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Carbon Fiber Reinforced Steel Spaceframe Techniques

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ABSTRACT

This paper presents several basic construction techniques involved in using carbon fiber sandwich boards to reinforce a tubular steel spaceframe. Also described are tests on modular panels of various designs utilizing carbon fiber sandwich panels as a supporting member. Comparison of a conventional, all steel truss to several carbon fiber reinforced spaceframe techniques has been made as well as an analysis of the stiffness per mass and ultimate strength of each design. The design using structural rivets to connect aircraft grommets in the panels to steel strips welded to the tubing yielded the greatest benefits in stiffness per mass and ultimate strength.

INTRODUCTION

The Formula SAE (FSAE) competition challenges engineering students to design, build, and compete with a formula style race car. Students are to assume a company has employed them to construct a prototype racecar. The car is intended for the non-professional driver racing in an autocross event. In a production run of 1000 cars, complete cost should be less than $9000. Cars are limited to a four stroke restricted engine with a maximum displacement of 610cc. With the exception of powerplant limitations, rules restrict car designs in few ways.

The relative openness of the Formula SAE rules has lead to a great variety of chassis designs. Hundreds of different chassis have been built by engineering students for the FSAE competition. Rules do not limit the design or construction of the chassis beyond some safety guidelines; consequently, several different construction techniques have been applied over the 17-year history of this event. Steel and aluminum spaceframes dominate while monocoques of aluminum and fiberglass have also competed.

A complete design of an FSAE chassis will be one that effectively handles all static and dynamic loads while maintaining proper kinematics of the suspension. The ability of the frame to carry loads lies primarily in the selection of material and orientation of frame structure to the applied loads. Geometric form and frame materials are directly related to the ability of the chassis to carry torsional loads - a main concern in chassis design. To insure that chassis and wheel movement are controlled by the suspension springs and not the flexing of the chassis itself, the torsional rigidity of the chassis should be an order of magnitude greater than the difference in roll stiffness between the front and the rear of the car. The brackets for the suspension nodes must also be integrated into the design such that dynamic loads do not cause unwanted, unpredictable geometric changes during vehicle operation. Many designs meet these requirements. The University of Minnesota FSAE team has developed a design which combines the ease of manufacture of a steel spaceframe with the high stiffness per mass ratio of carbon fiber. The concept is based on 2-dimensional modular spaceframe sub-structures and utilizes an outer steel structure with a carbon fiber honeycomb panel inserted between steel members (Fig 1). Modular "panels" are combined into a 3-dimensional design that forms the chassis. The completed structure offers a high stiffness to mass ratio at little sacrifice in cost and complexity. This type of construction has been the basis for both 1997 and 1998 U of MN formula car frames.

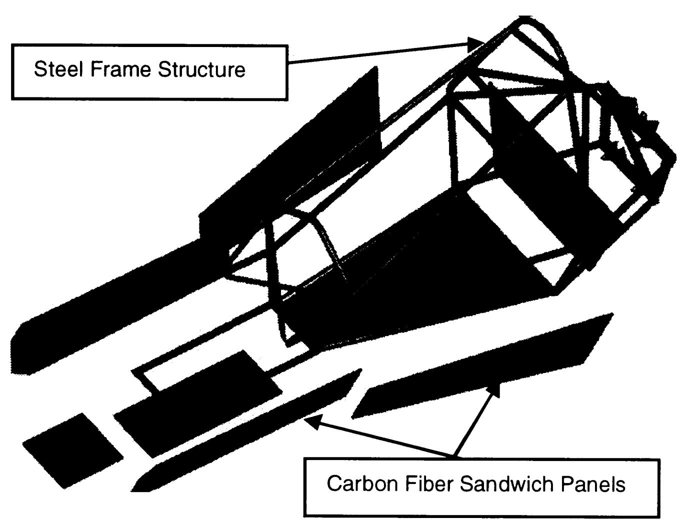


Figure 1. Frame Blow-out

This paper introduces the basic design criteria and specifications involved in designing and constructing an FSAE frame, an explanation of design and construction techniques of the steel/composite structure used in U of MN FSAE frames, and results from shear loading tests on panels approximating an average size sub-structure.

SPECIFICATIONS FOR FSAE CHASSIS DESIGN

Due to the nature of the Formula SAE event, students are encouraged to explore many options in the design of the vehicle. With the exception of a few rules regarding safety, which really do not restrict designs, chassis designs are unlimited.

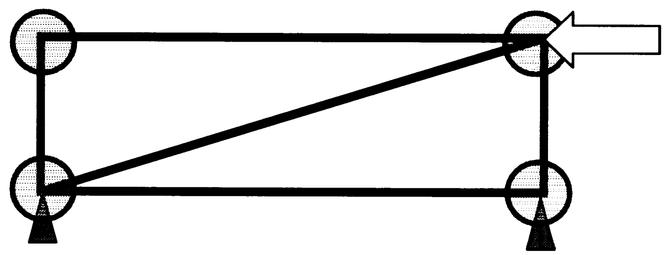
The design of an FSAE chassis begins with a close inspection of the rules governing the event[1]. With the exception of rudimentary rules stating size of car (wheelbase >1520mm (60")) and requiring suspension (car must have a suspension system with ±25mm of suspension travel - 50mm total), the only regulations in frame design pertain to driver and worker safety. Rollover protection, side impact protection, floor closeout, and driver position have requirements that must be considered when designing the frame.

Rules dictating safety measures for rollover protection include the approximate size and material for roll hoops and supports (Rule 3.2.1). Roll hoops must be of continuous closed section tubing and sized/positioned such that the tallest driver's helmet is no less than 50mm from a line drawn between the top of the front roll hoop to the top of the rear roll hoop. Furthermore, roll hoops must be constructed of mild steel (SAE 1010, 1020, 1025) tube with 25.4mm outside diameter and 2.41mm wall thickness or alloy steel (SAE 4125, 4130) tube with 25.4mm outside diameter and 1.65mm wall thickness. Composite materials are not permitted for roll hoop materials and other materials such as aluminum must be of strength equivalent to the steel tubing as specified by rules. Additional specifications for locations of roll hoop bracing are also stated. Placement of roll hoops and/or bracing may hinder the ability of the driver to exit the vehicle in the allotted time (rules require that the driver must be able to completely exit the vehicle in 5 seconds or less) and therefore should also be considered in the design.

