Experimental Investigation of the Crashworthiness of Scaled Composite Sailplane Fuselages

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The crash dynamics and energy absorption of composite sailplane fuselage segments undergoing nose-down impact were investigated. More than 10 quarter-scale structurally similar test articles, typical of high-performance sailplane designs, were tested. Fuselages segments were fabricated of combinations of fiberglass, graphite, Kevlar, and Spectra fabric materials. Quasistatic and dynamic tests were conducted. The quasistatic tests were found to replicate the strain history and failure modes observed in the dynamic tests. Failure modes of the quarter-scale model were qualitatively compared with full-scale crash evidence and quantitatively compared with current design criteria. By combining material and structural improvements, substantial increases in crashworthiness were demonstrated.

Introduction

AFTER one-half century of experience, the guidelines for the crashworthy design of metallic aircraft structures are well established.[1] The design of composite aircraft structures is guided by a more limited set of criteria, which are primarily applicable to subcomponents such as energy-absorbing devices and subfloor structures. These guidelines are of limited value in the design of primary structures, such as the forward fuselage of an all composite aircraft. Such designs are not as yet widespread in military, commercial, or business aircraft, but they dominate the design of one category of civil aircraft: modern high-performance gliders. Because of their high degree of structural and aerodynamic optimization and relative maturity as a composite structure, the modern glider fuselage was taken as a case study in the investigation of crashworthiness of composite fuselages.

In the traditional design of high-performance composite sailplanes (gliders), the forward fuselage is primarily thought of as aerodynamic fairing, which gives little protection to the pilot in the event of a nose-down impact.[2] Because aerodynamic performance is critical to sailplane design, the addition of any significant structure or wetted area exclusively for the purpose of crashworthiness is difficult to justify. However, this lack of pilot protection is thought to underlie a pattern in glider accident statistics. According to Federal Aviation Administration (FAA) and Soaring Society of America (SSA) statistics, stall/spin accidents account for 68% of all glider fatalities. These accidents commonly involve a nose-down impact after a low-altitude stall. This study was, therefore, conducted to understand and improve composite fuselage design in the area of survivability after nose-down impact. Although the specific application is to composite glider design, the test techniques and design guidance developed are generically applicable to composite fuselage design.

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Crashworthy Design Factors

In modern crashworthiness design, four factors are considered: maximum allowable deceleration, deceleration pulse shape, crush length, and structural-crush failure load. The maximum deceleration is set by the limits of human endurance. The optimum deceleration pulse consists of a steep rise, followed by a constant deceleration at this maximum deceleration level. For this pulse shape, the maximum deceleration level does not change significantly with impact speed, but the necessary crush length will increase with increasing kinetic energy. The fuselage should be designed to fail at a constant force, which corresponds to this deceleration. Since the deceleration will increase with decreasing aircraft mass, the maximum load the fuselage must withstand is set by the minimum expected aircraft gross weight.

The pilot's deceleration tolerance is limited by spinal loads. These have been measured under controlled laboratory conditions and simulated with dynamic-response models. These models evaluate the deflection of a lumped mass (representing the torso), connected to a spring (representing the spine) under the modeled g-loading.[3] The maximum load in spinal direc-

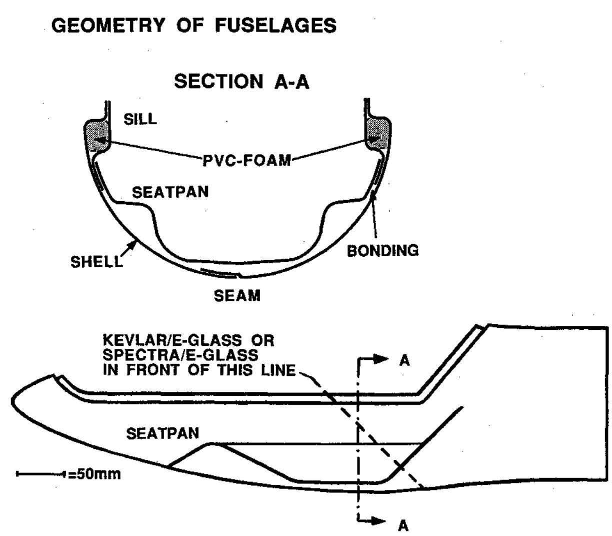

Fig. 1 Geometry of the baseline fuselage test articles.

tion for a typical impact of 0.1 s duration was found to be 16 g for a triangular deceleration pulse shape and 11 g for a rectangular deceleration pulse shape.[4,5] In the structural arrangement of a glider, the pilot's seat is closely coupled to the primary fuselage structure (Fig. 1). This arrangement does not allow for any significant energy absorption in the seat support. In such a case, the structural deceleration must be kept to the limits of human endurance. Current regulations for the certification of gliders do not reflect this line of reasoning in specifying the crashworthiness design criteria.

