Production of a Composite Monocoque Frame for a Formula SAE Racecar

Conference Paper · April 2013

DOI: 10.4271/2013-01-1173

4 authors, including:

Peter J Joyce
United States Naval Academy

SAE International

Production of a Composite Monocoque Frame for a Formula SAE Racecar

2013-01-1173
Published
04/08/2013

Leonard Hamilton, Peter Joyce, Chris Forero and Martin McDonald
US Naval Academy

doi:10.4271/2013-01-1173

ABSTRACT

A carbon fiber reinforced plastic (CFRP) monocoque racecar frame was designed and constructed by students for the 2012 Formula SAE (FSAE) collegiate design series competition. FSAE rules require that the monocoque frame have strength equal to or greater than the traditional steel space frames that they replace. The rules also specify minimum values for perimeter shear strength, main roll hoop attachment strength and driver harness attachment (pullout) strength. Overcoming limitations imposed by locally available finite element analysis tools, a variety of tests were devised to determine required laminate thicknesses and layup orientations. These included perimeter shear tests, pin shear tests, three point bend tests and tensile tests. Based on the results of these tests, a sandwich construction using composite skins fabricated from carbon/epoxy prepreg and aluminum honeycomb core was selected. Starting from the outside, the sandwich consisted of a single layer of bi-directional woven carbon/epoxy, three unidirectional layers of carbon/epoxy, a single layer of bi-directional woven carbon/epoxy, 16 mm thick aluminum honeycomb core, a layer of bi-directional woven carbon/epoxy, three unidirectional layers of carbon/epoxy and a final layer of bi-directional woven carbon/epoxy ($F/0_3/F/core/F/0_3/F$). Additional layers of carbon/epoxy weave were used in side impact regions and for various hard point attachments.

Details of the mold design and manufacture as well as the composite lamination are summarized. The monocoque frame resulted in a 53% reduction in component weight and a 43% increase in torsional rigidity as compared to a steel space frame. The composite monocoque frame also provided a qualitative improvement in vehicle handling and aesthetics and more importantly proof that composite techniques suitable for the motorsports environment are achievable on an undergraduate level.

INTRODUCTION

Each year hundreds of university teams from around the world compete in the Collegiate Design Series sanctioned by SAE International. One series known as Formula SAE or (FSAE) involves student designed and built small formula style (open wheel) racecars built to a strict set of rules [1]. Including both static and dynamic events, the FSAE competition truly tests the limits of student imagination, innovation, practical engineering and to some extent, driving skills. The majority of the dynamic events are based on an autocross format in which rapid speed and direction changes are required.

Among the most critical keys to success in the FSAE competition include the ability to reduce vehicle weight while maintaining high torsional rigidity of the chassis. Overall vehicle weight reduction enhances the ability to rapidly change vehicle speed and direction while high chassis rigidity provides a reliable and predictable platform for high performance handling [2]. Traditionally, FSAE teams from the US Naval Academy (USNA) have used tubular steel space frames to make up the majority of the FSAE vehicle chassis. However the most successful entries employ some form of composite monocoque construction for the vehicle chassis/frame. In fact seven of the top ten vehicles at the 2012 Michigan FSAE competition had a composite monocoque frame [3].

The use of composite structures at the highest levels of international motorsports is not new. Rather, it is the product of nearly thirty years of constant evolution, beginning with the brilliant McLaren MP4/1 that first raced in the 1981 Formula One Championship. Today, Formula cars are made up of approximately 80% composites by volume [4], especially in the most critically stressed components of the vehicle structure such as chassis, suspension arms, brake disks, aerodynamic devices, crash structures, and gearbox housings. Indeed, carbon/epoxy composites possess the superior combination of high specific strength, almost limitless formability, and specific stiffness required to handle the extreme stresses resulting from accelerations on the order of four times the force of gravity while conforming to a contorted aerodynamic shape and maintaining precise geometric alignment at all times.

Even though composites have become ubiquitous in high-performance race car structures, most companies and teams keep their construction techniques proprietary. Most available information concerning the design, construction, and repair of composite structures is published by the aerospace industry, which deals with substantially different geometries as well as loading and safety requirements.