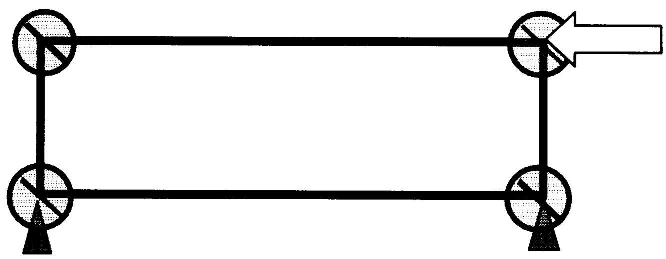
Other safety issues include side impact protection and floor closeout (Rule 3.2.2). Side impact rules require two frame members connecting the front and rear roll hoop and a diagonal member forward of the rear roll hoop and rearward of the front hoop connecting the top and bottom frame member, in effect, closing out the cockpit in an event of side impact. Frame members must be 25.4mm × 1.65mm mild steel tubing or equivalent alloy steel (25.4mm × 1.24mm). In addition to these measures the cockpit must be enclosed with sheets of an unspecified material (sheet aluminum is normally used). Sheets must placed on cockpit sides and floor and extend to the footwell area. Although steel tubes are normally chosen, materials and cockpit design can be substituted given that the design is proven to provide equal or greater protection to the driver.

U OF MN MODULAR PANEL APPROACH

The benefits that carbon fiber monocoque chassis carry over steel space frames in terms of mass, overall stiffness and safety are well known. Although FSAE chassis designs are not limited in the type of material used, the cost and complexity that goes with monocoque construction usually deters teams from this type chassis. Steel spaceframes are much more appropriate for an FSAE team with limited budget and resources, especially those new to racecar design and construction.



(a) Welded joints **do not** support moments.



(b) Welded joints **must** support moments.

Figure 2. Spaceframe Design

The ability to easily weld on suspension, engine, and other mounts and effectively transmit loads to the frame structure is one of the reasons for choosing the spaceframe design. The complexity that is required of a monocoque design, especially in the ability to transmit loads through the structure, is usually beyond that of a student FSAE team. There are however, many benefits that come with monocoque (especially carbon fiber) designs, namely greater stiffness per unit mass. The University of Minnesota team has developed a different kind of spaceframe design which incorporates some of the positive aspects of the carbon fiber monocoque chassis, including a greater stiffness per mass.

In a typical all steel spaceframe, chassis loads are normally directed along the longitudinal axis of a tube, i.e. frame tube members experience only tension and compression. In the ideal case, a pin joint could replace each welded joint (node) of a spaceframe design and the chassis would remain a rigid structure (Fig. 2(a)). In the less than ideal case - a result of poor design and/or manufacturing - welded frame nodes carry moments as in Fig. 2(b). Nodes, which are constrained to carry moments, signify a joint prone to failure and a less rigid frame.

FSAE rules require the cockpit and footwell areas be closed with some type of sheet. Aluminum is normally used for this purpose. If rigidly mounted to the frame members, the sheet will handle some of the loads of the chassis. If the sheet material is of great enough strength, it can effectively replace the triangulating (diagonal) member seen in the normal spaceframe (Fig. 2(a)). Loaded strictly in tension or compression the sheet or plate would tend to shear. This type of design presents some advantages over the single, diagonal frame member. One advantage being that the "shear plate" would serve the dual purpose of being a structural frame member and means of closing out the cockpit area as per FSAE rules. The second advantage comes in the ability of the plate to transfer loads throughout the entire structure. The extreme case of this shear plate design being a monocoque structure where loads are transferred through panels of aluminum or carbon fiber sandwich material.

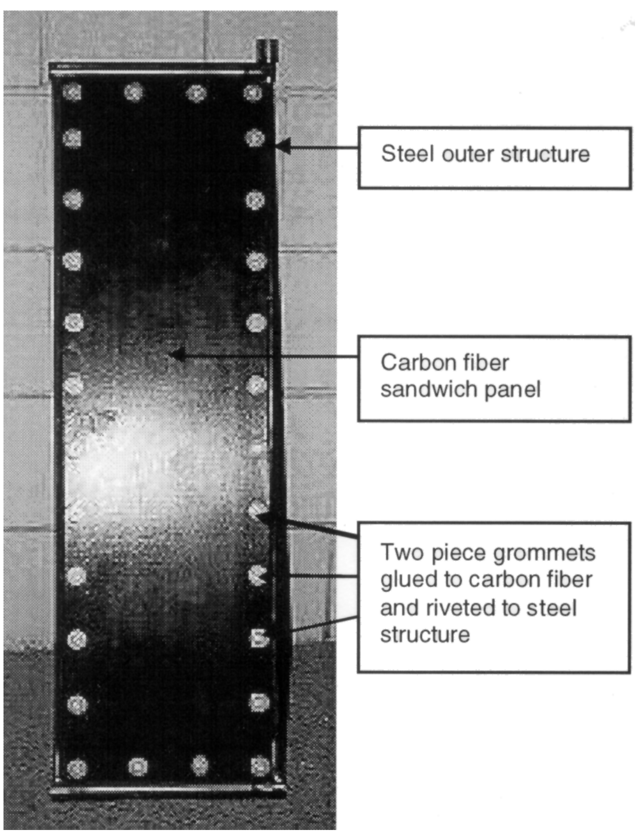


Figure 3. Modular Carbon Fiber Panel

The design utilized on both 1997 and 1998 University of Minnesota cars consisted of a carbon fiber reinforced spaceframe. The frame structure was constructed of thin wall 4130 steel tubing and carbon fiber honeycomb sandwich panels were inserted between steel members and rigidly attached (Fig. 3). The carbon fiber sandwich panels act as the shear plate, replacing the steel diagonal member.

Such a design was conceived to combine the ease of construction of the spaceframe with the high stiffness per mass of the carbon fiber sandwich panels. Different methods of attaching the panels have been tested to utilize the stiffness of the structural sandwich panels i.e. transfer the greatest amount of energy from the steel structure (where the loads are applied) to the carbon fiber panel (which exhibits high specific stiffness and tensile strength).

The methods of attachment include panels being bolted, riveted and epoxied with Kevlar tape. Outlined below are specific panel designs tested (See also Fig. 6).