High-performance sailplanes are traditionally designed to meet the Joint Airworthiness Requirements of JAR,[2] which require that a glider's forward fuselage endure a load of six times the gross weight statically applied at an angle of 45 deg (up and back) on the fuselage nose. Based on these requirements, a glider would only decelerate the pilot safely up to approximately 10 m/s impact (45 deg nose-down impact triangular deceleration pulse). Note that this is only half the typical stall speed of current sailplane designs. This inadequate energy absorption is thought to be a major factor in the high fatality ratio for glider stall/spin accidents.

Based on the pilot deceleration tolerances just discussed, estimates of the required improvement in performance can be made. Gliders suffer from two primary constraints: First, there is an almost direct coupling of the pilot's seat and the fuselage. This restricts the allowable fuselage deceleration to the level of the human endurance limit. Second, most sailplanes have a limited crush length. In typical glider fuselage geometries, therefore, the stopping distance necessary to decelerate the pilot safely is larger than the available between the pilot's seat and the ground at impact. For typical fuselage dimensions, the peak deceleration to stop the pilot prior to seat impact on hard ground would need to be on the order of 35 g (assuming a triangular deceleration pulse shape), and 17.5 g (assuming a rectangular pulse shape). Taking even the upper limit of human endurance of 16 g, it is clear that the pilot will not be stopped safely within the available crushing distance. If the impact were to occur on soft ground, however, the increased stroke and energy absorption capability provided by the ground could give the pilot a good chance of survival. Since the limited stiffness of the structure makes the ideal rectangular pulse impossible, it is therefore desirable to design the fuselage to fail at loads in the order of 16 g and to provide as much stroke as possible within the existing geometric constraints.

Research Objectives

It is the objective of this research to address the dual goals of developing and verifying the effectiveness of scaled model, quasistatic crash-simulation techniques and using them to develop improved design guidance for composite fuselages.

Two issues will be addressed that arise from the first and more generic of the research goals. The first question is whether a quasistatic test is sufficiently representative of the dynamic environment. To address this, both quasistatic and dynamic tests were conducted and their results compared. The second question is whether scaled models of composite structures sufficiently model the elastic-plastic behavior and failure mechanism to be used in developing meaningful crash data. In this research, full-scale tests were not performed, but the failure sequence and damge patterns of the quarter-scaled models were qualitatively compared with the field evidence of gliders damaged in crashes. Further, the failure loads measured in the laboratory were quantitatively compared to the JAR 22 design specification. Both the qualitative and quantitative comparisons indicate the scaled model approach is valid.

The second, more specific research goal of developing design guidance for gliders raises issues of understanding of fracture sequence, sensitivity of crash behavior to choice of fiber and structural detail, and the possibility of significant improvement in crashworthiness.

Experimental Approach

Model Scaling Critera

Crash simulations on quarter-scale, structurally similar replica models were conducted to investigate and improve fuselage design, and to verify the usefulness of quasisteady testing. For subscale testing to be useful, however, the structural response produced in a scale model impact must be the same as in a full-scale crash.[6] At a minimum, this requires good structural similitude in the model and proper application of the scaled loads. In order to accurately model the fuselage, the quarter-scale models were built of the same fiber materials as the full-scale aircraft, but with lighter-weight weave materials. When possible, the fabrics used were one-fourth the thickness of the full-scale fabrics, so that all dimensions, including interlaminar dimensions, were properly scaled. Because the models use the same laminates and material as the full-scale fuselages, the density, modulus, and strain under stress were the same. The quarterscale of the models implies that the mass and energy must be scaled by a factor of 64 and the forces by a factor of 16. For complete scaling, the gravitational acceleration should be increased by a factor of 4, however, during intial impact, the gravitational forces are small in comparison to the elastic and inertial forces that determine the structural response. Therefore, the improper scaling of gravity will not significantly influence the scaled crash response.

