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Design, Fabrication, and Testing of Composite Energy-Absorbing Keel Beams for General Aviation Type Aircraft

Sotiris Kellas and Norman F. Knight, Jr.
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December 2002

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Abstract

A lightweight energy-absorbing keel-beam concept was developed and retrofitted in a general aviation type aircraft to improve crashworthiness performance. The energy-absorbing beam consisted of a foam-filled cellular structure with glass fiber and hybrid glass/kevlar cell walls. Design, analysis, fabrication and testing of the keel beams prior to installation and subsequent full-scale crash testing of the aircraft are described. Factors such as material and fabrication constraints, damage tolerance, crush stress/strain response, seat-rail loading, and post crush integrity, which influenced the course of the design process are also presented. A theory similar to the one often used for ductile metal box structures was employed with appropriate modifications to estimate the sustained crush loads for the beams. This, analytical tool, coupled with dynamic finite element simulation using MSC.Dytran were the prime design and analysis tools. The validity of the theory as a reliable design tool was examined against test data from static crush tests of beam sections while the overall performance of the energy-absorbing subfloor was assessed through dynamic testing of 24" long subfloor assemblies.

Introduction

This report describes a small portion of the research in support of a multiyear NASA Langley led program in aviation safety and crashworthiness. One aspect of the research involves a demonstration of possible crashworthiness enhancements to existing aircraft by replacing their original subfloor with Energy Absorbing (EA) counterpart. Such a demonstration was accomplished by crash testing two similar GA (general aviation) aircraft. Occupant-load attenuation, due to the subfloor replacement, was estimated by comparing the two data sets, one from the original[1] and one from the retrofitted aircraft. Since it is not the objective of this report to present the crash data correlation from the two full-scale tests, the performance of the EA subfloor, used in the second aircraft, is presented through static crush test results from beam sections and two dynamic test results from assembled subfloor sections. The subfloor assemblages were fitted with a representative occupant plus seat mass and impacted on a flat rigid surface at approximately 31 fps, the same vertical sink speed for the two aircraft tests. Design and analysis efforts, which led to the development of the EA beam, are also presented.

Unlike crashworthy features which are an integrated part of a given design, a retrofit concept is particularly challenging and often limited in performance due to various factors such as undesired and/or unknown dynamic response of existing structure, geometric incompatibility, and installation constraints. In addition to the difficulties presented by the retrofit nature of the subfloor, the new keel beams had to be cost efficient, meet the flight load requirements of the original subfloor, and offer improved energy absorption in the event of a crash while maintaining adequate post-crash integrity. To meet these elaborate design requirements, a composite foam-filled cellular structure was chosen. The energy-absorbing beam evolved from preliminary work described in references 2 and 3 and covered under a US patent[4]. The concept consists of an inline assemblage of rectangular cross section cells, which form the cellular core of a sandwich beam with the cell axis oriented along the load direction. The main difference between the beams described in reference 3 and the one described herein is the glass reinforcement, which consisted of braided sleeving instead of woven fabric. The braided sleeving was mainly introduced to eliminate the painstaking process of wrapping each foam-core with fabric. The PVC foam core was also replaced by better quality polymethacrylimide foam.

The energy-absorption properties of a cellular structure are generally dependent on the cell size, the cell-wall mechanical properties, the cell-wall thickness, and the number of flanges or webs that meet at a junction. The greater the number of flanges or webs a junction consists of, the greater the crush strength usually is, due to the improved stability. Progressive crush response of thin-wall metal box sections and intersections have been studied by a number of researchers with the most notable work performed by Wierzbicki, Abramowicz, Jones and Hayduk, and documented in numerous publications[5–9]. These involved the mathematical description of the process of energy dissipation at web intersections resulting from empirical observations of the folding mechanisms and their influence on the mean crushing load. According to these researchers for most practical problems that involve progressive folding, without tearing, the energy dissipation can be classified in two categories: extensional and isometric (inextensional). In the isometric mode, the deformation is often confined to narrow zones, called fold lines[5]. Because the total deformation area is small relative to the entire structure, this mode of energy dissipation is not as efficient as the extensional mode. The mode that prevails in a practical situation depends on the number of flanges per intersection, and the relative thickness to width of the flanges. Typically, the more stable an intersection is the more likely it is that the extensional mode will prevail but in most cases a mixed mode takes place[5].

While composite structures as compared to metals are much harder to analyze, composites offer unique and unsurpassed advantages in fabrication and customizable structural response. The flexibility of a concept to meet the changing needs of a given project is particularly important and in many cases it is necessary.

For the sizing of a composite cellular structure using the conventional metal's approach, a question arises concerning the applicability of a plastic deformation theory to a fiber reinforced material that exhibits no true plastic deformation and which dissipates energy through many distinctly different local modes of damage initiation and propagation. It is believed that for thin laminated composite cell-walls where plastic-like folding is a likely mode of deformation, and hence energy dissipation, the theory for plastic metals can be applied with caution for as long as an apparent "flow" stress value for the material can be established. Typical examples of fiber reinforced laminates which deform quasi-plastically include angle plies, and to a lesser degree,

quasi-isotropic type laminates containing high strain to failure fibers and matrix materials. Since a combination of mechanical properties is usually needed, hybridization is often explored[3] to achieve among other properties the quasi-plastic deformation response. Typical reinforcement hybridization includes glass and kevlar or graphite and kevlar where glass and carbon are used for strength and kevlar for post-crash integrity and containment[3].

Another design challenge unique to the EA keel beam is the determination of the actual crush load requirement, which depends not only on the effective combined mass of the seat plus occupant but also on the way the seat-rail interacts with the beam that it is attached to. Knowing a priori the way the dynamic load is transmitted to the beam is as essential as the knowledge of the effective mass to be decelerated. Seat-rail deformation and load transmission from the seat legs to the energy-absorbing beams were studied using MSC.Dytran[10], an explicit nonlinear transient dynamics finite element computer code. The accuracy of the theoretical and finite element simulation results was examined against data from static and dynamic tests.

Cellular Beam Fabrication

The main fabrication steps for the EA beams and/or subfloor are described in figure 1 and consist of:

1. Dry glass-reinforcement placement over foam blocks (see figure 1a). Braided glass fiber sleeve was pulled over the closed cell foam cores, worked tied and secured at either end. The reinforcement was E-glass biaxial braided sleeve, 3.0" internal diameter, 10 oz/yd^2, approximately 0.013" thick. Note that while the nominal fiber orientation of the glass sleeving is ±45° and often referred to as such, the actual fiber orientation depended on the foam block cross-section dimensions. For example, the 4.0" by 1.25" cell had the glass fibers oriented at approximately ±52° to the loading direction. The foam-core was 2.3 lb/ft^3 polymethacrylimide (PMI) foam (Rohacell® 31 IG).