PANEL DESIGNS

<u>Reference steel triangulated panel</u> – The control design was a panel built according to the most direct interpretation of the FSAE rules. It is represented by figure 2(a). This all steel truss consisted of 4130 tubing 25.4mm × 1.65mm on the ends (representing front and rear roll hoops) and 25.4mm × 1.24mm material on the upper, lower, and diagonal members. An aluminum sheet was attached to the face of the structure with aluminum pop rivets (representing a panel separating the cockpit from the environment). The mass of this panel was 3.5kg (7.6lb) and it was called panel #1.

Figure 4. Carbon fiber panel bolted to steel strips welded on to steel tubing

<u>Carbon-fiber panels bolted to tabs on 25.4 mm (1") diameter steel tubing</u> – This attachment method involved drilling 13mm holes in Hexcel Fibrelam 2000 carbon fiber sandwich board (10mm section thickness) and bonding two-piece Shur-lok aluminum grommets in each hole using a proprietary two-part resin supplied by Ciba. Thin strips of 1.24mm (.049") wall 4130 steel sheet metal were welded lengthwise to 25.4mm × 1.24mm (1" × .049") 4130 steel tubing. Holes were drilled in the strips to cor-

respond with those in the panel. The panel was positioned inside the steel frame such that it was centered in the plane of the frame, so the strips were offset to allow for the 10mm (.4") thick sandwich board. NAS 1102-3 bolts were used to clamp the grommets to the strips. Spacing between bolts was 300mm. The test panel had a mass of 2.6kg (5.6lb) and was called panel #2. Simplicity of construction and ease of assembly and disassembly characterized this design, it was used as the construction technique for the 1997 University of Minnesota Formula SAE car, the integrated seat/cockpit side panel construction required that the side panels be removable to access electronics and fuel system components under the seat.

<u>Carbon fiber panels riveted to 12.7mm (.5") diameter steel tubing</u> – Reduced weight was explored by substituting 12.7mm upper and lower members for the 25.4mm diameter members used on most of the other structures. The test panel had a mass of 1.9kg (4.2lb). The intention with this type of construction was that the composite panel would be able to carry most of the loads between the 25.4mm × 1.65mm (1" × .065") roll hoops and the use of rivets as the fastening device would assure a good connection. As with the bolted panel above, holes were drilled in the carbon-fiber panels and grommets were glued in place. The holes were placed on 76mm (3") centers in both the panels and the corresponding steel strips welded to the rectangular frame. Unlike the strips in the bolted design, the strips welded to the riveted designs extend all the way around the inside of the steel frame and were welded to each other. The specified stitch welding pattern was 30mm of welding every 60mm. Huck Magna-Lock structural rivets were used to transfer the shear forces from the steel to the carbon fiber. These rivets are designed so that the pulling mandrel breaks off and remains in the shear plane of the rivet. The mandrel is 7075 aluminum and the rivet body is 5052 aluminum. The manufacturer states the shear strength of the 3/16" (4.76mm) rivet is 700 to 750 lbs. (3.2kN). This was called panel #3.

<u>Carbon fiber panels riveted to 25.4mm (1") diameter steel tubing</u> – This design was a primary area of investigation; it featured a sandwich board panel riveted to upper and lower steel elements with increased polar moments of inertia. The composite structure had 25.4mm × .89mm (1" × .035") 4130 upper and lower members along with the required 25.4mm × 1.65mm (1" × .065") roll hoop members. The construction procedure was as above for the panel using 12.7mm tubing. Initially a panel was built using the 76mm (3") spacing to compare stiffness and strength with panel 3. This was called panel #4. When initial results looked promising, decreased rivet spacing was investigated. A test panel was constructed which had rivets on 51mm (2") centers along one side and spacing of 38mm (1.5") and 25mm (1") in the remaining corners. This was called panel #6. The mass of panels 4 and 6 was not significantly different, they were both 2.5kg (5.5lb).

<u>Carbon fiber panels taped and glued to 12.7mm (.5") diameter steel tubing</u> – This panel had an outer frame similar to panel #3. A standard sized, sandwich board panel was placed in the center of a steel frame utilizing 12.7mm × 1.24mm (.5" × .049") upper and lower members and 25.4mm × 1.65mm (1' × .065") roll hoop members. Kevlar tape was coated in an epoxy and wrapped around the steel tubing and outer skin of the panel. Four strips of Kevlar 10cm (4") wide were used such that one strip wrapped each side of the structure. The lay-up was vacuum-bagged overnight. This design produced the lightest test panel; the mass was 1.8kg (4lb). This was called panel #5.

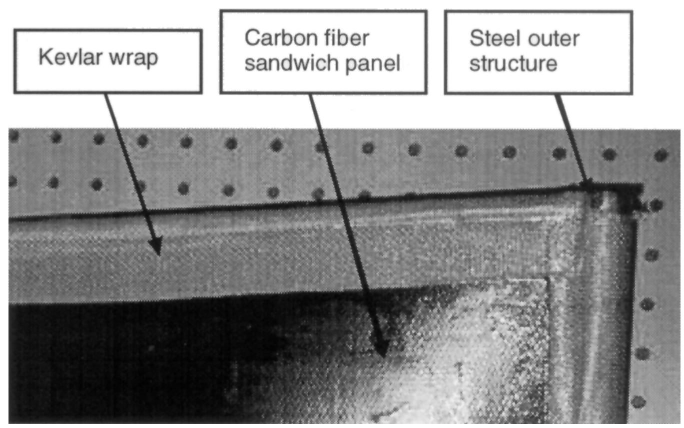


Figure 5. Kevlar taped carbon fiber panel

EXPERIMENTAL TESTING PROCEDURE

The shear loading tests were conducted at the University of Minnesota's main Civil Engineering laboratory. The test fixture is shown in figure 7. Test panels were held to the test fixture by steel mandrels inserted into the lower frame member. The fixture consisted of two 25mm thick steel plates fastened to a W 12 × 50 double "I" floor beam with 25mm bolts. This "I" beam was then fastened to the 1m thick floor with 30mm hardware. Panels were loaded and constrained as in figure 2(b) and 7(a). The corner opposite the load was pinned and the fixed corner nearest the load was free to slide in the direction of the load.

Force was applied on the panels by a 15-ton capacity come-along. A Sensotec 41/573-01 load cell (0 to 220kN) measured this force. A Measurements Group P-3500 strain indicator provided the conditioning and digital readout for the load cell. The force was transmitted to the test specimens by a doulbe threaded 13mm cable. The cable transmitted the load through various custom fitted adapters.