Baseline Fuselage

Table 1 lists the fuselage types for which results are presented in this article. The basic fuselage design is shown in Fig. 1. The fuselage structural arrangement and model layup were developed by examining the plans of four representative high-performance sailplanes. A mean value of shell thickness and representative fiber orientations were chosen to be typical of current design practice. The main structural members, which can be seen in Fig. 1, consist of an outer shell, a box beam canopy sill, and an inner seatpan. The model-construction technique was identical to that used in full-scale construction of glider aircraft (hand layup with female molds). As summarized in Table 1, the reference fiberglass fuselage was built with four layers of E-glass fabric and room-temperature-cure epoxy resin E 815. This fuselage is most representative of recent construction techniques.

Kevlar/E-Glass Fuselage

In the second fuselage, two of the four layers of E-glass were replaced with Kevlar[7] forward of the diagonal dashed line shown in Fig. 1. Unfortunately, sufficiently lightweight Kevlar cloth could not be obtained, so one ply of Kevlar cloth of approximately the same weight as two plies of E-glass was used. The seatpan of the second fuselage was also made of Kevlar. This fuselage is designated as the Kevlar/E-glass fuselage.

Spectra/E-Glass Fuselage

In the third fuselage, designated the Spectra/E-glass fuselage, the Kevlar was replaced by a layer of Spectra,[8] a new polyethylene fiber with an exceptionally high specific strength, made possible by an extremely high molecular weight.

Table 1 Fuselage Materials

Fuselage designation	Material, shell	Material, seatpan	Mass, g
Reference	E-glass	E-glass	498
Kevlar/E-glass	E-glass/Kevlar	Kevlar	506
Spectra/E-glass	E-glass/Spectra	Spectra	525
Graphite/Kevlar	Graphite/Kevlar	Kevlar	462
Improved	E-glass/Spectra	E-glass/Spectra	758

Graphite/Kevlar Fuselage Design

The fourth fuselage was similar to the Kevlar/E-glass fuselage in which the E-glass was replaced by graphite fabric (T-300). This was designated as the graphite/Kevlar fuselage.

Test Procedure

Ideally, quarter-scale dynamic tests should be run at four times normal speed for correct scaling. However, in the actual crash, the duration of the impact is significantly longer than the critical stress propagation time $2L/C$ (where L is the characteristic fuselage length and C the speed of sound in the material). This implies 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 identify any time-dependent effects such as the strain rate or viscoelastic behavior, a series of experiments were conducted to compare failure modes of identical test articles in both dynamic and quasistatic tests.

Quasistatic Test Setup

The quasistic test setup is shown in Fig. 2. Each fuselage segment was clamped by the lower clamp of a hydraulic testing machine with a maximum stroke of 127 mm (5 in.). This stroke limitation made it necessary to run the quasistatic tests in two steps to reach the desired stroke of 254 mm. The upper clamp of the machine held a greased steel plate with an inclination of 45 deg, which ensured that the resulting contact force acted upward and aftward in the glider reference frame. This test condition was chosen to simulate a severe nose-down impact and also the JAR 22 certification condition. Only the load component in stroke direction was measured. Five strain gages were bonded to the models at different locations, three of which are shown in Fig. 2. The tests were run at a constant stroke of 50 mm/min and were documented by video and still photography.[9]

Dynamic Test Setup

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

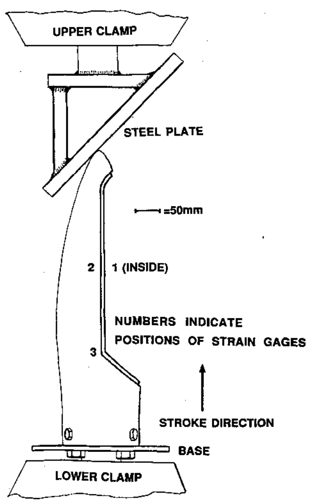

Fig. 2 Quasistatic test setup.

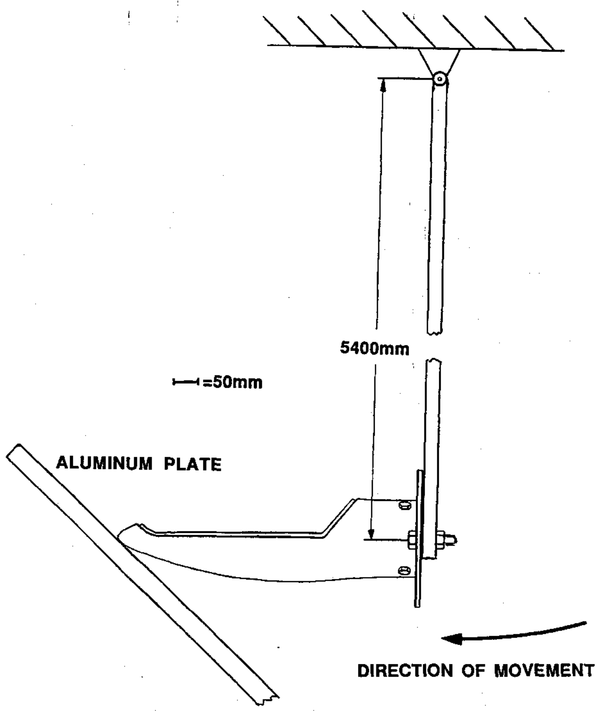

Fig. 3 Dynamic test setup.