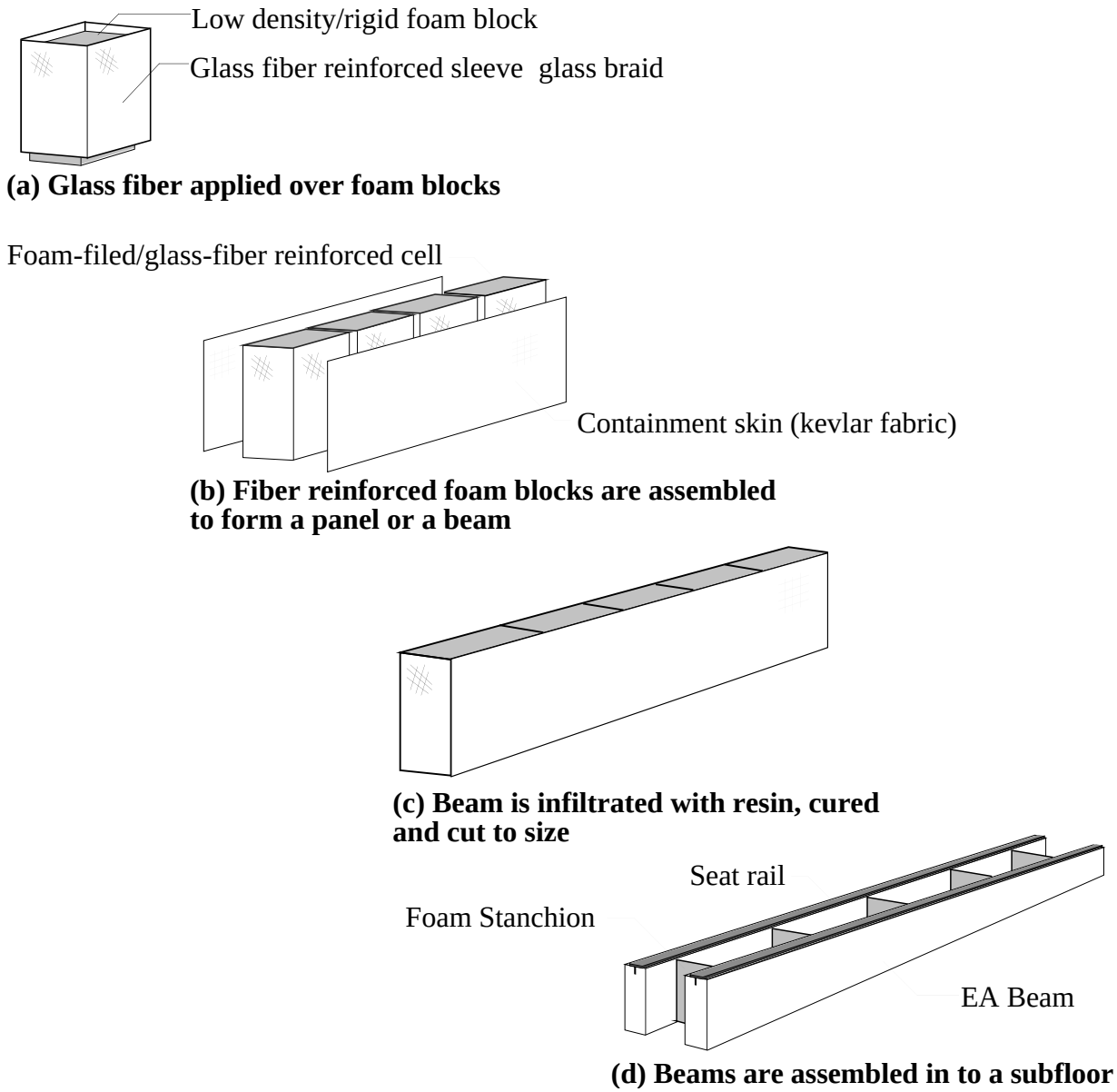


Fig. 1 - Schematic representation of the main steps used in the fabrication of the EA beams and subfloor.

2. Inline assembly of the fiber-reinforced blocks and integration using kevlar fabric face-sheets (see figure 1b). The face sheets were temporarily secured using a tack adhesive spray. The fiber type was kevlar-49, 5-harness satin weave, 5 oz/yd^2, approximately 0.011" thick. For optimum post crush integrity and containment the preferred kevlar fiber orientation is usually at ±45° to the loading axis, however for the retrofit aircraft beams the kevlar fibers were oriented at (0°/90°) due to fabrication constraints associated with the large size of the beams and material availability.
3. Resin infusion of the assembled beam (or panel) under vacuum and subsequent curing (see figure 1c). A multi-port infusion technique in conjunction with a low viscosity epoxy resin (180 °F cure) was used to ensure timely and uniform impregnation. For the retrofit aircraft

beams, a single panel was fabricated (112" by 32" with density of 7.88 lb/ft^3) from which four beams were cut. Each aircraft beam had the foam core partially removed, the bottom edge machined to match the aircraft's curvature, and the top edge fitted with a seat-rail as shown in figure 2. Detail of the seat-rail attachment is shown in figure 3.

4. Matched beam pairs were assembled into left and right subfloors as shown in figure 2. A series of foam stanchions was used to space and stabilize each pair of beams as shown in figures 1(d) and 2.

Rohacell® 31 IG stanchions, (1.5" thick) replaced the original graphite reinforced stanchions in the aircraft and acted both as stabilizing supports for the beams as well as main supports for the floor. The main difference between the new and original floor systems was in the floor attachment. In the original system the floor panels were attached to the graphite stanchions as well as the seat-rail. In the new system it was judged necessary to decouple the floor from the beams to allow for an independent and predictable mode of crushing.

While the "T" cross section of the original seat-rail was preserved, a new aluminum alloy was introduced to promote local deformation instead of fracture. The original seat-rail (aluminum 7075 – T6) was replaced with (2024 – T351). The web of the "T" cross section served as the main attachment point to the beam as shown in figure 3. Furthermore, in order to ensure that the beam/seat-rail coupling survives the crash event, kevlar tape was used for extra security. Slots measuring 0.1" wide by 2.0" long were machined into the seat-rail web at an interval of approximately four inches. Wooden-dowel pins (1/16" in diameter and 2" long) were used to secure the resin-impregnated kevlar tape onto the rail, as shown in figure 3, before it was inserted into the beam’s slot.

