stand arrangement for both tests is shown in Figs. 5 and 6. All acceleration and force signals were subjected to filtration according to standard SAE J211 [11].

Figure 5. Experimental stand arragement for Test 1

Figure 6. Experimental stand arragement for Test 2

CRASH EXPERIMENTS - TEST 1

This test allowed simulating an impact with the ground at a relatively low speed (slightly below the stall speed of the glider). Figure 7 presents selected movie frames from the experiments.

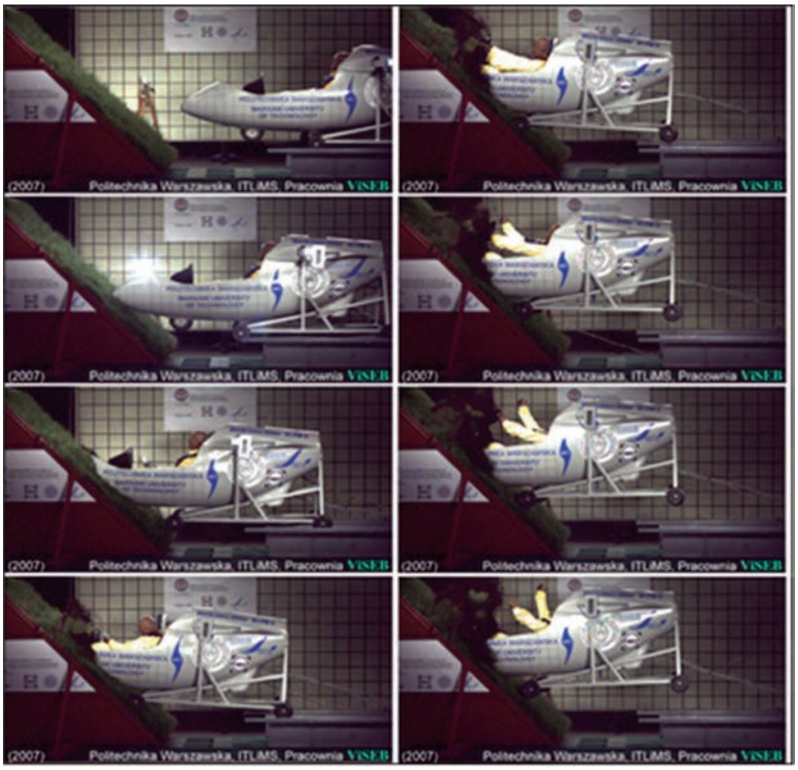


Figure 7. Selected movie frames illustrating the course of Test 1 (Δt = 50 ms)

In the course of the test, it turned out that the soil covered with grass was quite soft. 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 the AVSCOM recommendation CBR=25 [2], before similar tests are performed in the future). As a result, the loads acting upon the pilot as well as on the structure of the cockpit turned out to be relatively low, and the fuselage experienced only some non-critical damages in its front part. However, the analysis of the records from the high-speed cameras showed that there were some other potential hazards, e.g. a serious risk of the pilot being injured after his head and arms hitting against the canopy.

TEST 1 – results: loads acting upon the glider structure

The next part of the research involved the determination of the loads acting upon the glider structure and observation of structure damage. In order to achieve these aims, the accelerations were measured at three points on the fuselage while the 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 center: 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.