#	Panel Type	End Tube Material (Roll Hoop)	Upper/Lower Tube Material	Carbon Fiber Panel Attachment Method	Mass(kg)	Diagram
1	Steel Spaceframe	4130 Steel – 25.4×1.65mm	4130 Steel – 25.4×1.24mm	—	3.5	Similar to Fig. 2(a)
2	Carbon Fiber Reinforced	4130 Steel – 25.4×1.65mm	4130 Steel – 25.4×1.24mm	2 piece grommets glued to carbon fiber and bolted to steel strips at 300mm spacing	2.5	Fig. 4
3	Carbon Fiber Reinforced	4130 Steel – 25.4×1.65mm	4130 Steel – 12.7×1.24mm	2 piece grommets glued to carbon fiber and riveted to steel strips at 76.2mm spacing	1.9	Fig. 3
4	Carbon Fiber Reinforced	4130 Steel – 25.4×1.65mm	4130 Steel – 25.4×1.89mm	2 piece grommets glued to carbon fiber and riveted to steel strips at 76.2mm spacing	2.5	Similar to Fig. 3
5	Carbon Fiber Reinforced	4130 Steel – 25.4×1.65mm	4130 Steel – 12.7×1.24mm	Kevlar tape wrapped around steel structure and bonded with epoxy	1.8	Fig. 5
6	Carbon Fiber Reinforced	4130 Steel – 25.4×1.65mm	4130 Steel – 25.4×.89mm	2 piece grommets glued to carbon fiber and riveted to steel strips at 50.8, 38.1, 25.4mm spacing	2.5	Similar to Fig. 3

Figure 6. Test Panels

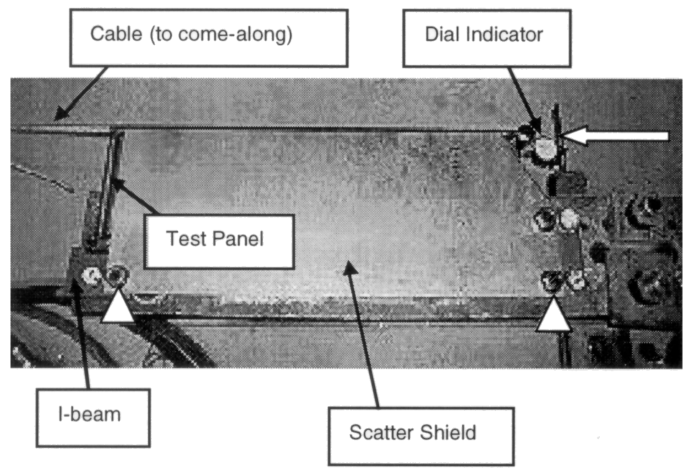
Deflection was measured using a dial indicator 20mm from where the load was applied. Panels 5 and 6 were equipped with Measurements Group Student strain gages. Strain gage rosettes were placed in the centers of the panels to determine overall stress levels and directions transmitted to the panels. Also investigated through linear strain gages was the stress level between rivets at 25.4, 38.1, and 50.8mm spacing. A Measurements Group SB-10 switch and balance unit was used to relay information from multiple gages to the strain indicator. Data was manually recorded from this point.

To begin a test, a panel was inserted into the fixture and covered with a scattershield. Initial tests conducted in November 1997 involved loading panels #1, #2, #3, and #4 to failure. Data was recorded at each ratchet-stop on the come-along. These tests demonstrated failure modes, weak points in each design, ultimate panel strength and the opportunity to determine stiffness.

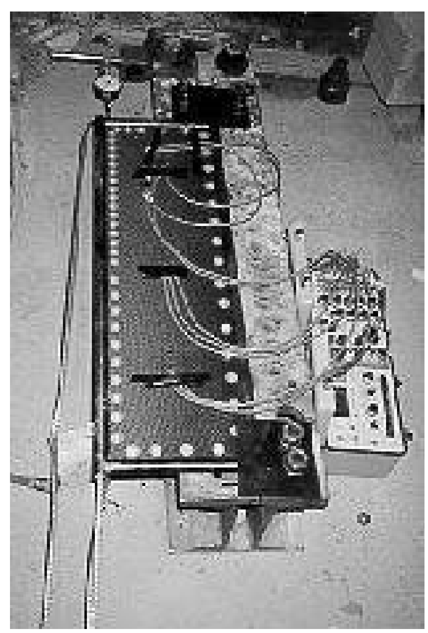
After the results were reviewed for the first four designs, a decision was made to construct the 1998 U of M car using a 50.8mm rivet spacing and 25.4mm × .89mm frame materials wherever possible (with the exception of the roll hoops). At this time the 50.8mm spacing had not been investigated but was assumed to be stiffer and stronger than the 76.2mm spacing which looked promising.

Further in-depth tests were conducted in June 1998 on panels #5 and #6 (Fig. 6(b)). These tests involved loading the panels up to about 9kN (2000lb) in small increments to obtain more accurate displacement data in the elastic region most likely to simulate loads encountered by a racecar chassis. Strain gage data was also collected at these times. Panel #5 was loaded twice in this manner before it was subjected to destruction testing.

Panel #6 was placed in the fixture in three different orientations to test the three different rivet spacings utilized in its construction. (A review of the destruction tests of panels #2 and #4 indicated that more stress was concentrated in the corner nearest the applied load, therefore testing a panel with differing construction in each corner seemed like a cost effective way to investigate several ideas.) Panel #6 underwent four loading cycles before a test to failure was conducted.