Over the past few years, the USNA FSAE team composite design efforts have ranged from simple fiberglass non-structural fairings to detailed studies on carbon fiber suspension components [5]. As a logical progression, the USNA FSAE team elected to go forward with a composite monocoque frame for the 2011 and subsequent competitions. This paper serves to document the design and fabrication of the monocoque frame. In the interest of brevity, most of the validation tests and results have been omitted in this paper but are well documented for the interested reader to investigate [6, 7]. It is the authors' hope that other teams with limited composites design and manufacturing experience can enjoy the vehicle performance benefits made possible with a carbon fiber reinforced plastic (CFRP) monocoque frame.

DESIGN PROCEDURES

This section outlines the design procedures followed in the construction of the composite monocoque frame. First, the overall monocoque type and dimensions were determined. The design process continued with understanding the applicable equivalency requirements needed to safely replace a traditional steel space frame with a CFRP monocoque frame. Next composite materials and layup techniques were selected based on advertised material properties and preliminary analysis tools. Once design choices were validated using various component level tests, the monocoque was completed.

Monocoque Type

For this class of vehicles, there are various ways to incorporate composite materials into the design. The simplest method is to replace some of the steel members of a traditional space frame with composite shear panels on the sides, top and bottom of the vehicle. These panels provide a modest weight reduction while adding some torsional rigidity to the frame. The other extreme is to replace nearly all of the steel tubing with a full monocoque frame. The competition rules still require a steel roll hoop for driver protection so it is not possible to replace all of the steel tubing. However, this approaches would likely result in the greatest weight reduction and also the greatest increase in rigidity. Unfortunately this method is also the most complex and requires extensive tooling. A more moderate approach is to mate a steel rear space frame module to a carbon monocoque forebody. This hybrid approach should result in significant weight savings and an increase in torsional rigidity over the steel space frame. Figure 1 shows the relative benefits associated with these various approaches. The Naval Academy team elected to use the hybrid frame approach.

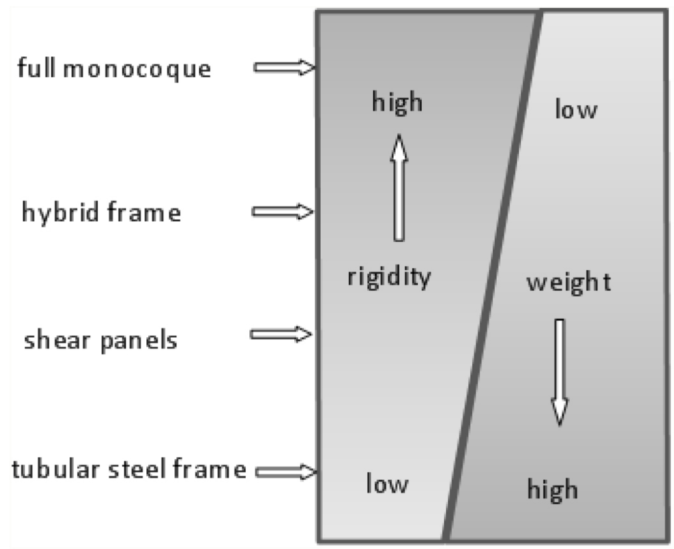


Figure 1. Frame types and relative advantages

Equivalency Requirements

The FSAE competition rules provide detailed requirements for teams who elect to deviate from the traditional steel space frame construction [1]. These safety-based requirements are meant to ensure that the composite monocoque frames are equivalent to or stronger than the SAE/AISI 1010 steel frames they are to replace in terms of energy dissipation and yield and ultimate strengths in bending, buckling and tension. Figure 2 shows areas on a typical monocoque frame that are specifically covered by the equivalency rules. Table A1 provides a summary of these rules.