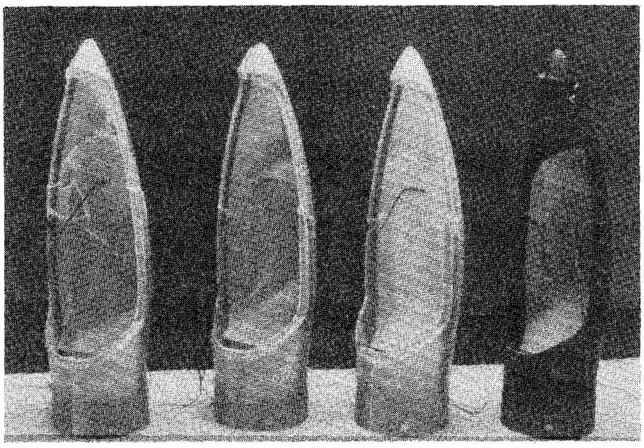

Fig. 4 Photograph of the quasistatic articles after the test. From left to right are the reference, the Kevlar/E-glass, the Spectra/E-glass, and the graphite/Kevlar fuselage segments.

Experimental Results

Baseline Fuselages

Quasistatic and dynamic tests were conducted on the four baseline fuselage designs to address the design issues of failure sequence and energy absorption characteristics, and the fundamental question of the validity of quasisteady scaled composite testing.

Quasistatic Results

The failure mechanism and energy-absorption characteristics observed in the quasistatic tests will be discussed first. They are summarized in Table 2, and the test articles are shown in Fig. 4. In these tests, the fuselages generally deformed elastically until the first damage, marked by the seatpan delaminating from the fuselage shell. This delamination can be seen in Fig. 5. The delamination resulted in a load drop, which occurrred at 55 mm stroke for the reference E-glass fuselage (Fig. 6), at 49 mm for the Kevlar/E-glass fuselage (Fig. 7), and from 19 to 56 mm for the Spectra/E-glass fuselage (Fig. 8). In the E-glass and Kevlar seatpans, the delamination was abrupt, but in the Spectra fuselage, the Spectra seatpan peeled slowly (Fig. 8). Spectra fibers were observed to have 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 second sequential damage site was at the nose, an example of which can be seen in Fig. 5. In the reference E-glass and Kevlar/E-glass fuselages, the seatpan delamination was followed by a fracture of the nose, which allowed the canopy sills to fold out and the longitudinal load to drop to a level of 500 to 600 N (see Figs. 6 and 7). When scaled to a corresponding full-scale resulting load, this load would correspond to a deceleration of only 3.5 to 4.2 g for a 330 kg gross weight glider. The Spectra layer of the Spectra/E-glass fuselage prevented the nose from fracturing, and therefore kept the load at approximately 800 N, corresponding to 5.6 g in full scale. It is clear that the seatpan and nose significantly stiffen the shell-sill structure. Therefore, the integrity of the seatpan bonding and the nose are seen to be important for maintaining a controlled deceleration pulse at the desired load.

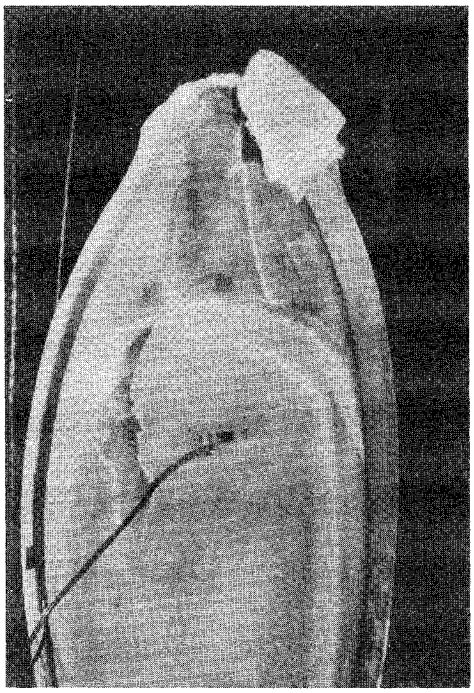

Fig. 5 Top view of the reference fuselage at 127 mm stroke showing seatpan delamination and nose fracture.

