Experimental Investigation of the Crash-worthiness of Scaled Composite Sailplane Fuselages

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Abstract

Studies were conducted to improve the crash dynamics and energy absorption of composite sailplane fuselages in a nose down impact resulting from stall/spin accidents. Quasistatic and dynamic tests were conducted on quarter scale structurally similar composite models. The quasistatic tests were found to replicate fully, the loads and failure modes observed in the dynamic tests. Fiber materials and cockpit design techniques were experimentally examined. Energy absorption was improved by over 280% over a typical fiberglass reference fuselage by the use of a combination of fiberglass and polyethylene fiber materials, the extension of the pilot's seatpan as a structural member and the reinforcement of the canopy sill.

Introduction

According to the FAA and Soaring Society of America (SSA) statistics, stall/spin accidents account for 68% of all glider fatalities. A study was, therefore, conducted to improve composite glider fuselage design in the area of survivability after nose down impact, which commonly occurs after stall at low altitude. For metal aircraft, design guidelines for crashworthy structures are based on years of experience and are well established [1]. The recent advent of composite aircraft primary structures results in a more limited set of design guidelines, which are generally restricted to subcomponents such as energy absorbing devices and the subfloor structure. These devices are of limited value for glider type designs. The forward fuselages of current high performance gliders are little more than an aerodynamic fairing which give very little protection during a nose down impact. Because aerodynamic performance is critical to glider design, the addition of any significant structure or wetted area only for the purpose of crashworthiness is difficult to justify, due to large performance penalties.

Most current high performance sailplanes are designed to meet the airworthiness standards of FAR/JAR 22 [2], which simply require a glider forward fuselage to withstand safely, the loads during aerotow and not to fail when a load of six times the gross weight is applied at an angle of 45 degrees (up and back) on the fuselage nose. A glider, designed according to current regulations, could decelerate the pilot safely in a 45 degree nose down impact at a maximum sinking speed of approximately 5m/sec, if a triangular deceleration pulse is assumed. It should be noted that the typical stall speed of current sailplane designs is about 20m/sec, and that during the stall the angle of attack and the pitch angle increase without changing the forward speed, thus increasing the sink speed. This implies, that for a typical stall/spin accident, only a small fraction of the kinetic energy at impact could be absorbed by the fuselage. The inadequate energy absorption is thought to be a factor in the high fatality ratio for glider stall/spin accidents.

In order to improve crashworthiness, the maximum fuselage load tolerance must be increased. In addition, the deceleration pulse should, if possible, be tailored to a more rectangular shape. The optimum deceleration pulse consists of a steep rise, followed by a constant deceleration at the maximum tolerable level. For this pulse shape, the maximum deceleration does not change significantly with impact speed, but the necessary crush length will increase with the kinetic energy. If the fuselage is designed to fail at a constant force, the deceleration will increase with decreasing glider mass. Therefore, the maximum load the fuselage must withstand should be calculated with the minimum glider gross weight rather than the maximum gross weight to avoid underestimating the deceleration peaks.

The pilot's deceleration tolerance is limited by spinal loads, which were simulated with a dynamic response model that evaluates the deflection of a lumped mass (representing the torso) connected to a spring (representing the spine) under actual g-loading [3]. Solving a differential equation yields an index, the DRI, which directly corresponds to survival possibility. The maximum load in spinal direction for a typical impact with 0.1 sec. duration was found to be 16g for a triangular deceleration pulse shape and 11g for a rectangular deceleration pulse shape [4,5]. As can be seen from Figure 1, the DRI rises slightly for an inversed or sine pulse shape, and is 1.4 times the value of the triangular pulse for a rectangular pulse shape.