(a)



(b)

Figure 7. Test Fixture Setup

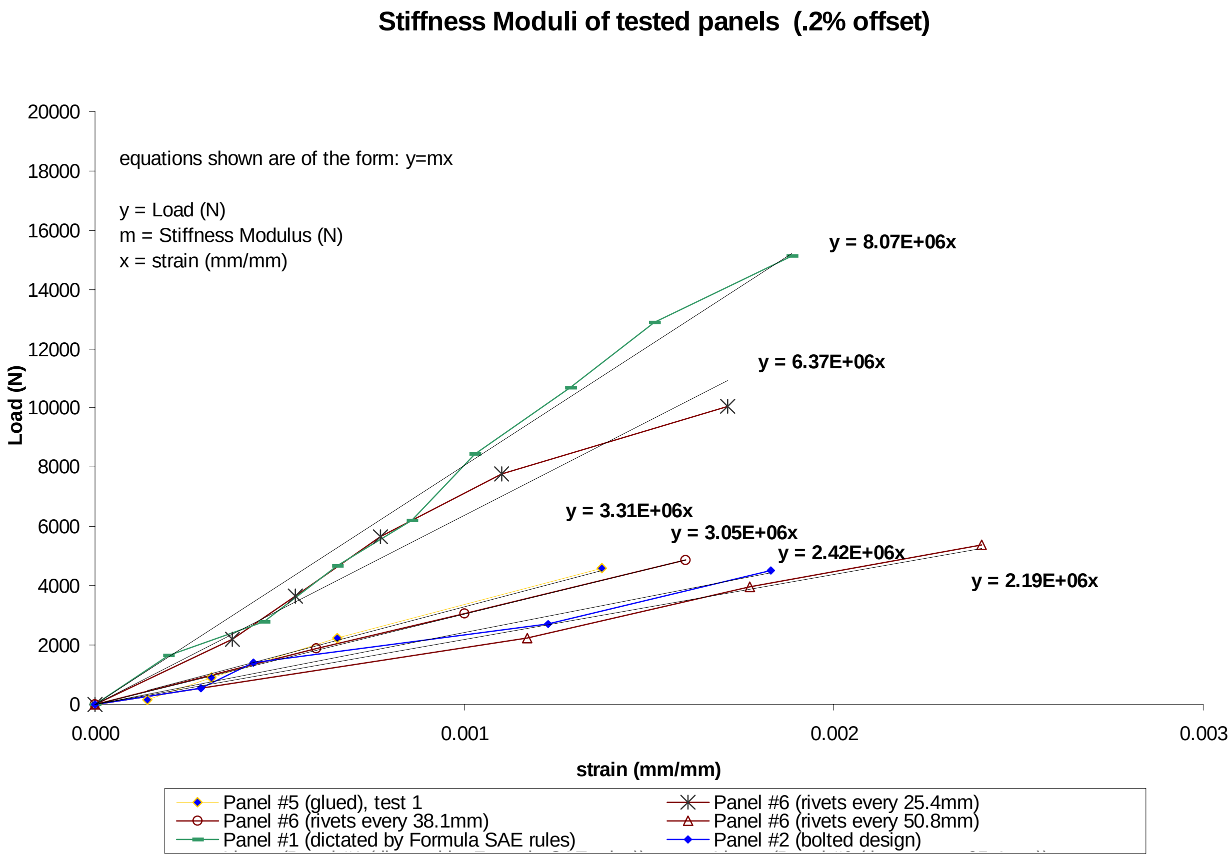


Figure 8.

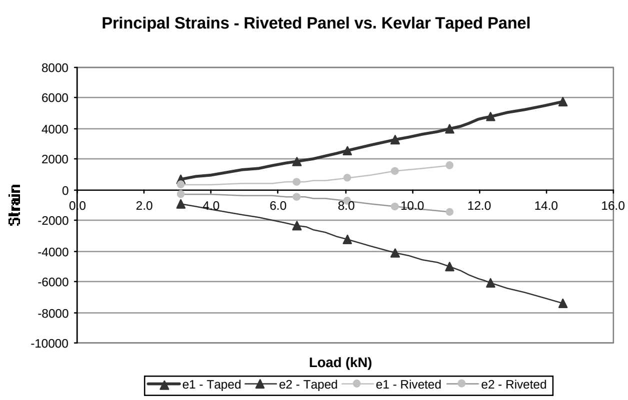


Figure 9.

ANALYSIS – Stiffness to Mass – The panel stiffness to mass ratio was the quality determined to be most important for consideration as an element in the overall chassis. If one design proves stiffer than another for a given mass, the stiffer one is more desirable. The assumption that stiffer two-dimensional elements lead to a stiffer three-dimensional chassis follows. A potential problem lies in the orientation of the panel elements within the chassis. If shear loads are not applied to each panel in a way similar to the loading of this experiment. It is quite possible that a different design is stiffer when twisted, for example.

Applied load data and calculated strain figures from the test were used to arrive at a stiffness modulus for each panel design. The strain was calculated using Eqn. 1

$$e = (l - l_o) / l_o \qquad \text{(Eq. 1)}$$

The initial length used (lo) was the longitudinal length of the test panel: 890mm (35"). The load was plotted with respect to this strain (similar to the stress vs. strain plot used to determine Young's modulus). A least squares fit was used to determine the equation of the line through each set of points (forced through the origin). This stiffness modulus was determined in the region less than .002 strain. For example, the equation for the line which best fit the data from panel #1 was y=8.07*10^6*x. The slope of the line is the stiffness modulus and in this case represents the stiffest specimen. This .2% offset curve can be seen in figure 8.

The stiffness of the panels should be related according to the proportional strains experienced by each component comprising a test panel and the moduli of each of those components. When minimum mass is a concern, each componemt of the test panel must be fully stressed. Likewise, it is important to bring more stress to the stiffer components of the panels.