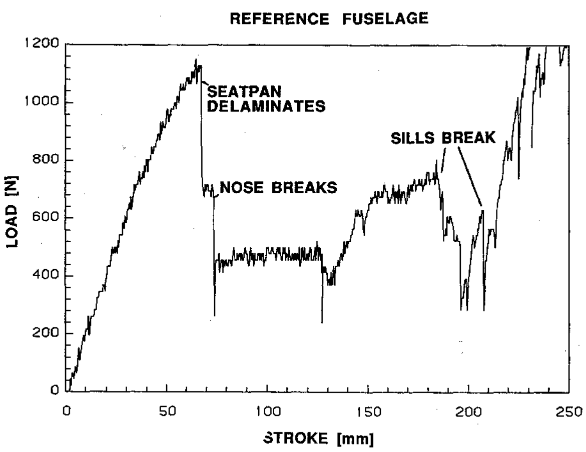

Fig. 6 Load vs stroke for the glass fiber reference fuselage.

The third failure site was in bending at the middle (fore to aft) of the canopy sill as can be seen on several of the test articles in Fig. 4. The canopy sill failure in the E-glass and Kevlar/E-glass fuselages occurred between 160 and 228 mm stroke. This resulted in a total energy absorption for the scale model of 152 and 142 J, respectively, up to the maximum stroke of 247 mm, when the pilot's seat would have impacted the ground. Because the nose of the Spectra/E-glass fuselage did not fail, higher stresses developed in the canopy sills at lower stroke. As a result, the two sills failed at their longitudinal midpoint at strokes of 125 and 152 mm, respectively. Because of the early failure of the canopy sill, the energy-absorption capability of the Spectra/E-glass fuselage was 148 J, similar to the reference E-glass and Kevlar/E-glass fuselages. However, the more constant load distribution provided a more favorable deceleration profile.

The graphite/Kevlar fuselage showed essentially the same pattern of damage, but a higher maximum load and energy absorption (Table 2). However, due to the brittleness of graphite, the fuselage showed an unfavorable fracture behavior. The graphite structure broke catastrophically, resulting in large load changes. In addition, the fracture resulted in sharp forward-facing edges,which have been observed in several accident investigations by the authors to dig into the ground, and are thought to result in high g-loads in longitudinal direction.

In establishing the failure sequence and load characteristics of the quarter-scale model, questions of how well the full-scale behavior was simulated remains. In the absence of well-documented full-scale data, two comparisons were made: a qualitative comparison with field evidence and a quantitative comparison with the design criteria, which presumably the full-scale aircraft satisfy. Five actual forward glider fuselages

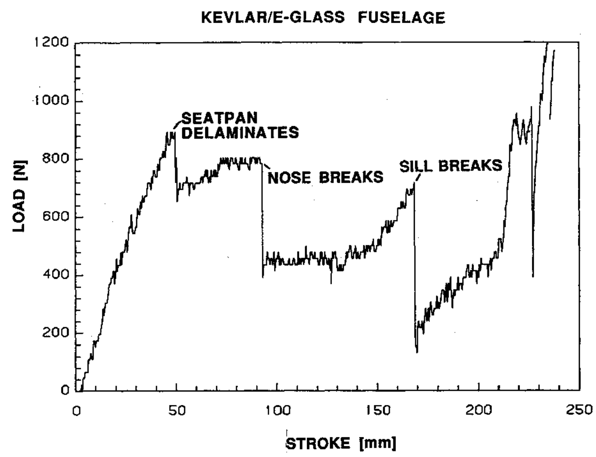

Fig. 7 Load vs stroke for the Kevlar/E-glass fuselage.

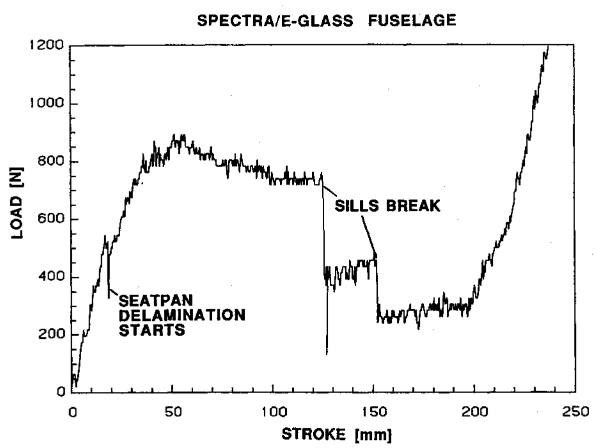

Fig. 8 Load vs stroke for the Spectra/E-glass fuselage.