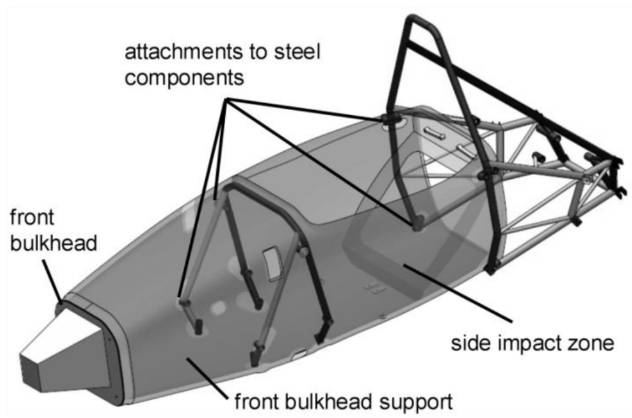


Figure 2. Monocoque with rear space frame and front impact attenuator attached.

Laminate Selection and Testing

A honeycomb sandwich structure was selected for the monocoque construction and the design team relied on donated materials. These materials included bi-directional woven carbon/epoxy fabric and unidirectional carbon/epoxy Cytec CYCOM 5215 Prepreg and Hexcel 5056 Aluminum honeycomb overexpanded core [8], [9]. This core material provided superior strength to weight ratio which was especially important for impact protection [10], [11]. Additionally, FM-300-2 film adhesive and Cytec FM-410-1 adhesive foam were used in the construction [12].

Literature from the Hexcel Corporation listed the properties of the core material, described common failure modes of sandwich structures, showed how to analyze panels under a variety of loading conditions and offered practical suggestions for sandwich panel construction [13]. Sandwich panels were conceived, constructed and tested in order to meet competition rules requirements outlined in Table A1 [14]. More details on the analytical methods used for predicting panel strength and stiffness can be found in a previous paper [6].

Two different sandwich configurations were ultimately chosen based on the testing summarized below. The final configurations were [$F/0_3/F$/core/$F/0_3/F$] for the front bulkhead support region and [$F/0_7/F$/core/$F/0_3/F$] for the side impact zones. In these layup descriptions, the 'F' refers to the bi-directional fabric and the '0' refers to the unidirectional tape and the subscript numeral refers to the number of layers. The fabric layer preceding the core was a fabrication requirement that will be presented later. The core was 15.8 mm thick aluminum honeycomb with film adhesive on both sides.

Flexure Testing

To test the stiffness and strength requirements, two 0.2 m × 0.5 m flat test panels, [$F/0_3/F$/core/$F/0_3/F$] and [$F/0_7/F$/core/$F/0_3/F$], were constructed for a three point bend test as shown in Figure 3. Table 1 provides a summary of the test data. Both configurations were determined to be stiffer than a single steel tube, and stronger than two tubes as required by the equivalency rules. The primary failure mode was buckling of the upper skin due to compression.

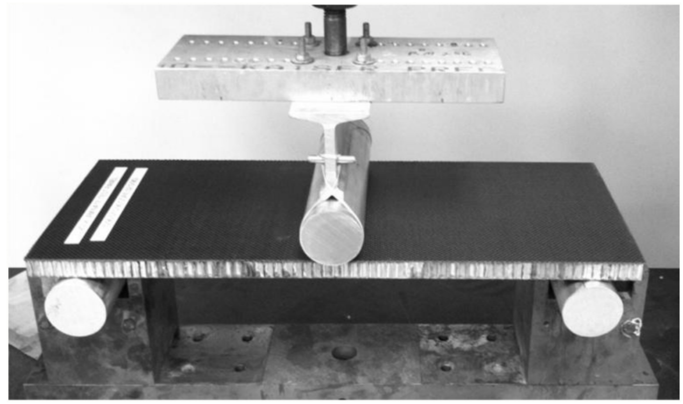


Figure 3. Three point bend test of 0.2m × 0.5m flat sandwich panel

Table 1. Three point bend test results

Specimen	Ultimate Flexural Load (N)	Stiffness (N/m)	*EI* (N-m^2)[1]
25.4 x 1.65 mm 1010 Steel Tube	3500	1.2e6	2000
[$F/0_3/F$/core/$F/0_3/F$] panel	7000	1.7e6	2800
[$F/0_7/F$/core/$0_3/F$] panel	10300	2.0e6	3400

[1]Determined experimentally from $EI = \dfrac{PL^3}{48\delta}$

Perimeter Shear Testing

Next, the two sandwich configurations were evaluated for perimeter shear strength using a 25.4 mm diameter section. To accomplish this test, a 25.4 mm steel rod was pushed through the test samples as shown in Figure 4. As show in Figure 5, both configurations passed the equivalency requirements for side impact zone strength.