Fig. 2 - Photograph of the exposed subfloor showing the EA keel beams and foam stanchions as installed in the general aviation airplane.

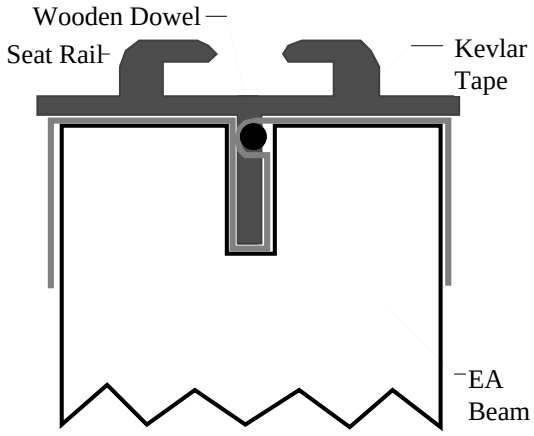


Fig. 3 - Schematic of the "T" cross-section seat-rail coupled to the EA beam using kevlar tape.

Cellular Beam Theory

The cellular beam concept was chosen in part for its customizable features such as adjustable Sustained Crush Load (SCL), and post crash integrity, but also for the options in fabrication techniques and material combinations which resulted in cost efficiency. Sizing of the cellular structure was accomplished with the aid of a theory[5-9], originally developed to describe the crush response of plastically deformed thin metal box structures and/or intersecting flange elements such as angles and cruciforms. The theory was modified appropriately to account for the foam core and laminated construction of the composite cellular beam. The main challenge in the application of the theory was found to be the selection and measurement of the appropriate input parameters, which for the laminated composite walls was not as straightforward as in ductile metals.

In addition to the usual assumptions that are required for the formulation of the theoretical solution[5-9], the following assumptions were also employed here for the theoretical prediction of the SCL.

1. The composite cell-walls of the EA beam deform quasi-plastically in bending. For the (±45°) glass and (±45°)/(0°/90°) glass/kevlar hybrid laminates, the flow stress used in the analysis is taken as 80% and 70% of the measured laminate tensile ultimate-strength, respectively.
2. Composite cell-walls are treated as quasi-isotropic.
3. Ply delamination does not dissipate a significant amount of energy compared to other modes and therefore it is neglected.
4. A nominal value for the laminate thickness is used based on the combined fabric thickness plus 0.001 in. per ply to account for the resin.
5. The resistance imposed by the foam core on the folding flanges is uniform throughout the folding process and foam/skin disbond is neglected.
6. For low-density foam core, the expansion of the foam due to crushing is neglected.

In accordance with the original theoretical procedure[5-9], the cross section of the cellular structure was divided into its most basic element, the "T", see figure 4. Moreover, the "T" element was regarded as being composed of three sub-elements, two foam filled angle elements with glass walls and a flat plate (kevlar). It was assumed that the total energy absorbed during the folding of the "T" element consists of four distinct contributions:

(1) Energy dissipated at the corner of each constituent angle, through extensional deformation. The toroidal shell section formed during the deformation process is assumed to have a minor radius b. The total energy for both angle elements, assuming that the ±45° glass layer will locally delaminate from the kevlar is given by equation 1, with the variables defined in figure 4.

$$E_1 = 4.64\, \sigma_g\, t_g\, b\, H \qquad (1)$$

(2) Energy dissipated by moving horizontal hinges during flange folding. Accounting for the different thickness and length of each flange of the "T" element, the total energy is given by equation 2.

$$E_2 = \frac{\pi}{2}\left(\sigma_h\, t_h^2\, c_2 + 2\sigma_g\, t_g^2\, c_1\right) \qquad (2)$$

(3) The total energy dissipated by the inclined hinges for the two angle elements is given by equation 3. The fact that the composite properties for the inclined hinges are different than those of the horizontal hinges is neglected through the assumption of quasi-isotropy.

$$E_3 = 2.22\,\sigma_g\, t_g^2 \frac{H^2}{b} \tag{3}$$

(4) Finally, the total energy dissipated due to the foam-core resistance to flange folding plus the crushing of the foam core (with D being the hole diameter and n the number of holes in the core) is given by equation 4.

$$E_4 = \frac{\pi}{4} H^2 \sigma_f^t \left(2c_2 + c_1\right) + \sigma_f^a H \left(c_1 c_2 \pm \frac{n\pi D^2}{4}\right) \tag{4}$$

Note that equation 4 is general and applies in cases where the core is removed totally (foam stress = 0), or partially ($n \neq 0$). Furthermore the superscripts a and t of the foam-core strength σ_f are used when the axial and transverse foam strengths are different.

Assuming that the "T" element is folding with a wavelength of 2H under a mean SCL, P_m, the energy balance for the element is given by equation 5.

$$\begin{aligned} P_m = \frac{1}{2H}\left(E_1 + E_2 + E_3 + E_4\right) &= 2.32\sigma_g\, t_g\, b \\ &+ \frac{\pi}{4H}\left(\sigma_h\, t_h^2\, c_2 + 2\sigma_g\, t_g^2\, c_1\right) \\ &+ 1.11\,\sigma_g\, t_g^2 \frac{H}{b} + \frac{\pi}{8} H \sigma_f^t \left(2c_2 + c_1\right) \\ &+ \frac{\sigma_f^a}{2}\left(c_1 c_2 \pm \frac{n\pi D^2}{4}\right) \end{aligned} \tag{5}$$

With the parameters b and H being dependent on the condition of minimum energy, or load, given by equation 6.

$$\frac{\partial P_m}{\partial H} = \frac{\partial P_m}{\partial b} = 0 \tag{6}$$

Solution of equations 6 produces equations 7 and 8;

$$b = \frac{1.11\sigma_g\, t_g^2}{\frac{\pi}{4H^2}\left(\sigma_h\, t_h^2\, c_2 + 2\sigma_g\, t_g^2\, c_1\right) \pm \frac{\pi}{8}\sigma_f^t\left(2c_2 + c_1\right)} \tag{7}$$

and

$$H = 2.09\,\frac{b^2}{t_g} \tag{8}$$

The simultaneous solution of equations (5), (7) and (8) produces a value for the mean SCL, P_m, for a single "T" element from which the mean SCL per unit beam length, P_l, can be obtained;

$$P_l = \frac{2P_m}{c_2} \tag{9}$$

The mean crushing load per unit beam length was used for the preliminary sizing of beams for the required crush loads and was compared to static test data from actual beam sections, which are described below.