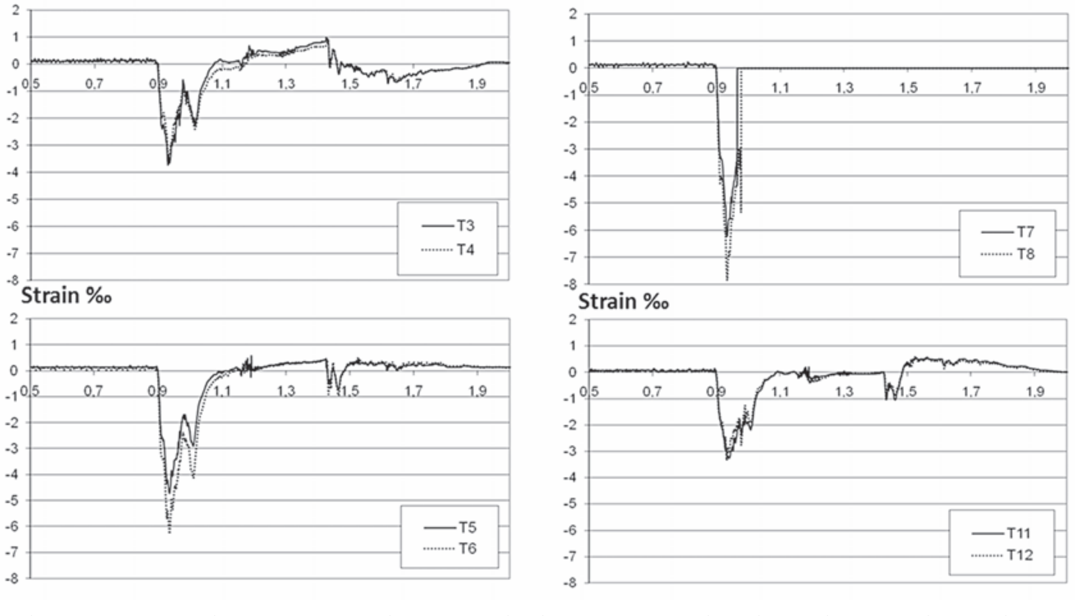


Figure 8. The time course of the strain in the cockpit still points (ref. to Fig. 4)

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

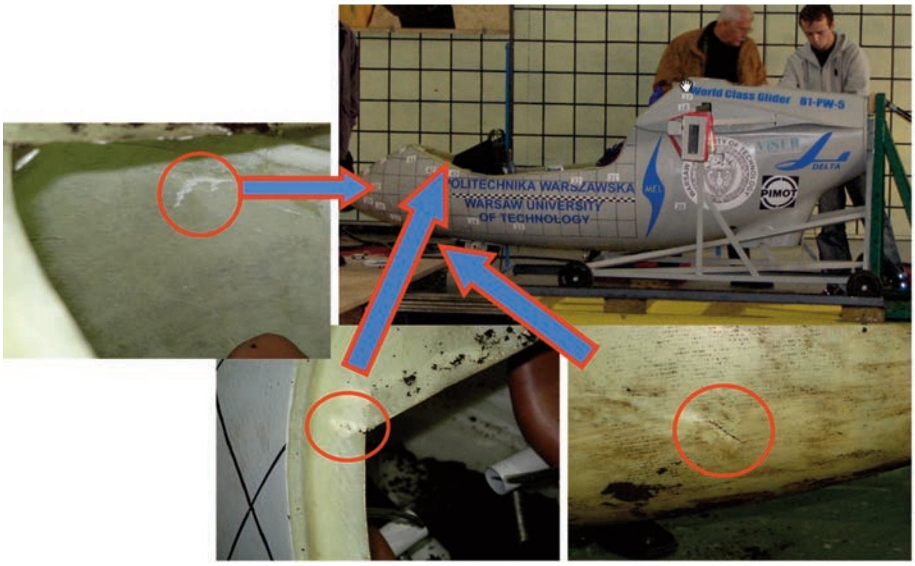


Figure 9. Location of small damage of the fuselage composite shell obtained during Test 1