In typical glider fuselage geometries, the stopping distance necessary to decelerate the pilot safely is larger than the available distance between the pilot's seat and the ground at impact. For such a fuselage design, the peak deceleration would need to be in the order of 35g, assuming a triangular deceleration pulse shape, and 17.5g assuming a rectangular pulse shape, to stop the pilot prior to seat impact on hard ground. The limit of 16g (resp. 11g) implies, however, that the pilot will not be stopped safely within the available stopping distance. However, if the impact occurs on soft ground, the increased stroke and energy absorption capability provided by the ground can give the pilot a good chance of survival. Since the limited stiffness of the structure makes the rectangular pulse impossible, it is desirable to design the fuselage to fail at loads in the order of 16g and to provide as much stroke as possible within the existing performance constraints.

Method of investigation

Crash simulations on quarter scale structurally similar models were conducted to investigate and improve fuselage design with the goal of decelerating the pilot at a constant level, corresponding to the maximum human deceleration tolerance in spinal direction. An advantage of the composite materials used in glider aircraft is that the original structure can be modeled accurately at subscale by use of lighter weight, finer weave materials for the model construction.

For subscale testing to be useful, however, the structural response produced in a scale model impact must be the same as in the full scale crash [5]. Because the models use the same materials as the original fuselages, the density, modulus and stresses are the same. Therefore, the quarter scale of the models implies that the mass and energy must be reduced by a factor of 64 and the forces by a factor of 16. Gravity, which should, in principle, be increased by a factor of 4, cannot be changed. However, it is of importance only after impact, when the aircraft slides on the ground and friction forces determine the load on the structure. During the primary impact, the gravitational forces are small in comparison to the elastic and inertial forces that determine the structural response. Therefore, gravity can be neglected in the impact analysis.

Ideally, the model tests should be run at 4 times normal speed for correct scaling. However, the duration of the impact is longer than the critical time 2 l/c (where l denotes the maximum length and c the speed of sound in the material). This implies that the stress distribution should not be time dependent and that quasistatic testing should be an appropriate technique to study fuselage impact behavior. Quasistatic testing allows improved monitoring of the structural response and more careful control than dynamic testing. To confirm the quasistatic approach and to identify any time dependent effects such as strain rate or viscosity, a series of experiments were conducted to compare failure modes of identical test articles in dynamic and quasistatic tests.

Test setup

The tests involved both models of different structural design, as well as different materials such as E-glass, aramide, graphite and ultra high molecular polyethylene. The fuselage model layup was developed from original plans of four representative high performance sailplanes to resemble a mean value of shell thickness and fiber orientation. The main structural members, which can be seen in Figure 4, consist of a shell, a box beam canopy sill and a seatpan. The model construction technique was identical to that used in full scale construction of glider aircraft (hand layup with female molds). A total number of 13 fuselages were tested, and the results of five are presented here in detail. The first fuselage was built with E-glass/epoxy Epon 815. To offset the relatively high specific weight and low specific strength of E-glass, two layers of E-glass were replaced by one layer of Kevlar 49 of approximately the same weight in the shell of the second fuselage forward of the line shown in Figure 4. The seatpan of this fuselage, labeled the Kevlar/E-glass fuselage, was an all Kevlar construction. In the third fuselage, the Kevlar was replaced by a layer of Spectra 900, a new polyethylene fiber with an exceptionally high specific strength, made possible by an extremely high molecular weight. In addition, a fuselage similar to the Kevlar fuselage in which the E-glass was replaced by graphite (T-300) was added to the tests.

The quasistatic test setup is shown in Figure 2. Each fuselage was clamped in the base of a hydraulic testing machine with a maximum stroke of 127mm (Y). This stroke limitation made it necessary to run the quasistatic tests in two steps to reach the desired stroke of 250mm. The opposite clamp of the machine held a greased steel plate with an inclination of 45 degrees, which ensured that the resulting contact force acted parallel to the backrest and the pilot's spine. This corresponds to a pitch angle 6 = 40 degrees. Only the load component in stroke direction was measured. Because the contact plate was angled under 45 degrees, the resulting load applied to the fuselages was 1.41 times higher. Five strain gages were bonded to the models at different locations, three of which are shown in the figure. The tests were run at a constant stroke of 50mm per minute and were documented by video and still photography.