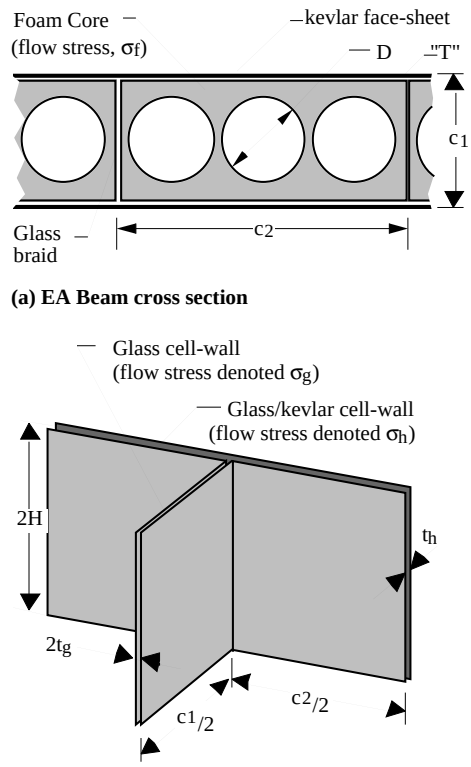


Fig. 4 –Schematic of (a) typical energy absorbing beam cross-section and (b) basic"T" element.

In early phases of this work the crush initiation load was calculated using a semi-empirical technique suggested by Gerard[11] to calculate the crippling strength of multi-corner elements. However, preliminary testing[3] indicated that attenuation of crush-load initiation was necessary for optimum response. Therefore, this type of calculation was made redundant and is not presented herein.

Experimental Results

Static Tests

EA beam constituent material tests were performed at various stages of the program and used in the calculation of the sustained crush load using equation 9.

Foam-core samples (2.25" diameter cylinders) were tested to study their energy-absorbing performance under static and dynamic loading conditions and to obtain a representative flow stress value. The typical foam-core crush responses of figure 5 highlight both the orthotropic nature of the material as well as the effect of loading rate. The difference of approximately 33% between the transverse and axial orientations was found to be independent of the loading rate. An additional

25-28% increase in crush strength was measured when the loading speed was increased from 2 in./min. to 13.5 ft/s.

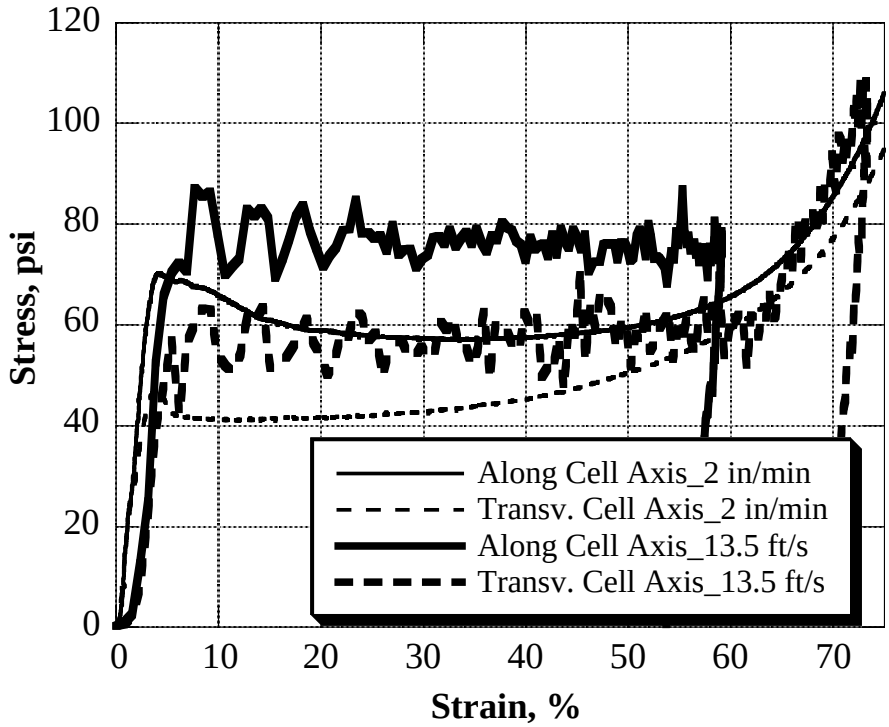


Fig. 5 - Typical crush response for PMI 31 IG foam core in two mutually perpendicular orientations and two loading speeds.

Cell-wall strength measurement tests were performed in quasi-static tension. Coupon specimens were removed either from laminated flat panels or virgin beam sections and tested to determine the ultimate strength of various cell-wall materials. Typical results from this series of tests are shown in figure 6 for samples removed from a beam section similar to the one used in the aircraft. Note that the hybrid cell-walls were not symmetric and therefore the measured ultimate strain may be somewhat conservative.

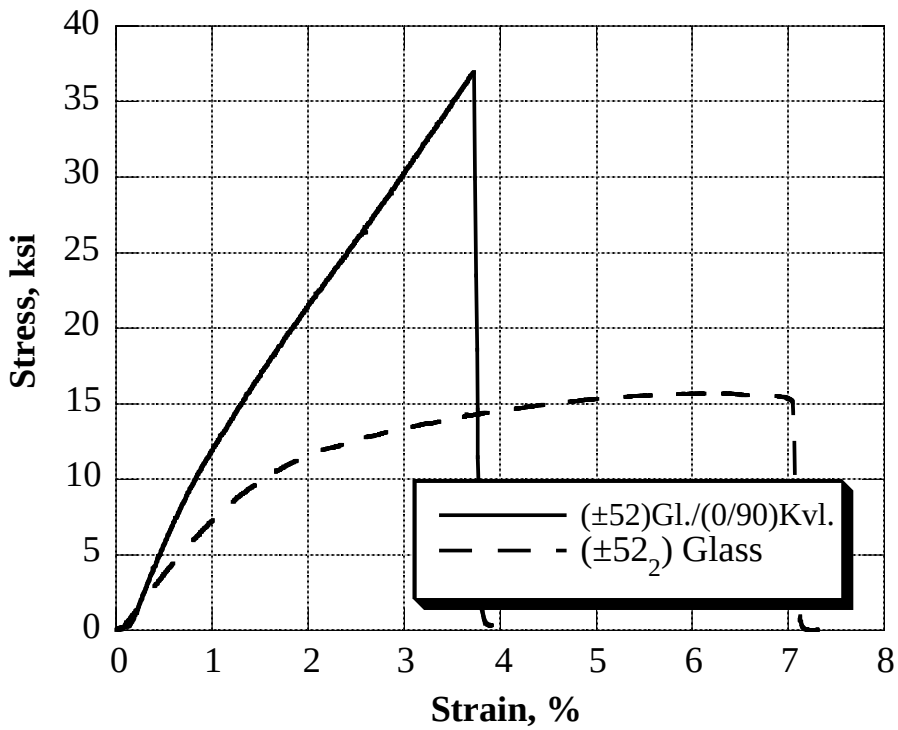


Fig. 6 - Typical tensile EA beam cell-wall properties for the beam configuration used in the aircraft.