Table 2 Summary of the quasistatic tests

Fuselage designation	Absorbed energy, J	Longitudinal load component, N	Resulting maximum load, N	Specific energy absorbed, J/g	Fractional energy absorption, %[a]
Reference	152.9	1150	1626	0.307	24.5
Kevlar/E-glass	141.5	890	1259	0.280	22.7
Spectra/E-glass	148.0	880	1245	0.282	23.7
Graphite/Kevlar	214.1	1230	1739	0.463	34.3
Improved	432.1	2540	3592	0.570	70.0

[a]Percent (%) of kinetic energy absorbed, based on a 330 kg sailplane impacting at 45 deg with a velocity of 20 m/s.

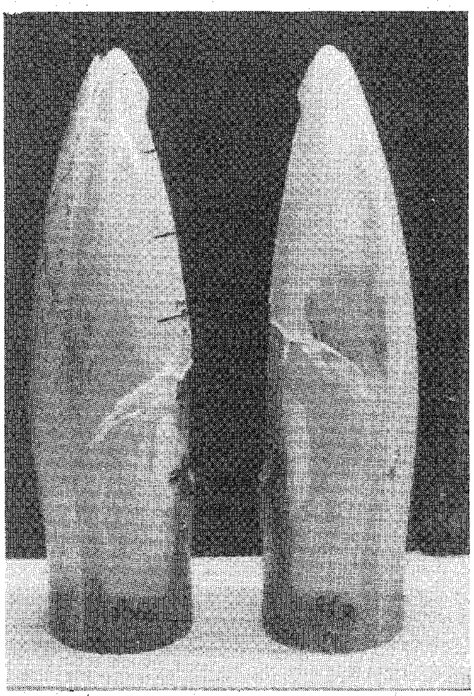

Fig. 9 Damage comparison between the dynamic (left) and quasistatic (right) test articles.

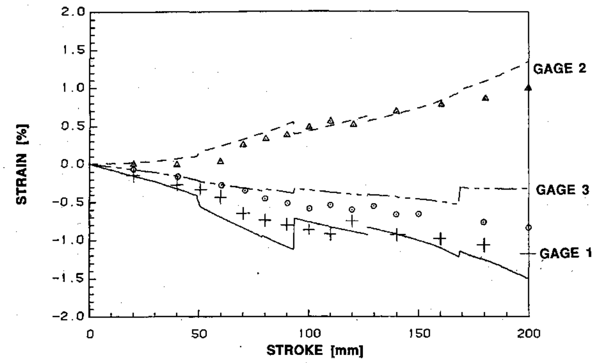

Fig. 10 Comparison of the strain gauge mesurements for quasistatic and dynamic tests. Quasistatic results are indicated by lines. Dynamic results are indicated by points. Strain gauge locations are shown in Fig. 2.

that had impacted in a nose-down attitude were examined in the field. The damage sites observed in the models of seat delamination, nose separation, and especially canopy sill buckling/failure were common to the full-scale fuselage damage observed.

Of the scaled model fuselages tested, the reference fuselage most closely reproduces existing design practice. The maximum load on the reference fuselage resolved into the 45 deg upward aft direction was 1626 N (Table 2). If translated to full scale, this corresponds well to the 6 g certification requirement in JAR 22 for a typical sailplane maximum gross weight of 480 kg. As a final check, the model fuselage mass of 498 g (Table 1) scales to 32 kg at full scale, which is in good agreement with typical forward fuselage structural masses. The good agreement in damage site, scalal loads, and structural masses between model and actual sailplane fuselages enhances confidence in the scaling approach and the test results.

Dynamic Test Results

The results of the dynamic tests corroborated the results of the quasistatic tests by producing the same failure mode and fracture patterns as shown in Fig. 9. The only difference between both test modes was a slight unintentional upward rotation of the fuselages in the dynamic test, due to the flexibility of the swing apparatus. This delayed the failure events slightly. An example of the strain history is shown in Fig. 10 for the Kevlar/E-glass fuselage and its identical counterpart used in the dynamic test for three srain gauge locations shown in Fig. 2. The strain gauge values are almost identical in the dynamic and quasistatic tests, apart from a delay of about 20 mm (equivalent to a rotation of 2 deg) for the events in the dynamic test. The minor discrepancies between the reading of gauges 1 and 2 in the quasistatic test from 170 mm stroke on are thought to be due to the occurrrence of delamination of the canopy sill exactly at the gauge 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. Similarly good agreement between the quasistatic and dynamic failure modes was observed. Thus, it appears that the quasistatic tests sufficiently replicate the dynamic crash environment. This may imply that for such a relatively low-impact velocity, the dynamic and viscoelastic effects are not sufficiently large so as to alter the primary mode of failure.