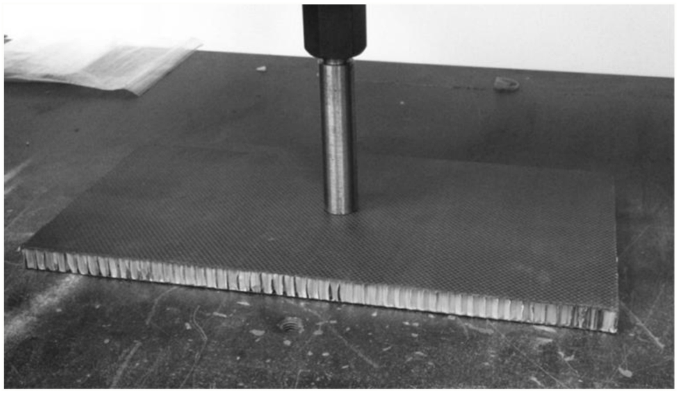


Figure 4. Perimeter shear test

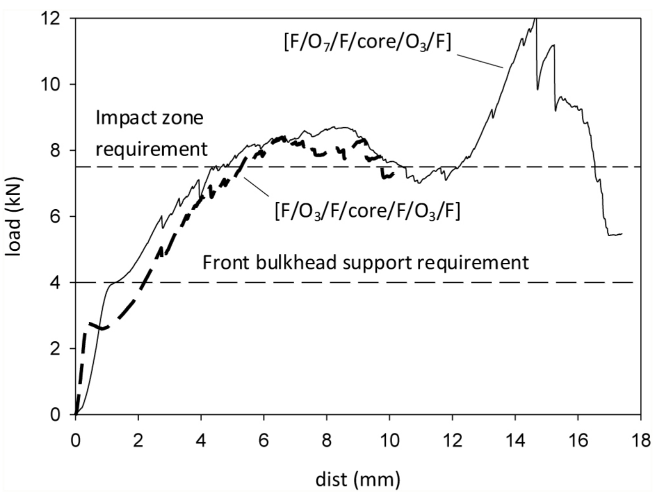


Figure 5. Perimeter shear test results

Monocoque Side Impact Validation

Finally, the [F/0_7/F/core/0_3/F] configuration was evaluated against the side impact zone stiffness requirements listed in Table A1. The vehicle cockpit sidewalls were designed to be 0.48 m tall and the side impact zone (by definition in the rules) corresponds to a 0.33 m tall section of the sidewall. Table 2 shows a comparison of *EI* for the sandwich panel and the baseline steel tubing. The first row of data comes directly from the three point bend test data. The final two rows of data are derived from the linear relationship between *EI* and number of tubes or panel width. From these data, it is clear that the [F/0_7/F/core/0_3/F] configuration meets the *EI* requirement for the 0.33 m impact zone and the total side panel design height of 0.48 m.

Based on the results of both the three point bend and perimeter shear testing, the final sandwich configuration chosen for side impact protection was [F/0_7/F/core/0_3/F].