Preliminary tests on beam sections were performed quasi-statically, ranging in speeds from 2 to 20 in./min., to determine the mean SCL and to study the mode of collapse and energy dissipation. The static crush response of a typical EA-beam/seat-rail section is shown in figure 7 and a photograph of the crushed section in figure 8. The results of figure 7 indicate a desirable crush performance, with a relatively flat response up to approximately 80% stroke. Crushing of the beam initiated at approximately 370 lb./in., fell briefly to 200 lb./in. before recovering to a SCL of approximately 284 lb./in.

Earlier studies[3], have shown that crush initiation, initial load degradation, and SCL depend primarily on the way the load is introduced in the beam. In cases where a crush-initiation load attenuator was used, initial load degradation was practically eliminated and the SCL was enhanced. As shown in figure 8, the 3-cell beam section was loaded through a typical seat leg support, which could not be centered perfectly due to fixed seat-rail hole spacing.

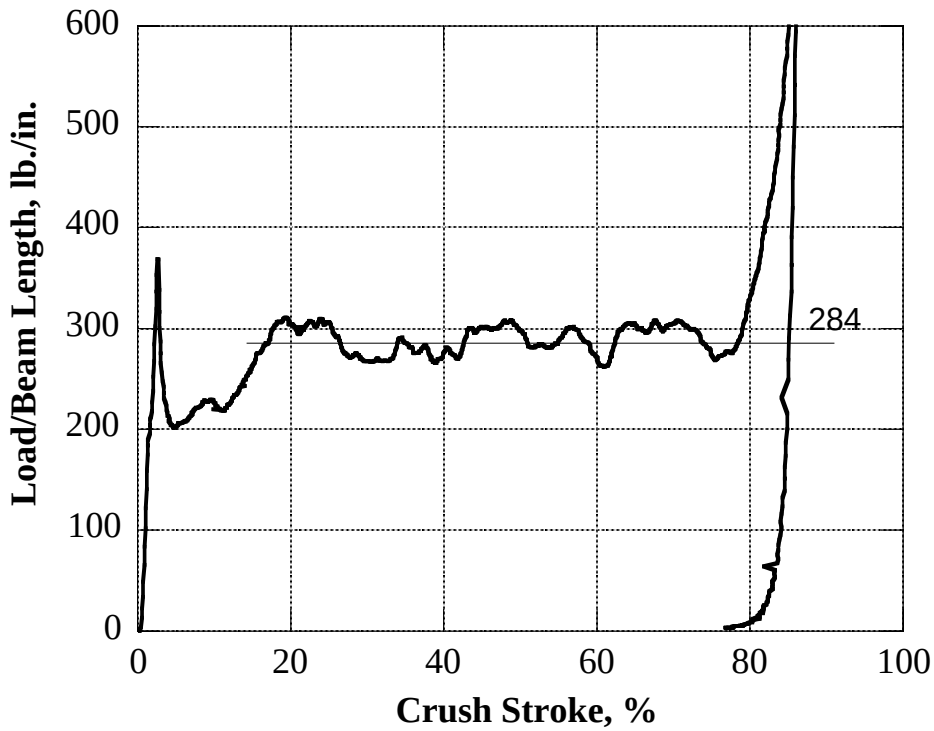


Fig. 7 - Typical static crush response of a 9" long EA beam sample. Cells were 1.4" by 3.0" reinforced with one braided glass sleeve. The kevlar containment was at ±45°. Speed of test was 20 in./min.

The effect of the small eccentricity for the relatively short (9.0") beam section was a lower, than typical, crush initiation but a relatively large subsequent load degradation. This discrepancy was thought to be due to partial loss of seat-rail contact with the beam face-sheet, as indicated at the back top right-hand corner of the section. Subsequent to this test, the seat-rails were slotted and beam/seat-rail coupling was reinforced with kevlar tape as shown in figure 3. An important role the slots served was to reduce the shear stiffness of the seat-rail and thus promote more localized deformation under the seat legs. The more localized the rail-deformation could be made, the more rigid a beam could be designed without exceeding the maximum desired sustained crush load value. This was thought to be a necessary requirement for a subfloor beam that under normal operating conditions would be required to endure many years of flight, landing and occupant foot traffic loading conditions.