Design Analysis and Results of Improved Fuselage Test

Baseline Fuselage Models

Analysis of the results from the baseline models indicates that the delamination of the seatpan and failure of the canopy sills control the maximum load and energy-absorbing characteristics. The results from both the dynamic and quasistatic tests show that the seatpan stiffens the fuselages by holding the sides of the canopy sill together. Since the seatpan failure marked the maximum load, its delamination controls the maximum load the glider can withstand. The ultimate useful load prior to pilot impact was established by sill failure. 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.

The E-glass, Kevlar, and Spectra fibers all appear to have advantages in fuselage design. Because of the low compression strength of the organic fibers (Kevlar and Spectra),[7,8] they have a lower effective bending stiffness than E-glass. This allowed the early delamination of the seatpan in the Kevlar

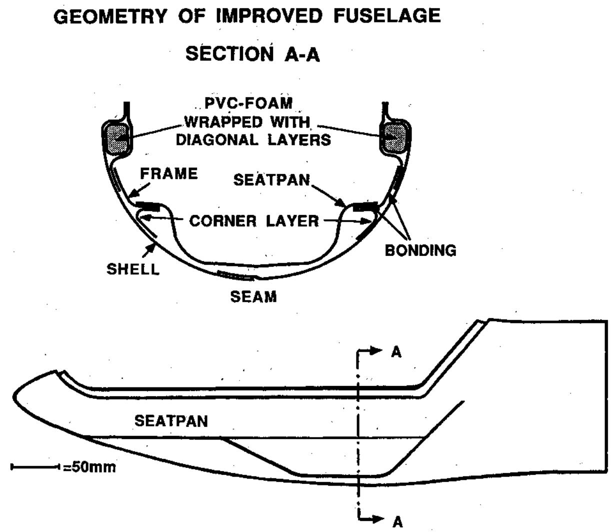

Fig. 11 Geometry of improved fuselage.

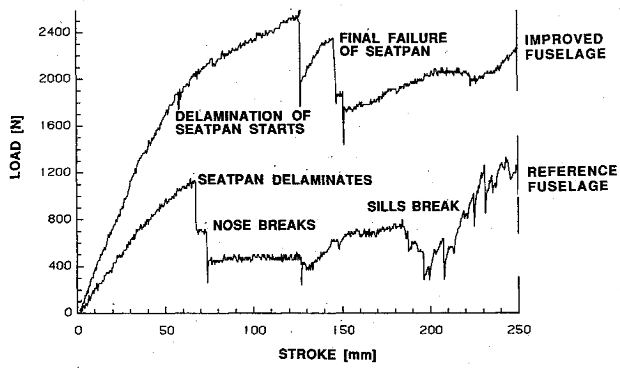

Fig. 12 Load vs stroke of improved and reference fuselages.

and Spectra fuselages. The high tensile strength of Kevlar delayed the nose failure in the Kevlar/E-glass fuselage. When considering its use in crashworthy designs, the brittleness of graphite tends to offset the advantage of its highter strength. Because of its toughness, Spectra has the potential of preventing premature failure of the structure with little weight increase. However, due to its low compression strength, 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, due to its low modulus. A combination of fiberglass and Spectra appears, therefore, to be the best material choice of those examined.

Based on the insight gained into the failure sequence and influence of materials, it was possible to design an improved fuselage. For optimum crashworthy behavior, a quarter-scale fuselage should reach a maximum load of at least 2280 N (corresponding to 16 g in full-scale deceleration) and maintain the load up to the maximum stroke. This load history could be achieved by a controlled delamination of the seatpan at this high load and by reinforcing the canopy sill to prevent early delamination. For optimum structural response, it is desirable to design the seatpan so that it carries load until the maximum applied load is reached and then fails gradually as a load-limiting device until finally the entire load is carried by the canopy sill alone. To avoid elastic storage of the impulse energy that would result in a second acceleration pulse caused by the rebound of the structure, the canopy sill should break when the maximum stroke is reached.