The dynamic test setup is shown in Figure 3. Fuselages were mounted to a swing assembly consisting of two wire braced aluminum bars. The same base structure used in the quasistatic tests was employed. A rigid aluminum plate acted as the contact surface. Because of apparatus limitations, it was not possible for both the impact speed and the energy to be scaled properly at the same time. The impact speed was, therefore, set to 6.5m/sec to match the scaled energy of the quasistatic tests. The signals from three strain gages and an accelerometer measuring deceleration in longitudinal direction were monitored with a digital oscilloscope. A strobe synchronized video camera was used to provide stop action video of each impact.

Results

In the quasistatic tests, the fuselages generally deformed elastically until the seatpan delaminated from the fuselage shell. This resulted in a load drop, occurring at 55mm stroke for the E-glass fuselage (Figure 5), and was followed by a fracture of the nose, which allowed the canopy sills to fold out and the longitudinal load dropped to a level of 500N to 600N. This reduced load would correspond to a deceleration of only 3.5 to 4.2g for a 3301 gross weight glider. The Kevlar/E-glass fuselage behaved similarly, its seatpan de-bonding at 49mm, again to be followed by the fracture of the nose and a load drop to 500N to 600N (Figure 6).

In comparison to the E-glass and Kevlar seatpans, the Spectra seatpan did not break abruptly but peeled slowly (Figure 7), so that the fibers were pulled out of the matrix. After the test, the bonded side of the seatpan consisted only of fibers, which had been pulled out of the epoxy matrix on the fuselage shell. The Spectra layer of the third fuselage prevented the nose from fracturing and, therefore, kept the load at 800N, corresponding to 5.6g. Because the nose did not fail, higher stresses resulted in the canopy sill of the Spectra/E-glass fuselage, which broke near their longitudinal midpoint at strokes of 125mm and 152mm, respectively. The canopy sill failure in the F-glass and Kevlar/E-glass fuselages occurred between 160mm and 228mm stroke, which resulted in an energy absorption of 152J and 142J, respectively, up to the maximum stroke of 247mm, when the pilot's seat would have impacted the ground. Due to the early failure of the canopy sill, the energy absorption capability of the Spectra/ E-glass fuselage was similar at 148J, however, the more constant load distribution provided a more favorable failure behavior.

The maximum load of the E-glass fuselage in spinal direction of 1626N, if increased to full scale, corresponds well to the 6g certification requirement in JAR 22 for a typical sailplane gross weight of 480kg. The model fuselage mass of 498g scales to 32kg at full scale, which is in fairly good agreement with typical forward fuselage structural masses. The good agreement in scaled loads and structural masses between model and actual sailplane fuselages enhances the confidence in the scaling approach and the test results.

The dynamic tests supported the results of the quasistatic tests by producing the same failure modes and fracture patterns. The only difference between both test modes was a slight rotation of the fuselages in the dynamic test, due to the flexibility of the swing apparatus which delayed the failure events slightly. An example is shown in Figure 8 for the Kevlar/E-glass fuselage and its identical counterpart used in the dynamic test. The strain gage values are almost identical in the dynamic and quasistatic tests, apart from a delay of about 20mm (equivalent to a rotation of 2 degrees) for the events in the dynamic tests. The minor discrepancies between the readings of gages 1 and 2 in the quasistatic test from 170mm stroke are thought to be due to the occurrence of delamination of the canopy sill exactly at the gage locations on the quasistatic test article. Comparison tests were also conducted for the Spectra/E-glass fuselage and a fiberglass fuselage with internal structural modifications with similarly good agreement between the quasistatic and dynamic failure modes.

Discussion of the results

The results from both the dynamic and quasistatic tests indicate that the seatpan could well be used to stiffen the fuselages by holding both sides of the canopy sill together. Also, since seatpan failure marked the maximum load, its delamination controls the maximum load the glider can withstand. The failure mode of the canopy sill was, in all cases, a delamination of the inner and outer fiberglass layers, resulting in a compression failure in each separated layer. Therefore, the integrity of the seat pan bonding and the nose are seen to be important for maintaining a controlled deceleration pulse at the desired load.