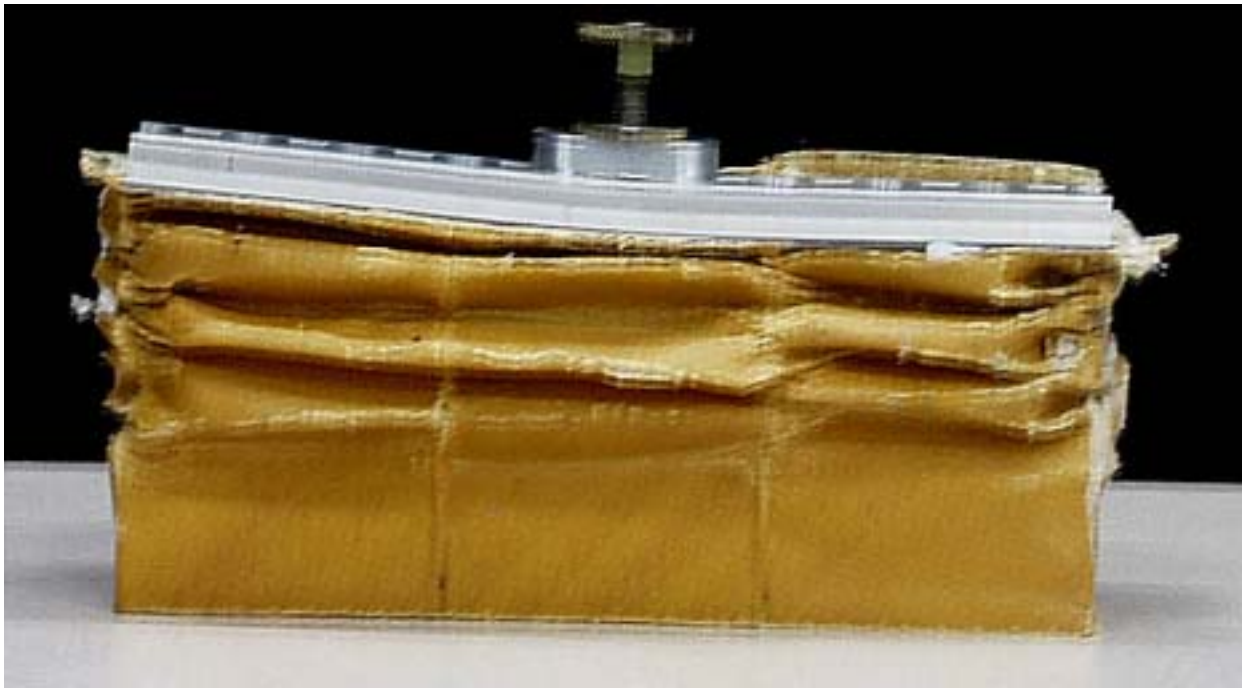


Fig. 8 Statically crushed sample of a three-cell EA-beam section showing the composite skin, folding pattern. The specimen consisted of 1.4" wide by 3.0" long solid foam-cells reinforced with one braided glass sleeve (~ ±45°) and one layer of ±45° kevlar fabric.

Dynamic Tests

Dynamic tests on beam constituent materials were performed on foam core material only. Due to experimental constraints, the maximum impact velocity was limited to approximately 13.5 ft/s. Typical dynamic crush responses for the foam core were summarized in figure 5.

Due to anticipated rate effects it was deemed necessary that assembled sections of the subfloor be assessed experimentally prior to installation in the aircraft. Each test article contained two 24" long beams (8" tall) spaced 9.25" apart, two seat-rails, three foam stanchions each 1.5" thick, plywood base, four seat leg attachments (11" apart), and a relatively rigid mass of 141 lb. which was attached to simulated seat-legs as shown in figure 9. The main difference between the two test articles was the way the stanchions were attached to the beams. In the first case, the stanchions were bonded directly to the beam faces whereas in the second case additional glass reinforcement was used in the corner junctions. Each section was instrumented with two accelerometers and was guided through a free-fall drop of 15 ft.

Fig. 9 - Photograph of assembled subfoor prior to dynamic drop testing. The subfloor consisted of two 24" long EA beams spaced apart by three foam stanchions. A lead mass was attached to the seat-rails to simulate the expected mass of a seat plus occupant.

The average acceleration response from a subfloor section test is presented in figure 10 and shows a SCL of approximately 63 g. The acceleration represents the average of two accelerometer readings which were filtered using a low-pass digital filter (500 Hz) before being averaged. Two accelerometers (placed approximately 6" apart) were used instead of one to capture possible off-axis impact conditions. The 0.6 ms phase shift between the two accelerometer responses confirmed a near flat impact condition.

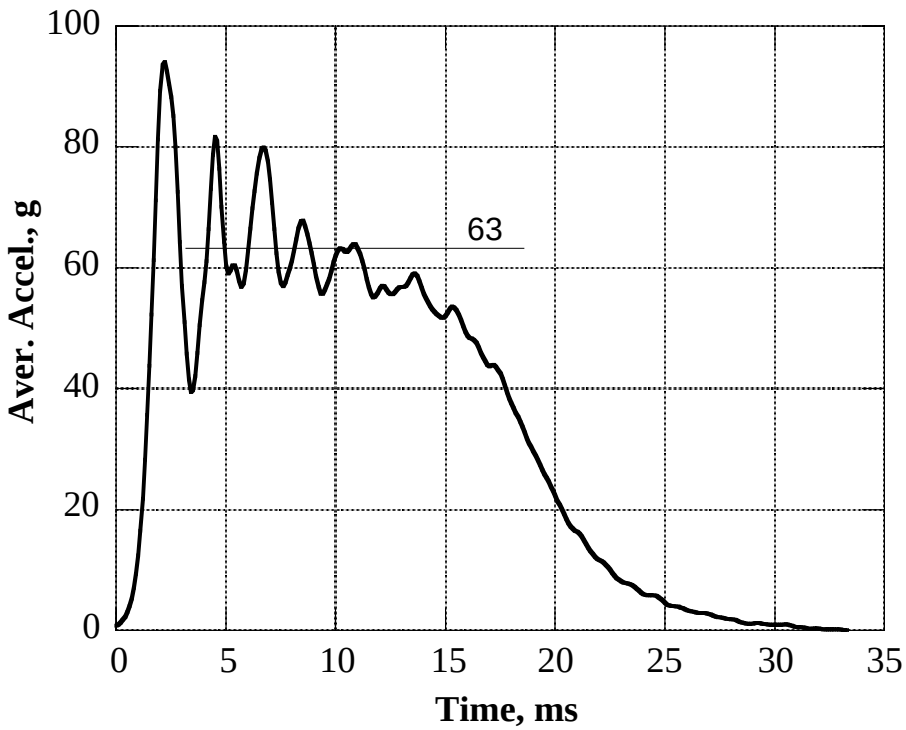


Fig. 10 – Acceleration/time response of 24" long subfloor section typical of one used in the aircraft. Mass decelerated by the EA beams=141lb., velocity at impact = 31 ft/s, beam spacing = 9.25", seat-leg spacing = 11". Data were acquired at 10 kHz and filtered at 500 Hz.