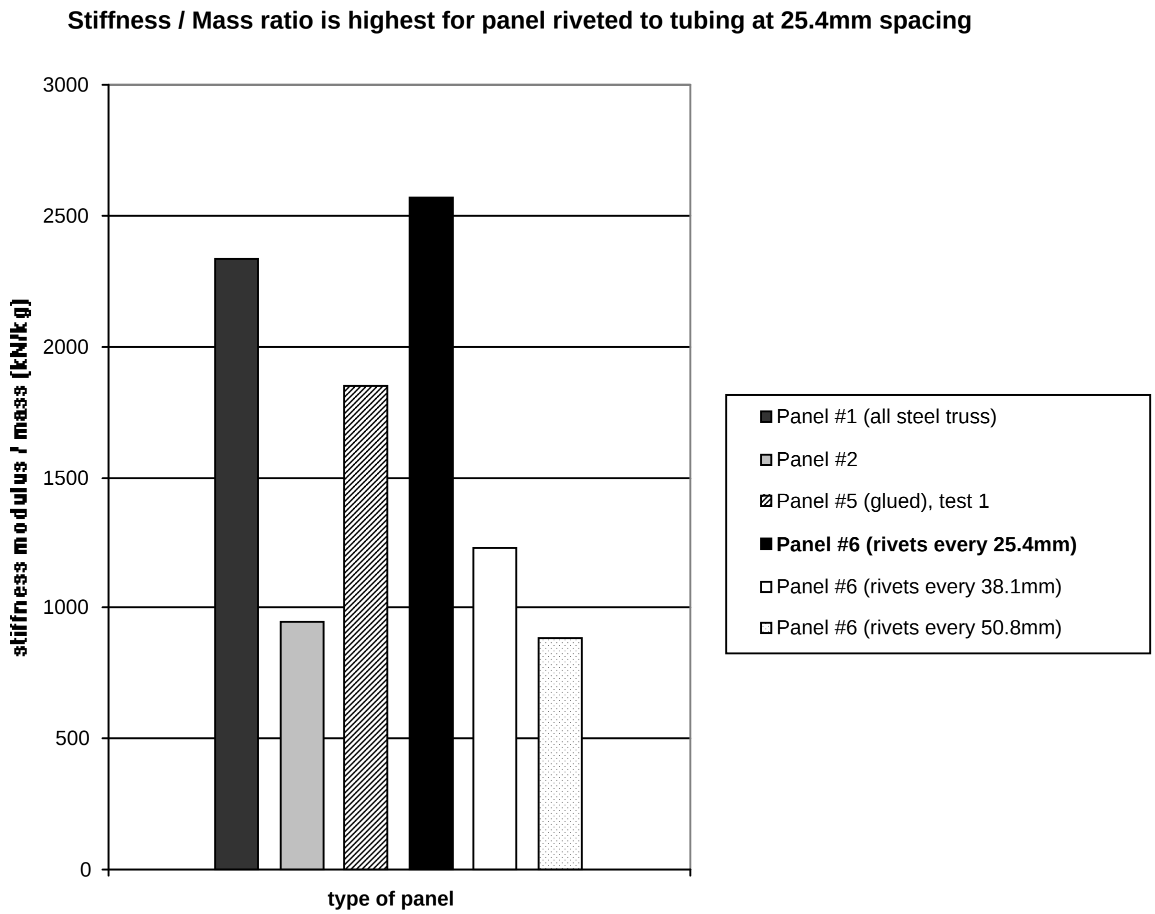


Figure 10.

Panel 1, the diagonally braced steel structure, proved to be the stiffest specimen. The modulus of the riveted specimen did increase significantly as the spacing between the rivets was reduced. The panels using rivets were probably limited by the modulus of aluminum. As more rivets were added to a structure, they could effectively distribute more of the stress to the stiffer steel and carbon fiber they were fastening. Strain gage data[3] taken between rivets at these three spacings confirms this.

The stiffness of the panel taped and glued to the steel frame was between that of the panels with 25.4mm and 38.1mm spacings. The bolted specimen exhibited a low modulus.

The sandwich panel taped and bonded to its steel frame did the best job of fully stressing the carbon fiber panel. This was determined through analysis of strain rosettes placed in three locations on the surfaces of specimens 5 and 6. Three strain gages were placed in similar, central locations on the two panels. Figure 9 shows principal strains at one of the gage locations for both panels (remaining gages produced similar results). Principal strains in the taped panel were significantly greater than the riveted panel design. Increased stress in the carbon fiber board is important because it signifies that more energy is transferred from the steel structure to the carbon fiber sandwich board, which yields at a much greater stress. The bolted panel design probably suffered from some movement in the steel strip - bolt - grommet interface. The clearance necessary to install the bolts would have to be taken up before the fasteners could load the panel. This was one of the reasons for testing a riveted design. The fact that only eight bolts were used also contributed to poor load transmission to the carbon fiber panel.

Factors contributing to accuracy in stiffness results include strain in the test fixture mounting and cable. These two factors would have been relatively equal for each of the specimens subjected to testing. Relative stiffness values are still valid with this uncertainty. Another area of possible difference between the structures using the sandwich board panels was the tightness of the press fit into the steel frame. In general, all carbon fiber panels were individually finished to the tightest tolerances that would still allow a press fit by hand. Tolerances of the press fit were difficult to quantify and surely there were differences between specimens. These differences could have had an effect on the stiffness modulus. A final area of concern involves the fact that the tests conducted on rivet spacing of 25.4, 38.1, and 50.8mm all occurred on the same specimen. Specifically, the stiffness test was first conducted on the corner with the closest spacing, the load was relaxed, the panel was repositioned in the fixture, and the same test was conducted on a different corner. This repeated cycling of the structure, although well within what should have been the elastic region, may have caused some setting of the rivets or the carbon fiber panel itself. This error was difficult to quantify.

Because racecars are designed to be capable of high accelerations, minimum mass is always a concern. The most interesting aspect of this investigation was to find which type of construction yielded the highest stiffness per mass ratio. Figure 10 is a plot of the stiffness of each panel (as determined above) versus each panel's respective mass. The height of each of these bars represents the stiffness / mass ratio in units of Newtons / kilogram. This unusual conglomeration of units is a result of using the applied force indicated on the testing procedure's load cell for moduli calculations instead of a stress.

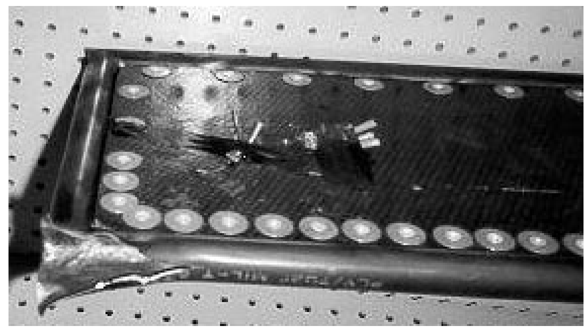
The highest bar belongs to the panel with rivets spaced closest together. Interestingly, the next highest bar is demonstrated by the traditional steel structure with cross-bracing.

<u>Ultimate Strength and Failure Mode</u> – A complete destruction test of each panel occurred after stiffness (deflection) readings were taken. The purpose was to gauge the ultimate strength of similar sized panels of different construction, and secondly, to determine the mode of failure of each panel at the point of yielding.