Due to the low compression strength of the organic fibers (Kevlar and Spectra), they have a lower bending stiffness than E-glass. This allowed the early delamination of the seatpan. The high tensile strength of aramide could not prevent, only delay, the nose from breaking. Also, the graphite/Kevlar fuselage showed an unfavorable fracture behavior, although absorbing 40% more energy. The graphite structure broke catastrophically, resulting in high load changes. In addition, the fracture resulted in sharp forward facing edges, which have been observed in accidents to dig in the ground, resulting in high g-loads in longitudinal direction.

The use of Spectra has the potential of preventing premature failure of the structure with little weight increase. Due to its low compression strength, however, Spectra should be employed only in areas loaded in tension. Therefore, the canopy sill, which loads mainly in compression, should be made of fiberglass, enabling the sill to remain intact up to high strokes owing to its low modulus. A combination of fiberglass and Spectra appears, therefore, to be the best material choice of those examined.

Improved fuselage results

Numeric simulation using a finite element code (ADINA) were run on a MicroVax II computer to investigate the potentials of finite element codes in crash research. The load distribution and the deformation could be modeled very accurately for the different fuselage geometries in the linear deformation range. Since no realistic failure could be simulated even when nonlinear material models were used, the computations were only useful for optimizing seatpan design and strain gage locations and comparing the load distribution at different impact angles. It could be shown, that the seatpan can be used as a load limiting device in order to control the maximum load in an impact. After seatpan failure, proper dimensioning of the sills allows to keep the load at the desired level.

To investigate the benefits of the proposed modifications, an additional, improved fuselage was built and tested. The seatpan geometry is extended forward so as to distribute the stress peak in transverse tension, which leads to early delamination. In addition, an improved construction technique, which reduces the peel sensitivity of the seatpan bonding, is employed. This is accomplished by first bonding in an E-glass frame and then adding an opposing E-glass corner layer (see section in Figure 9). A thicker canopy sill can be used to raise the stiffness, but will have a higher stress level at the same stroke and, therefore, fail earlier. The thickness chosen in the model (10mm) ensured that the canopy sill kept the load at a high level up to the maximum stroke. The canopy sill was built around a tube of diagonal layers wrapped around a foam core, the fibers ran from the outside to the inside layers to prevent delaminations.

The materials used in the improved model were a combination of Spectra and E-glass. Since Spectra with its extreme specific strength had proven to efficiently prevent fractures, the shell and the seatpan consisted of a Spectra layer, covered on both sides with a thin glass layer for better bending stiffness and bonding properties. The seatpan frame and the canopy sill used only E-glass, because here the bonding and compression strength are of greatest importance. Because of material availability, only bi-directional fabric was used, so weight increase was 50% higher than necessary. If unidirectional layers would have been employed for the reinforcement, the weight would have been about 650g. The structural improvements would correspond to an increase of only 3.8% of the sailplane empty weight.

In the quasistatic test, the delamination of the seatpan began at a load of 1850N and a stroke of 60mm and resulted in a flattening of the load increase (see Figure 10). The maximum load was reached at a stroke of 125mm with 2535N, equivalent to 18.4g in an impact. The load drop at 127mm is artificial and caused by the resetting of the testing machine due to the limited maximum stroke. The drop at 146mm and 151mm stroke indicates the final failure of the seatpan. The bonding of the frame to the fuselage shell partially peeled and the frame partially broke. The high number of layers in the canopy sill limited the load drop to 1770N and let it grow to 2220N at 245mm. At this point, the test was discontinued, neither the canopy sill nor the nose having failed. At 153mm the glass layers of the shell began to develop cracks, but the polyethylene layer prevented them from growing and leading to a premature failure of the canopy sill. On the inside of the canopy sill, the layer on the surface showed delamination bubbles, indicating extreme compression. The absorbed energy was with 432J approximately three times larger than for the earlier fuselages, and the failure mode was extremely favorable, being almost universally away from the pilot and leaving the seatpan nearly undamaged. The higher apparent stiffness of the improved fuselage is partially a result of an improved test mounting. Figure 11 summarizes the results of each quasistatic test and includes the specific energy, which is the absorbed energy related to the mass of the fuselage, and the absorbed energy referred to the kinetic energy of a 330kg sailplane in an impact with pitch angle α = 40 degrees and angle of attack θ = 10 degrees at 20m/sec.