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

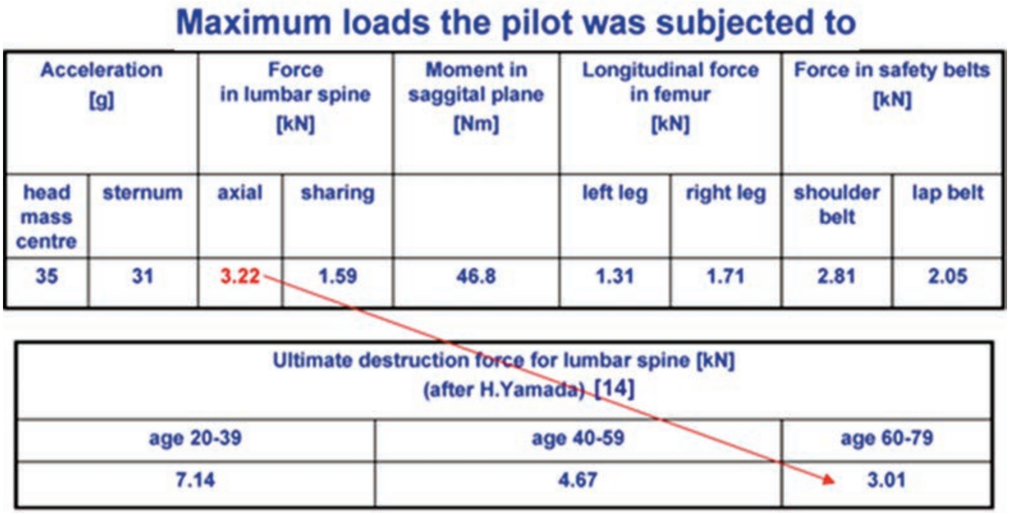
Figure 10. Examination of the fuselage structure after the Test 1

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

TEST 1 – results: loads acting upon the pilot

The test results were obtained from 13 registration channels that 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 the sternum (3 DOF), force (axial and shearing, 2 DOF) and moment (in the sagittal 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 the definition of the maximum loads the pilot was subjected to. The results are shown in the Table 1.

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) [14]		
age 20-39	age 40-59	age 60-79
7.14	4.67	3.01

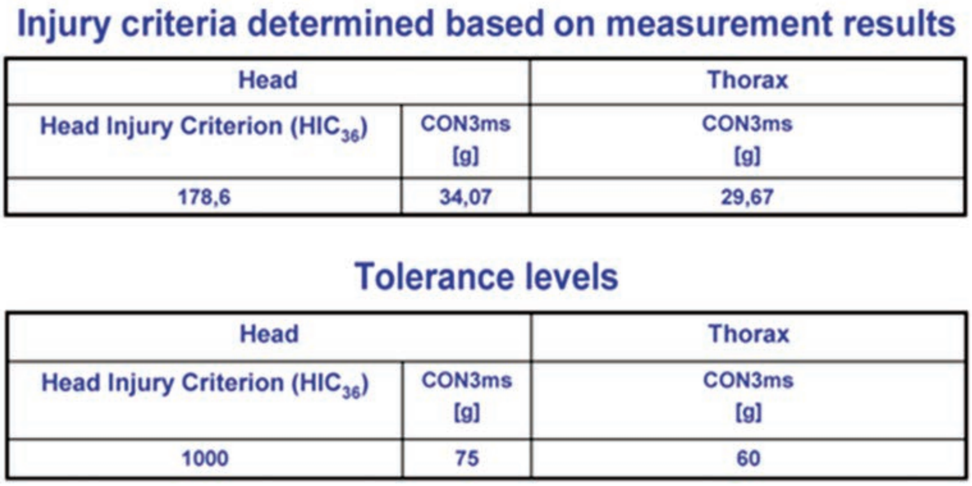
Generally, the values obtained were far below the tolerance limits of the human body. However, one of the loads is worth considering. In Table 1, one can see that the force in the lumbar section of spine exceeds 3.2 kN. It is a "safe" value for the pilot up to an age of 60, but for older persons it could 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 1.31 kN for the left leg and 1.71 kN for the right one. Based on Fig. 7 (from Ref. 13), one can conclude that the legs are part of the 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 also applied to the thorax. The results of the analysis and the tolerance limits are shown in Table 2.