Panel design #6, with sandwich board grommeted and riveted at 25.4mm spacing, proved to be the strongest of all panels tested. Failure of this test panel was mainly a function of the test fixture itself. The eyebolt through which the cable was looped split the upper tube where the load was applied (Fig. 11a). Had the loading been applied in a similar manner to a real chassis (e.g. Rod end bolted to a welded on suspension pick-up) the ultimate strength of this panel would most likely have been greater.

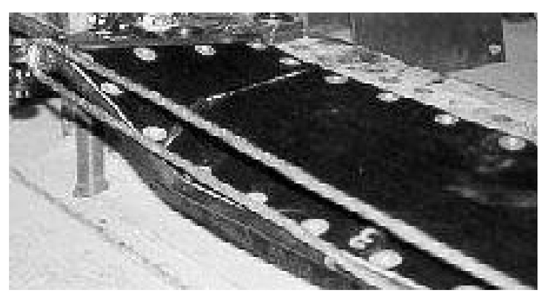
The second strongest panel was that which used a similar grommet/rivet attachment method except at a different spacing - Panel #4 with 76.2mm rivet spacing. Panel #4 provided 87% the ultimate strength of panel #6. Panels #5 and #1 followed with 79% and 75% the strength of panel #6 respectively. The bolted design (#2) was the weakest of all panels.

Failure modes differed greatly between panel designs. Failure of the all steel panel (#1) was result of the diagonal member buckling. An analysis of this simple truss proves the same failure mode - buckling of the diagonal member because of the high compressive loads placed on it in this particular loading situation. Test panel #2, the design using a bolted in sandwich board, failed in a much different manner. Grommets glued to the sandwich board pulled out along the top edge of the panel, a result of the limited strength in the glue bond between the grommet and the carbon fiber skin. Unlike panel #2, test panel #4 was limited to the shear strength of the rivets, which attached the sandwich board to the steel, rather than the glue area of the grommets. In this case the panel failed when rivets sheared along the to edge of the test specimen, followed immediately by a skin and core fracture near the loaded end (Fig 11b). Panel designs using 12.7mm steel tubes as upper and lower members both failed as a result of the upper member (tube nearest the load) buckling (Fig 11c and d). The skin and honeycomb core of the sandwich panel also fractured near the buckling location of the tube. Failure of the sandwich board is most likely a result of forces acting perpendicular to the shearing plane produced when the upper member buckled rather than an ultimate failure of the board itself in shear. It is also interesting to note that both panels, despite different methods of attaching the sandwich board, buckled at almost the same point and neither buckled in the center (measure lengthwise) of the tube.

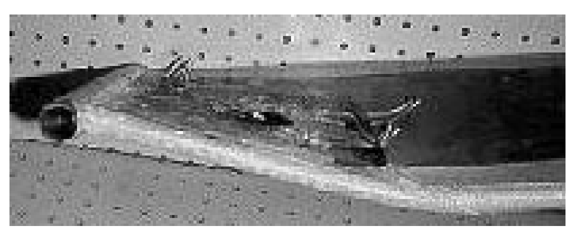


(a) Panel #6

(b) Panel #4



(c) Panel #3



(d) Panel #5

Figure 11. Test Panel Failure Modes

Chassis stiffness increases as panels are riveted to the structure, composite frame stiffness is 1220 N*m / deg (900 ft*lb / deg)

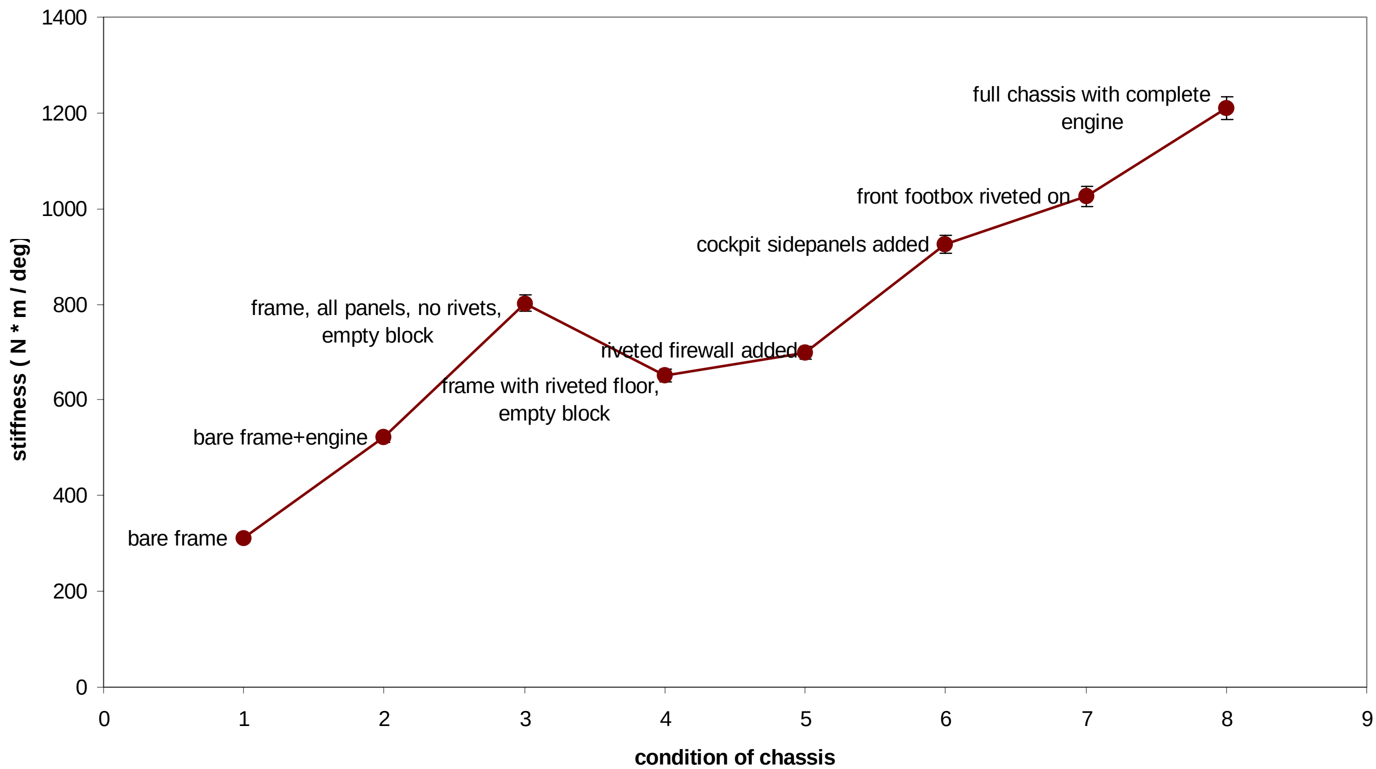


Figure 12.