Improved Fuselage Model

To investigate the benefits of the proposed modifications, an improved fuselage was built and tested. The seatpan geometry was extended forward so as to distribute the stress peak in transverse tension that leads to early delamination. In addition, an improved construction technique that reduces the peel sensitivity of the seatpan bonding was employed. This was accomplished by first bonding to the fuselage an E-glass frame and then adding an opposing E-glass corner layer (see section in Fig. 11). A thicker canopy sill can be used to raise the stiffness, but will have a higher stress level at the same stroke and will therefore fail earlier. The thickness chosen in the model (10 mm) ensured that the canopy sill broke late in the test and therefore 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 in such a way as to minimize delamination on the inner side of the sill.

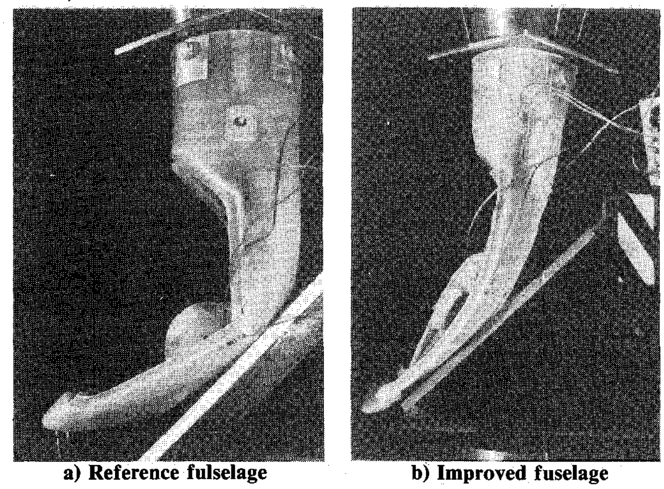

Fig. 13 Comparison of the deformation between the reference and improves fuselages at 254 mm stroke.

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 effectively prevent fractures, the shell and seatpan were built up of a single thick Spectra layer (equivalent to two full-scale layers), covered on both sides with a glass layer. The E-glass improved bending stiffness and bonding properties. The seatpan frame and canopy sill used only E-glass, because the bonding and compression strength are of greatest importance. Because of material availability, only bidirectional fabric was used, so the weight increase was 50% higher than necessary. If unidirectional layers had been employed for the reinforcement, the weight of this fuselage model would have been approximately 650 g. This would correspond to an increase of only 3.8% of the sailplane empty weight.

In the quasistatic testing of the improved fuselage, significant improvements were observed. Delamination of the seatpan began at a load of 1850 N and a stroke of 60 mm and resulted in a flattening of the load-stroke trend (see Fig. 12). The maximum load was reached at a stroke of 125 mm with 2535 N, equivalent to 18.4 g in an impact. The load drop at 127 mm is artificial and caused by the resetting of the testing machine due to the limited maximum stroke. The drop at 146 and 151 mm 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 1770 N and let it grow to 2220 N at 254 mm. At this point, the test was discontinued, neither the canopy sill nor the nose having failed. At 153 mm, 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 432 J, approximately three times larger than for the earlier fuselages (Table 2). The failure mode was extremely favorable, with nearly uniform deceleration, the failures being almost universally away from the pilot and leaving the seatpan almost undamaged. The higher apparent intitial stiffness of the improved fuselage is partially a result of an improved test-mounting. A comparison of the final deformation between the reference and improved fuselages is shown in Fig. 13.

Conclusions

The dynamics of a nose-down impact were investigated using quarter-scale composite sailplane fuselage segment models. The following conclusions can be drawn:

1) Impact behavior of model composite sailplane fuselages segments was found to be similar in quasistatic and dynamic model tests, both in terms of failure modes and strain at failure.

2) Qualitative comparisons with field observations of actural crash damage and quantitative comparison with full-scale design criteria indicate that the models failed in the same failure mode as full-scale fuselages and at appropriately scaled loads.

3) The geometries of typical sailplane fuselages and the limited deceleration tolerance of the pilot make the safe deceleration of the pilot in a nose-down impact possible only with significant changes in fuselage design and/or additional energy absorption by the ground.

4) The best energy absorption was achieved with a fuselage using a combination of Spectra and E-glass. Because of its high tensile strength, Spectra yielded the best results by successfully preventing tension cracking, and E-glass showed the best performance for structural components loaded in compression.

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

6) Energy absorption was improved by a factor of 2.8, from 152 J for the reference fiberglass fuselage to 432 J, by modification of the structural combination of Spectra and E-glass fabrics.

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