As one can see, the calculated values of the HIC36 were small. Also, the CON3ms, determined for the head and the thorax, were significantly smaller than their tolerance limits (the values were about a half of the limits).

Table 2. Results – loads acting upon the pilot



Injury criteria determined based 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

The chart presenting time course of acceleration acting upon the pilot is shown in Fig. 11. The stages of the crash are correlated with the frames of the movie.

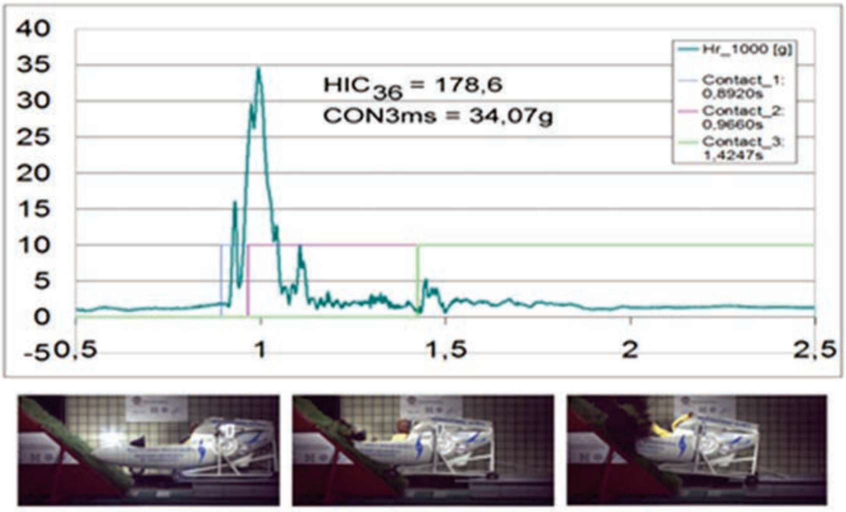


Figure 11. Time course of acceleration acting upon the pilot's head

The first stage is the time between the moment when the glider hit the ground barrier and the time when the front wheels of the sled contacted the ground. In this phase one can observe the highest increase in the structural deformation (the sled structure did not affect the cockpit's structure behavior) because all loads were entirely transmitted by the composite cockpit. In this period of time the glider's nose cone penetrated the soil softly, which was the reason why the loads affecting the pilot were relatively low. This phase of motion occurred to be the most important from the cockpit structure's point of view.

The second stage lasted until the moment when the rear wheels of the sled impacted the rigid track of the experimental stand. In this phase, the accelerations were increasing as a result of the front wheels of the sled contacting the ground. It was the reason for a significant increase in loads acting upon the pilot.

In the next part of this period, the glider’s nose cone was continuing penetration but high soil energy absorption caused the accelerations values to decrease. Besides the penetration along the direction of motion, the whole structure was falling (under the force of gravity) and the nose cone rotation was observed. This type of behavior typically occurs in accident situations when a glider hits the ground at an angle not perpendicular to the surface.

CRASH EXPERIMENTS - TEST 2

During the test, the authors focused on the cockpit’s structural damage and deformation. Using a higher speed and a different barrier made it possible to observe some interesting phenomena associated with deformation and damage processes during the crash.

In the course of the test, one can distinguish two stages. The first stage is the time between the moment when the glider hits the rigid wall barrier (t = 0.067s after starting the registration) and the time when the cockpit starts to rotate (t = 0.095s). During this phase of the crash, one can observe the rapidly increasing structure deformation leading to damage of the frontal part of the cockpit. The structure was heavily damaged. From the experiment’s point of view, this 30ms is decisive. After this time (the motion of the failed structure), the registration of deformations and accelerations has no practical meaning considering the later validation problems and safety issues.

Selected movie frames illustrating the test No 2 are shown in Figure 12.

Figure 12. Selected movie frames illustrating the course of Test 2 (Δt = 10 ms)

TEST 2 – results: loads acting upon the glider structure

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 majority of points exceeded 20 ‰ (registration limit) and the cockpit was heavily damaged,
- in the course of the examinations, complete damage of the nose cone, cockpit sill and frontal part of the fuselage were observed. This means that the structure of the cockpit failed under the loads imposed.