Finite Element Simulation

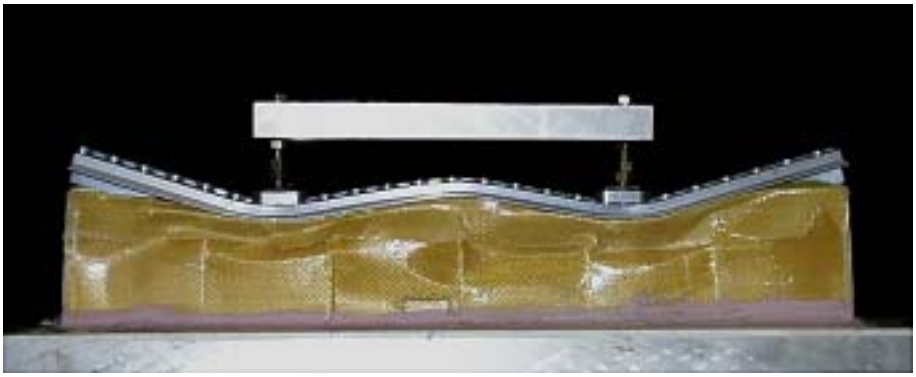
A dynamic finite element analysis using MSC.Dytran was carried out with the objective of studying the effect of seat-rail/beam interaction for various seat-leg spacings, seat-leg pad size and relative seat-leg positioning with respect to the cell interfaces.

The model was constructed to simulate the assembled subfloor section used in the dynamic tests with the following simplifications and/or assumptions.

1. Owing to symmetry only one beam with one half of the total mass was considered.
2. The transverse constraint effect of the center foam stanchion was neglected.
3. The circular perforations in the foam-core were modeled as square holes.
4. The "T" cross section seat-rail was modeled using shell elements with equivalent mechanical and plastic bending properties determined from component testing.
5. The slots in the rail and kevlar tape used to improve the seat-rail/beam coupling were neglected.
6. Composite material properties were treated as isotropic using test data (figure 6) with an ultimate strain at failure specified.
7. Foam material properties accounted for the elastic, plastic and densification phases (figure 5).

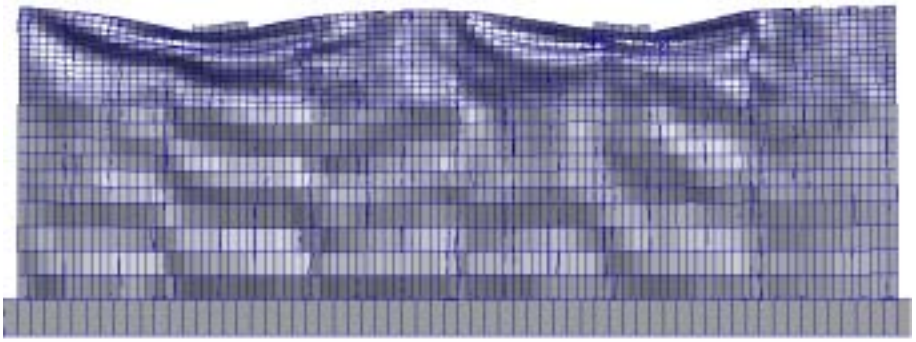
Concentrated masses were specified along the middle of each seat attachment bracket to represent the combined mass used in the dynamic test and equally distributed to each seat leg (35.3 lb.). All nodes were given an initial vertical velocity just before impact of 31 fps.

The finite element discretization of the cellular beam structure was graded towards the expected stress concentration region and was fine enough to capture the folding pattern, as shown in figure 11b. A total of 7,200 shell and 8,712 solid elements were used with over 17,000 nodes. The discretization was also sufficient to capture the sustained crush load adequately for the first 1.5 ms (within approximately 10% of the measured value). However, once local failures initiate, substantial refinement in the discretization would be required to track the damage progression.



(a) – Two-point beam/seat-rail test.

(b)



(b) – Two-point beam/seat-rail finite element simulation.

Fig. 11 - Two-point crush test and simulation of EA beam/seat-rail/seat-leg assembly. Cell dimensions were 4.0" by 1.25" with three 1.0" holes per cell.

Contact is monitored between the base of the EA subfloor beam and the impact surface (master-slave contact), between the beam outer faces with themselves (single-surface contact), and between the foam and the seat-rail if the foam cells have holes (master-slave contact). If holes are present, then additional single-surface contact surfaces need to be defined as the interior surfaces of each hole. Related modeling information and studies are given in reference 12.

Discussion

Preliminary studies[2] on composite replacement keel beams included several concepts, some of which were previously considered for use in composite helicopter subfloors[13]. The concepts

considered for general aviation aircraft[2-3] included a sine-wave, a sandwich sine-wave, a flat-face sandwich, and various cellular beams. The foam filled cellular beam concept was chosen because it offered flexibility in structural tailoring and fabrication to meet most anticipated design challenges. In particular, the option to manipulate the SCL, by altering the cell geometry and/or cell-wall properties, without sacrificing shear stability and/or post crush integrity was the most appealing aspect of the concept. Fabrication, machining, and cost of retrofitting, though secondary, were also considered in the final choice of the EA beam concept.

An effective crash-energy management design requires knowledge of several pertinent parameters including available stroke, impact orientation, effective mass of the cushioned object and fragility, reaction response of supporting structure, etc. When the object to be cushioned is a human occupant plus seat, the determination of a unique effective mass value is not straightforward. The difficulty arises not only by the large mass variation in the human population but also by the fact that internal damping which serves to reduce the effective mass (or total energy to be managed) is related to the occupant mass and/or age. Moreover, the seat and in particular its cushion is far from rigid thus contributing further to the combined effective mass uncertainty. Therefore, a design effort aimed at a single element, such as the subfloor beam, can not be as effective as a crush energy management system that incorporates every important element (aircraft fuselage, subfloor, floor, seat-rail, seat, seat cushion, and occupant). As a result an alternative design philosophy was proposed[3] to help eliminate the above difficulties. In the proposed concept the external EA subfloor is used to decelerate the entire fuselage mass. Since the total fuselage mass is relatively insensitive to individual seat/occupant mass variations and/or number of occupants, the concept offers a simpler energy absorbing engineering challenge.

The retrofit nature of the design, presented in this study, demanded that several compromises be accommodated in order to achieve crashworthiness improvement by replacing the aircraft keel beams alone. For example, based on a survivable (no injury)[14] vertical spinal load of 20 g, a vertical impact speed of 31 fps, and assuming an ideal subfloor crush response (SCL remains uniform for the duration of the crush), the required crush stroke is approximately 9". Accounting for the fact that typical crushable energy absorbers use only about 80% of their total original length[3-9], the EA beam depth requirement, to ensure occupant survivability, is 11.25". Excluding the fuselage frames (which reduce the useful crush stroke by the amount of their depth) the maximum possible beam depth that the aircraft could accommodate was approximately 8" (inboard beams) and approximately 4" when the fuselage-frame depth was taken into account (outboard beams). Clearly, due to stroke limitation alone, a 31fps survivable crash could not be achieved without energy being dissipated by other components of the aircraft structure and/or seats. Consequently, a dynamic load limit of approximately 60 g was selected as the appropriate design value for the EA beams with a resulting requirement for beam depth of 3.75" (assuming a perfect crush response and 80% crush stroke). Bearing in mind that floor accelerations in excess of 150 g, and dummy pelvis accelerations close to 100 g were recorder in the unmodified aircraft[1], a 60 g seat-leg acceleration limit for the retrofit aircraft would represent a big improvement.