Specific Stiffness to Mass Ratio for the Entire Chassis – After a carbon fiber reinforced steel spaceframe construction technique was chosen, a complete chassis was fabricated. The structure shown in Figure 1 is a combination of panel-reinforced elements and spaceframe elements. All major suspension loads are introduced at nodes or are oriented directly into the plane of a carbon fiber panel. The mass of the engine, which subjects the chassis to large static and dynamic loads, is also treated this way. The driver's weight is spread over large areas of the floor, seatback and sidepanels.

A test fixture was constructed to test torsional rigidity of the chassis. Figure 13 This fixture was designed to pin the frame at the two rear bellcrank pivots and provide a vertical support at one of the front bell crank pivots. In this way, the stiffness of the chassis is measured across the sprung base of the car.

A torque arm was connected between the front bellcrank pivots and a load was applied at the outboard end. Vertical motion of both front nodes was measured with digital calipers and the chassis was twisted until 1 degree of rotation had been achieved. This procedure was carried out with a bare frame and successively as carbon fiber reinforcing panels were riveted in. Results are shown in Figure 12.

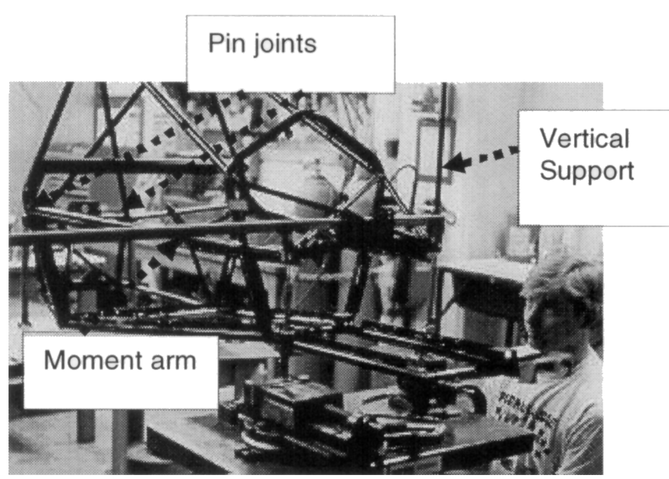


Figure 13. Frame Torsion Test Setup

Another way of gauging a successful chassis is to compare the torsional stiffness of the frame with the mass of the material used to obtain that stiffness. Data from several successful Formula SAE teams is compared to data from several well known chassis types[2,4,5,6]. This information is compared in Figure 14.

CONCLUSION

The approach of testing a simple, two-dimensional, modular panel as an element in a complex three-dimensional structure answered some questions and raised several more.

Panel #5 exhibited much higher stresses in the carbon fiber sandwich board than similar riveted panels. The outer steel structure was an inadequate supporting structure and the test panel proved to be less stiff and failed at a lower loading than the riveted design. Further tests of a panel using 25.4mm × .89mm (1" × .035") upper and lower members taped and bonded to a carbon fiber sandwich panel would probably produce very high stiffness to mass ratios. This type of panel is especially difficult to incorporate in a 3-D chassis because many of the intersecting and adjoining 2-D elements would need to share the Kevlar tape. The tape would also prevent any welding of additional brackets to the steel frame after the panels were installed. Once the adhesives set, there would be little chance of removing pieces for repair or adjustment. The option to add or relocate brackets is important in prototype fabrication.

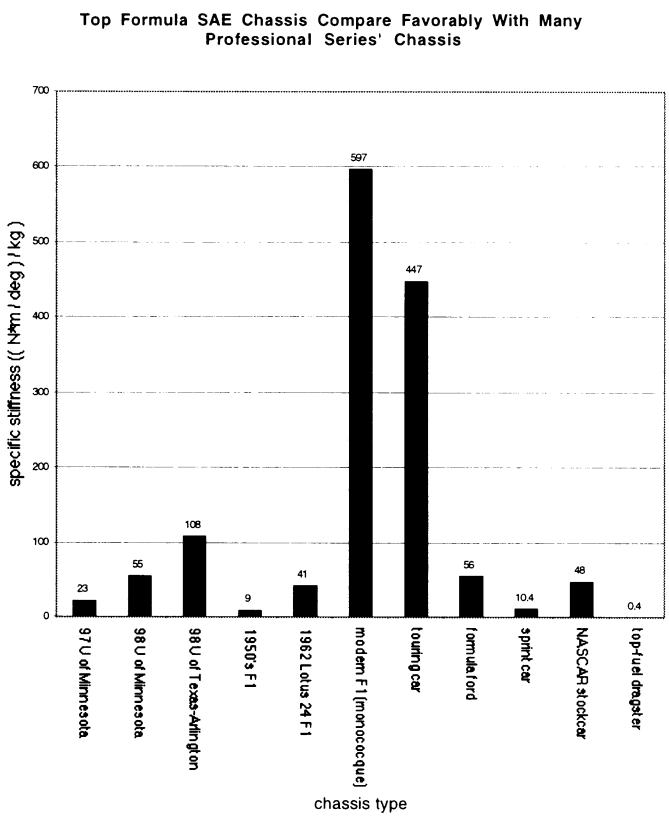


Figure 14.

Tests conducted proved the carbon fiber reinforced spaceframe a competitor to the typical all steel spaceframe. A direct comparison of stiffness per mass and ultimate strength of test specimens of similar size in identical loading situations, indicates that a carbon fiber reinforced frame can exceed steel spaceframe performance. A chassis using this technique as a large part of the design has a torsional stiffness per mass comparable to similar racecars. In addition, the carbon fiber reinforced steel spaceframe is simple to build and even has panels that can be removed for service or damage repair.

Performance of the carbon/steel spaceframe is however, directly related to the attachment method of the carbon fiber sandwich board to the outer steel frame. Rivet and bolt spacing proved critical in the ability of loads to transfer from the steel to the stiffer, carbon fiber panel. Generally, closer hole spacing provided a stiffer panel. Rivet shear strength also played a role in the ultimate strength of test panels.

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