TEST 2 – results: loads acting upon the pilot

As for this ultimate test a simplified manikin without any sensors was used – no signal was recorded. The manikin was completely destructed, which means that for a real human being this would be an accident leading to death.

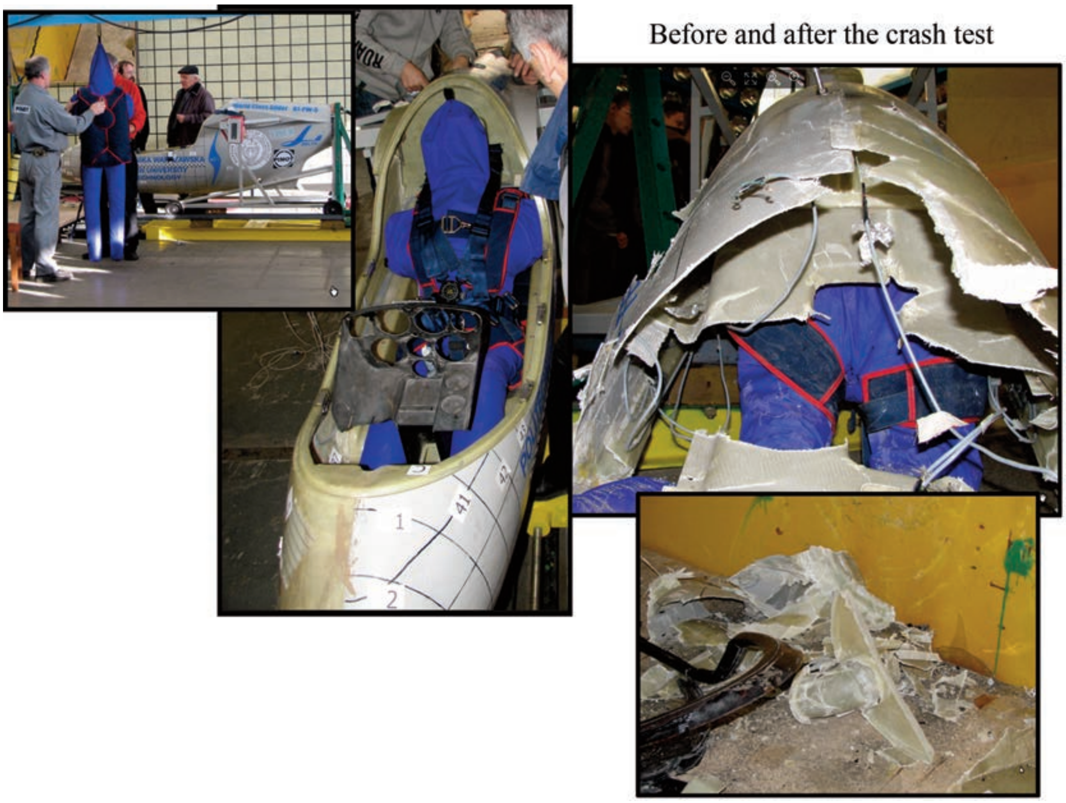


Figure 13. View of the fuselage and manikin before and after Test 2

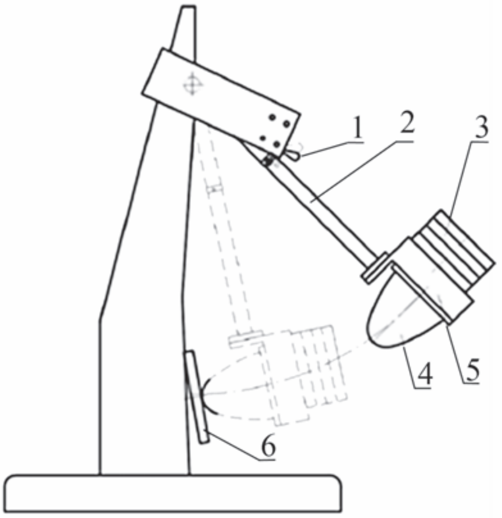
CRASH PHENOMENON MODELLING WITH MADYMO SOFTWARE

The most important aim of the experimental investigations was to collect the data necessary for validation of a numerical model of the crash phenomena to be subsequently applied to further research into glider crashworthiness and pilot safety.