Conclusion

The dynamics of a nose down impact occurring after a stall at low altitude were investigated and quarter scale composite model tests were conducted to improve sailplane fuselage design and testing technique. The following results were observed:

-Sailplane fuselage geometries and the limited deceleration tolerance of the pilot make the safe deceleration of the pilot in a nose down impact only possible with significant changes in fuselage design or additional energy absorption from the ground.

-Impact behavior of composite fuselages was found to be similar in quasistatic and dynamic tests, both in terms of failure modes and stress at failure.

-Fuselages constructed of glassfiber, Kevlar 49, graphite T-300 and Spectra 900 polyethylene fiber were tested. The best energy absorption was achieved with a fuselage using a combination of Spectra and fiberglass. Owing to its high tensile strength, Spectra yielded the best results by successfully preventing tension cracking, and glassfiber showed the best performance for structural components loaded in compression.

-Modifications in the geometry of structural members, including the extension of the seatpan and improvement of the bonding to lower peel sensitivity, and reinforcement of the canopy sill were found to improve energy absorption significantly.

-Energy absorption was improved by a factor of 2.8, from 152.9 Joule for the fiberglass fuselage to 432.1 Joule, by use of the structural changes mentioned above and the correct application of Spectra and E-glass.

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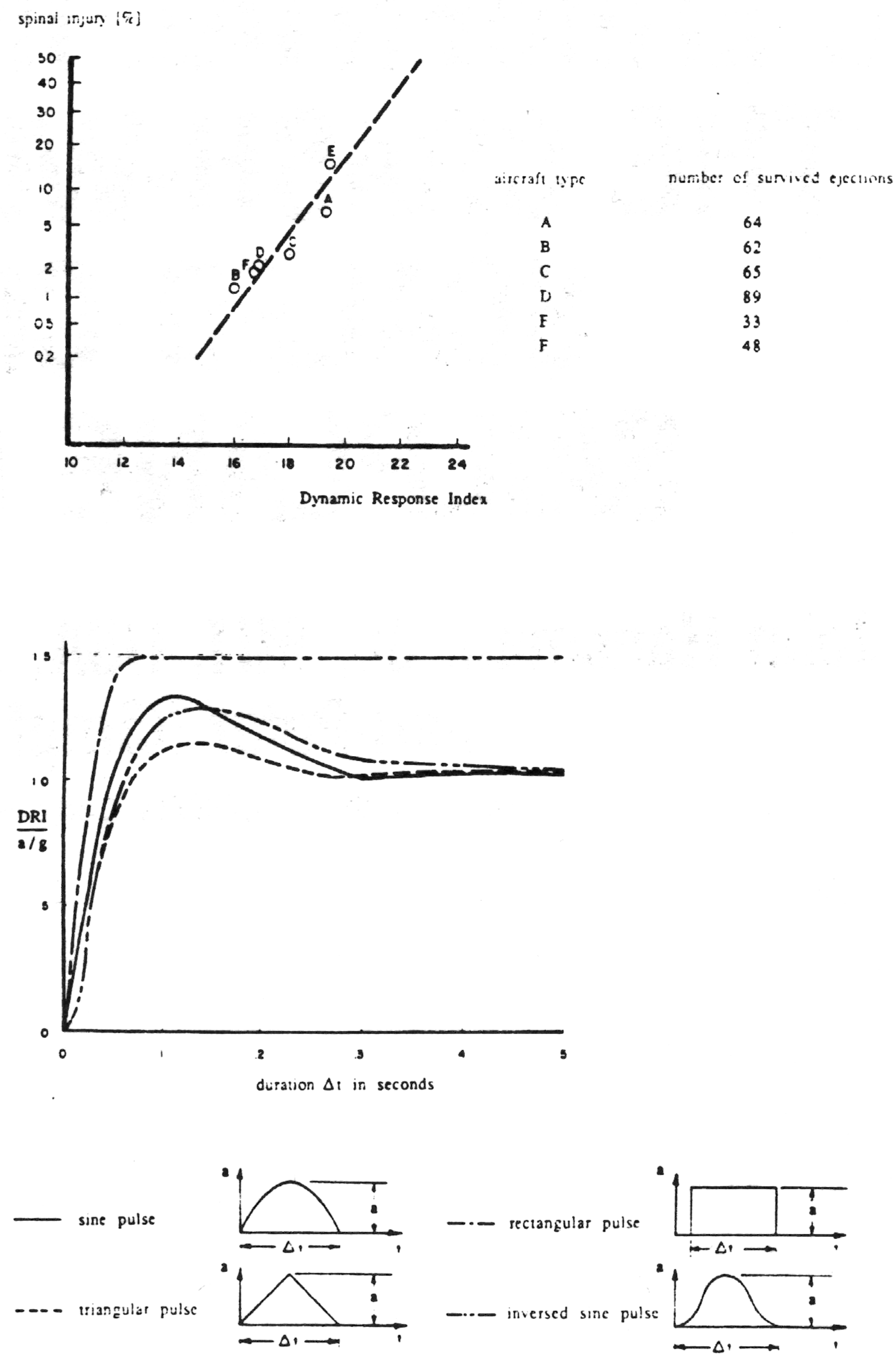