With the upper dynamic load limit established, an effective mass and beam load distribution had to be determined to allow for the SCL to be identified. The effective mass calculation was based on the 50% percentile male dummy-occupant, which was used in the full-scale aircraft tests. Using an average seat mass of 30 lb. plus the dummy-occupant mass, minus the legs, in conjunction with a knockdown factor of 0.9 the value of 145±10 lb. was determined. Neglecting seat-rail details,

initial estimates for the SCL requirement, assuming that each of the four seat legs would engage approximately 8" of beam length, resulted in a crush load per unit beam length of 270±20 lb./in. For this calculation, the energy dissipated by the seat-rail itself was neglected.

Preliminary EA beam tests and seat-rail attachment studies highlighted the need for the seat-legs to engage more beam length in order to ensure seat-rail post-crush integrity. In effect, localized deformation needed for a sturdier beam competed against seat-rail fracture and/or seat retainment. In addition to suitable material yielding characteristics, the chosen seat-rail had to offer a convenient mounting feature. Typical off-the-shelf seat-rails are designed for rigidity and therefore were incompatible with the design objectives of this study. Since the design of a custom seat-rail was not an objective of this work a standard "T" section rail was chosen with modified material properties (aluminum 2024 – T351 instead of the standard 7075-T6) with the 0.7" long web being used for mounting onto the beam. The choice of the more ductile seat-rail was based solely on the desire for localized plastic deformation and other commonly important factors, such as the forward strength, were not considered.

When preliminary tests on seat-rail/EA-beam sections indicated the need for more plasticity the seat-rail was annealed fully to what was thought to be a “0” condition. Even with the seat-rail fully annealed the minimum EA beam engagement was approximately 10-12” per seat-leg. For such a beam engagement a more appropriate SCL requirement was found to be in the range of 200±30 lb./in. This load was used in conjunction with the theory, equation 9, to size the beam, which was subsequently used in the dynamic subfoor tests. It was assumed that once a plastic hinge is formed in the seat-rail the SCL would be similar to the theoretical predicted value for as long as no additional beam material was engaged during the crush. In effect, it was assumed that seat-rail deformation controlled two parameters: the length of EA beam engaged during crushing, and the crush initiation load.

A comparison of experimental and theoretical SCL (equation 9) for two beam configurations are summarized in Table 1 where it is shown that the theoretical predictions are reasonably good but consistently low, approximately 11%. Underestimation of the SCL can be attributed to several factors including omitted terms from the total energy formulation such as, for example, delamination, material property uncertainty (effective yield strength measured from tensile tests), altered material properties for the inclined plastic hinges, etc. Compared to the complexity of the crush problem, the relatively simple theory proved to be a very useful design tool, allowing for beam configuration adjustment to be made readily.

Table 1: Comparison between theoretical and experimental SCL.

Fiber Angles (glass braid)/(kevlar faces)	Cell Width /Length in. / in.	Loading Speed ft./s	Exp. SCL lb/in.	Theor. SCL lb/in.
(±52°)/(0°/90°)	1.25 / 4.0 (Three 1.0" Holes)	0.028	204	181
(±52°)/(0°/90°)	1.25 x 4.0 (Three 1.0" Holes)	31.0	222*	198
(±45°)/(±45°)	1.40 x 3.0 Solid Core	0.028	284	250

* Based on average engagement length of 10" per leg.

To the contrary, the finite element simulations provided limited input to the design evolution. Existing constitutive material models limit simulation of the crush event involving complex material failures due to inadequate representation of damage initiation and propagation. Sensitivity of the crush initiation is also dependent on the contact simulation and local seat-rail response. Parametric studies proved to be ineffective in aiding the design because of the dependence on measured constitutive response for each component of the cellular beam.

Mold-less fabrication of the beams proved to be a real asset of the chosen concept and allowed for several different beam configurations to be fabricated readily and tested. Although earlier studies[3] have shown conclusively that for optimum post-crush integrity the kevlar face sheets had to be oriented at ±45°, the 0°/90° fiber orientation for the beams, installed in the aircraft, was based on material availability at the time of fabrication, and overall keel-beam length (appr. 112").

Conclusions

Energy-absorbing composite keel beams were designed fabricated and retrofitted in a general aviation type aircraft to improve crashworthiness. Sizing of the beam was achieved with the aid of a simple theory, which was originally developed to describe the crush response of thin-wall metal box structures. Even though, the crushing loads were underestimated, by about 11%, the theory predicted crush strength trends well enough to be a useful design tool.

Finite element simulation of the cellular beam provided limited additional insight. Success of the simulation required careful definition of material data from the as-fabricated cellular structure and seat-rail. Prediction of damage propagation for composite cellular structures is not possible with existing constitutive material models. While simulation of a specific configuration can be done with some effort, cellular structure design using nonlinear finite element codes remains a challenge.

Owing to the retrofit nature of the design, several unforeseen obstacles were encounter, the hardest one was related to the seat-rail interaction with the crushable keel beam. In particular, the requirement that a standard seat-rail be used that would deform plastically without fracturing, and remain attached to the beams following the crash was found to be extremely difficult.

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14. ABSTRACT

A lightweight energy-absorbing keel-beam concept was developed and retrofitted in a general aviation type aircraft to improve crashworthiness performance. The energy-absorbing beam consisted of a foam-filled cellular structure with glass fiber and hybrid glass/kevlar cell walls. Design, analysis, fabrication and testing of the keel beams prior to installation and subsequent full-scale crash testing of the aircraft are described. Factors such as material and fabrication constraints, damage tolerance, crush stress/strain response, seat-rail loading, and post crush integrity, which influenced the course of the design process are also presented. A theory similar to the one often used for ductile metal box structures was employed with appropriate modifications to estimate the sustained crush loads for the beams. This, analytical tool, coupled with dynamic finite element simulation using MSC.Dytran were the prime design and analysis tools. The validity of the theory as a reliable design tool was examined against test data from static crush tests of beam sections while the overall performance of the energy-absorbing subfloor was assessed through dynamic testing of 24" long subfloor assemblies.

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