Such a model, capable of simulating crash phenomena quite well, was developed (Fig. 14). The FEM modelling approach in the MADYMO [13] environment was adopted (for more information see [8]).

Figure 14. Glider's canopy model [8].

Figure 15. Selected frames from computer simulation of the Test 2 [8].



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

Figure 16. The impact test stand.

The specimens used in the experiments were composite cones made from 2 layers (4 layers together with the overlaps at the nose cone) of glass fabric (300 g/m2) 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 the pendulum and the signal from the accelerometer placed in the center of the cone-fastening were recorded. On this basis, the authors estimated the impact's energy and its dissipation. The signal from the accelerometer was used to calculate the impact force. Selected results obtained from the experiments and the view of the specimens are shown in Fig. 17.

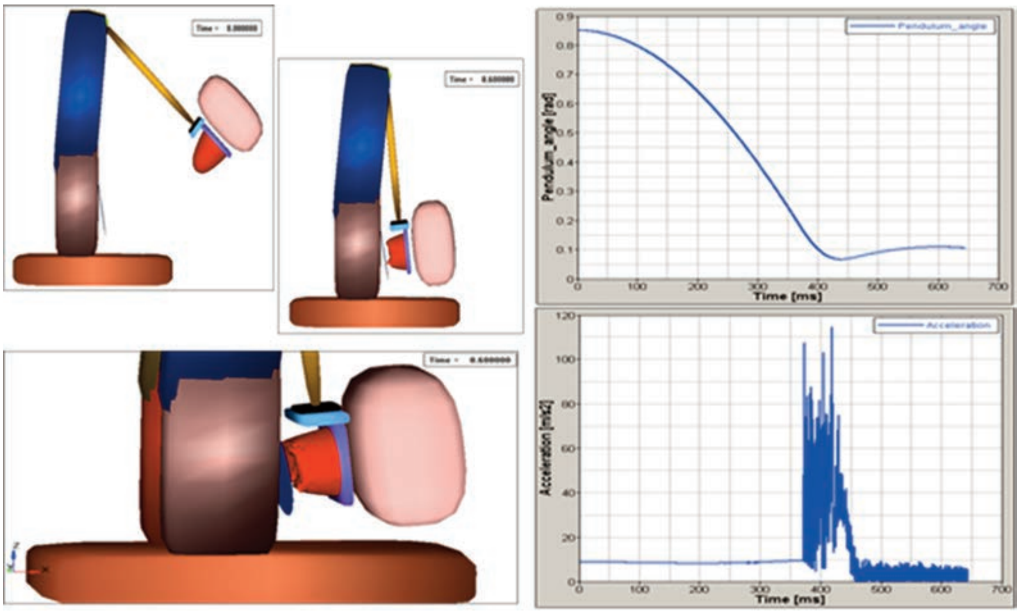


Figure 17. Results of an impact test stand experiment

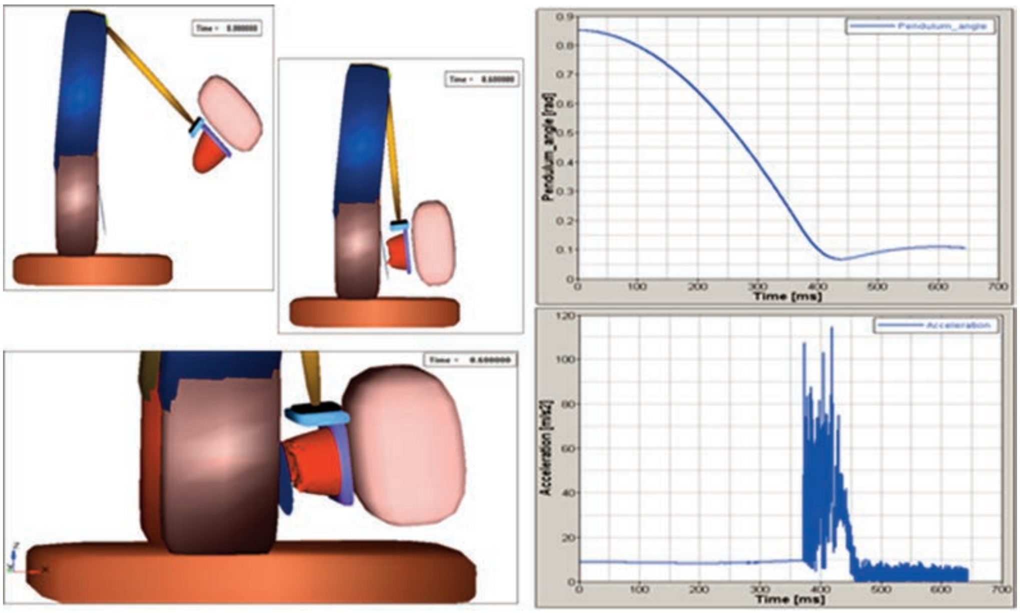


Figure 18. Results of numerical simulation (MADYMO)

Time histories of some quantities (pendulum angle and acceleration) allow for validation of a numerical model by choosing proper values of the model parameters. One can observe that the values as well as the time histories obtained from the numerical simulation (Fig. 18) are in quite good accordance with the results of the experimental test.

CONCLUSIONS

The experimental investigation reported here led to the following conclusions:

- The glider accident simulated in the Crash Test No 1 can be considered a minor one in view of both the glider structure and the pilot. Crash at the limited speed (54.7 km/h) does not cause any serious damage to the glider cockpit structure which successfully ensures an adequate safety level. Also, based on load time histories and the injury criteria, it is reasonable to expect the pilot would have survived the accident without any serious injuries. It should be emphasized that high deformability of soil (due to high energy absorption) was decisive for the results obtained. In the case of a crash onto a