Figure 1 Correlation of the DRI and dependence on deceleration pulse shape.

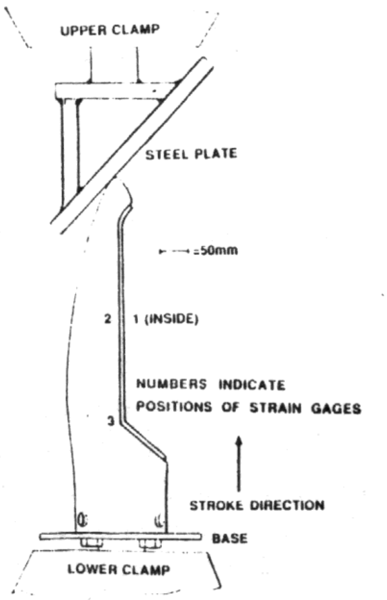

Figure 2 Quasistatic test setup.

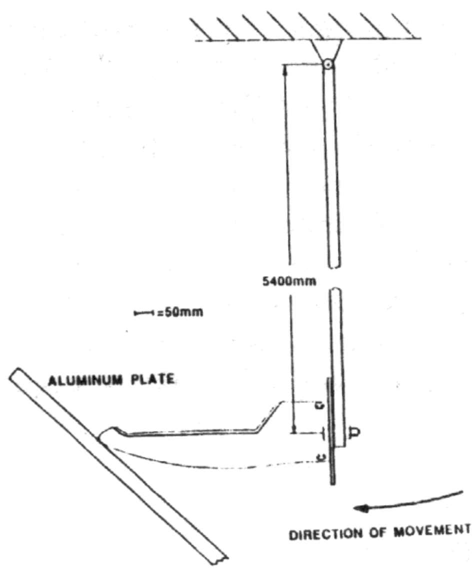

Figure 3 Dynamic test setup.