real airfield, an outcome could have been 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 low loads. The highest loads were acting upon the spine, which is commonly observed in glider accidents. This was due to the pilot's body position and orientation relative to the cockpit (close to the direction of loads) as well as the fact that the pelvis and spinal column are 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 by the automotive industry). However, direct comparison of the results presented here and the data included in the regulations on cars is impossible due to different designs and arrangements. It seems desirable that in the future some criteria for the loads in the glider safety belts be formulated. There was no canopy in the Crash Test 1. However, the movie proves that the dummy must have definitely hit the canopy, which could generate additional loads acting upon the pilot's head and arms.
- Shortages in the experimental equipment made it necessary to ignore the forces acting upon the neck and pelvis, the injuries of which are commonly observed in real life.
- Crash Test 2 showed, as expected, that hitting a rigid barrier at a speed of about 80 km/h caused severe damage to the cockpit structure. The resulting large values of accelerations led to the collapsing of the structure leaving the pilot with no chance of surviving.
- The results of Crash Test 2 indicate how valuable is the experience gained from the Formula 1 racing where appropriate design (and manufacturing) of a structure gives good protection of the human body even in the case of a crash at a speed exceeding 200 km/h. It should be strongly recommended that all glider constructors increase the crashworthiness efforts during the design process.

- The results of the computations made with the MADYMO software give reasons to believe that in the nearest future simulating of a crash in a realistic way will be possible. Using a numerical model of a crash phenomenon allows saving of experimental research funds as well as the time needed for the investigations. Numerical modeling of the crash will be a great advantage from the research point of view.

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