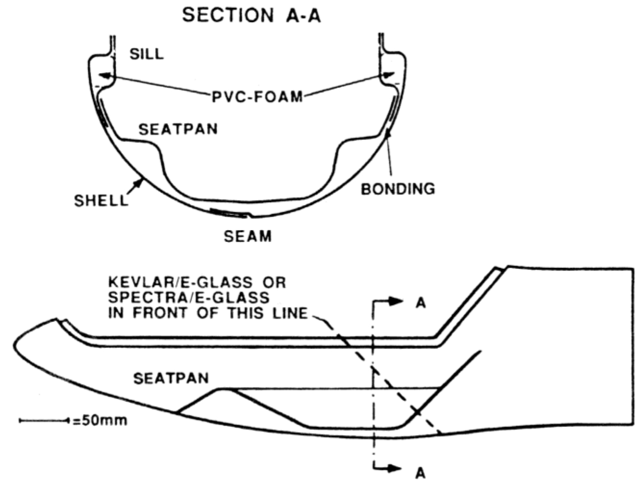

Figure 4 Geometry of the test fuselage articles.

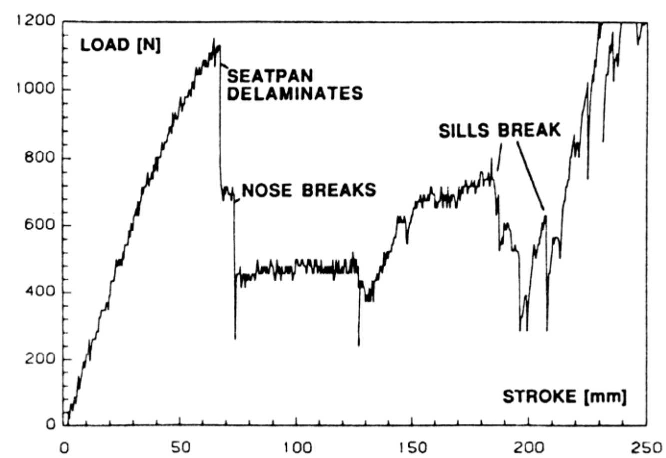

Figure 5 Load vs. stroke for the E-glass fuselage.

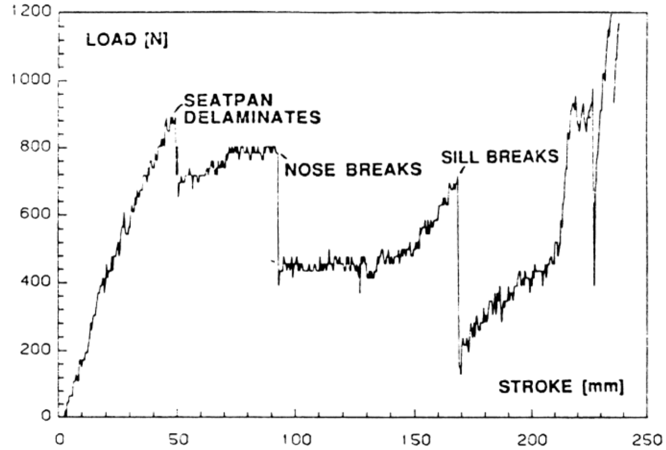

Figure 6 Load vs. stroke for the Kevlar/E-glass fuselage

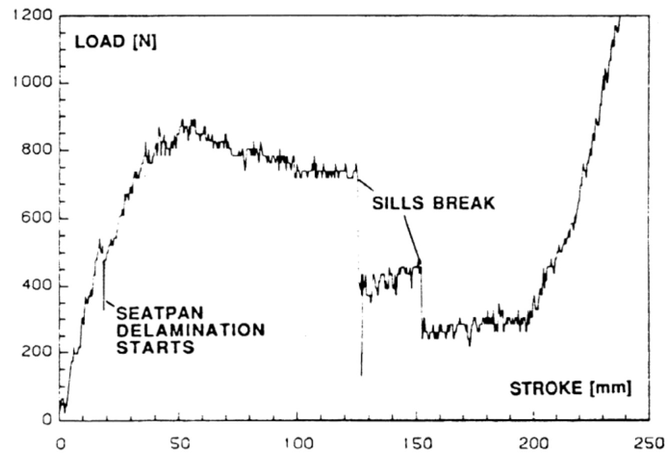

Figure 7 Load vs. stroke for the Spectra/E-glass fuselage

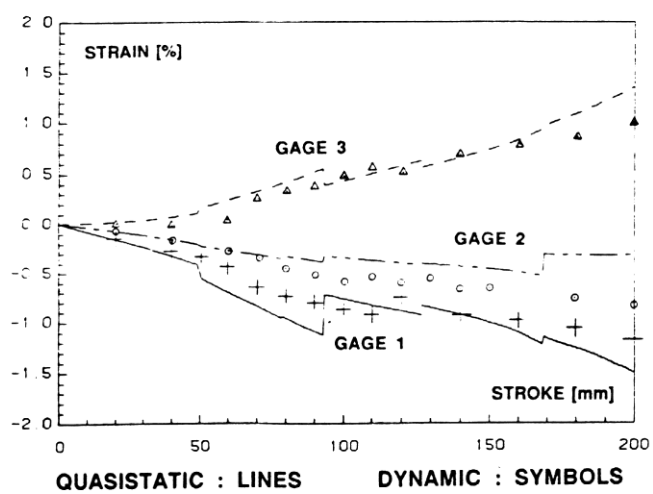

Figure 8 Comparison of the strain gage readings for quasistatic and dynamic test.

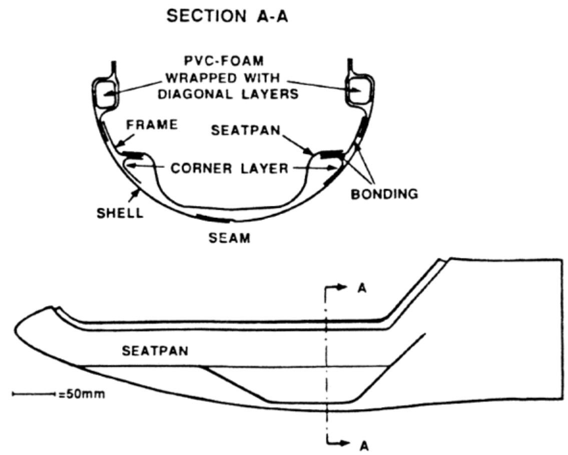

Figure 9 Geometry of improved fuselage.

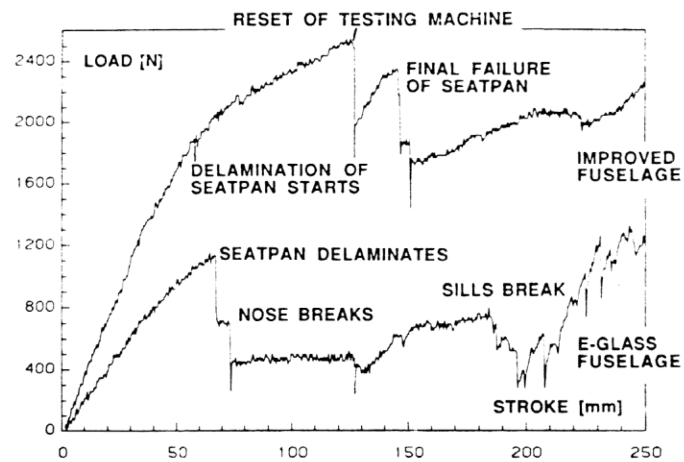

Figure 10 Load vs. stroke for the improved fuselage and comparison to E-glass fuselage.

Fuselage	Absorbed energy [J]	Longitudinal load component [N]	Resulting maximum load [N]	Specific energy [J/g]	Specific energy absorption [%]
E-glass	152.9	1150	1626	0.307	24.5
Kevlar/E-glass	141.5	890	1259	0.28	22.7
Spectra/E-glass	148.0	880	1245	0.282	23.74
Graphite	214.1	1230	1739	0.463	34.3
Improved	432.1	2540	3592	0.57	70

Figure 11 Summary of the quasistatic tests.