Table 2. EI comparison for side impact

Rule application	25.4 x 1.65 mm 1010 Steel tube		[F/0_7/F/core/0_3/F] panel	
	# of tubes	*EI* (N-m^2)	Panel width (m)	*EI* (N-m^2)
Test panel	1	2000	0.20	3400
Impact zone	1.5	3000	0.33	5600
Total side height	3	6000	0.48	8200

Front Bulkhead and Front Bulkhead Support

Details of the design, fabrication and testing of the anti-intrusion bulkhead and supporting structure were presented in a previous paper on collision systems for this vehicle [7]. The final bulkhead design consisted of a 4 mm aluminum anti-intrusion plate mounted to a "picture frame" consisting of [F/0_{18}/F/core/F/O_{18}/F] members that were 25 mm wide. Figure 6 shows the bulkhead frame during the construction phase. Note that the frame members are thin to permit maximum access to the front of the vehicle for servicing vehicles components such as the brake and throttle pedal assembly. Figure 7 shows flexure test data for the front bulkhead members. The test panel had an ultimate load of 10.5 kN and an *EI* of 3600 N-m^2 far exceeding the baseline tubing values. Despite the obvious overdesign, no further redesign and retest were attempted due to time constraints.

With the bulkhead member design complete, the next step was to qualify the mounting points for the impact attenuator attached to the front of the vehicle. By the rules, each 8 mm Grade 8.8 bolt had to fail before the attachment to the bulkhead itself failed. This equated to an out-of-plane tensile force of 23.0 kN. To meet this requirement, 38 mm diameter aluminum disks were embedded in place of the core material at each of the bulkhead corners. Each disk was drilled, tapped and fitted with a helicoil to receive the impact attenuator bolts and bonded to both the upper and lower skins as shown in Figure 6. Use of the aluminum disks enabled both the upper and lower skins to support the tensile load imposed on the attachment bolts. During testing the bolt actually suffered a tensile failure at 30kN before the aluminum disks tore out of the sandwich structure.

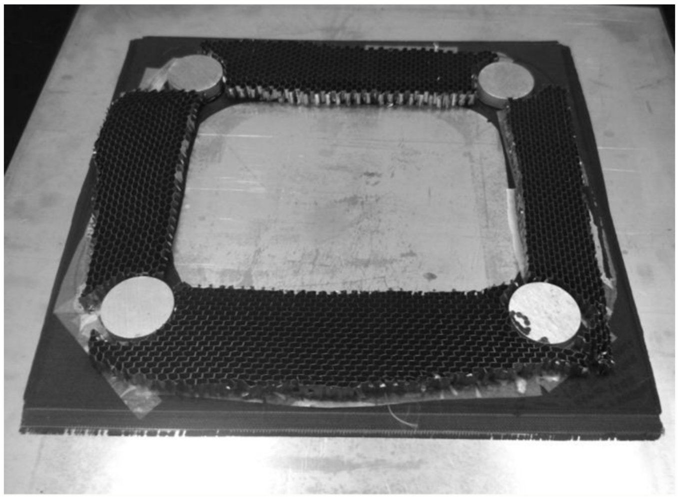


Figure 6. Front bulkhead under construction with aluminum inserts for bolts

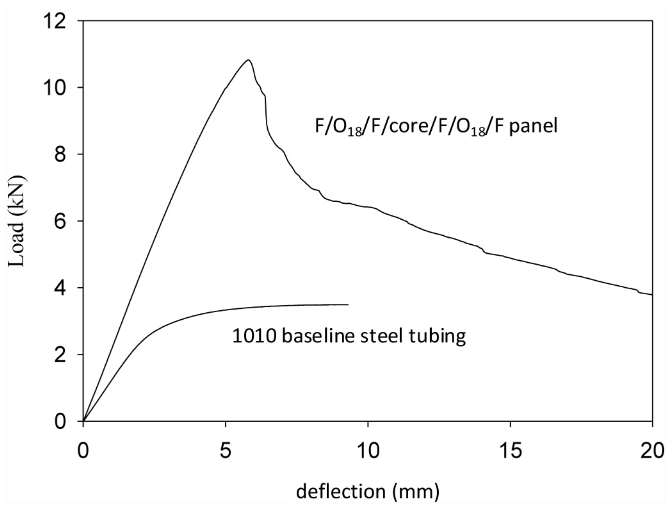


Figure 7. Bulkhead flexure test data

Table 3. Bulkhead support EI comparison

Rule application	25.4 x 1.65 mm 1010 Steel tube		$[F/0_3/F/core/F/0_3/F]$ panel	
	# of tubes	*EI* ($N\text{-}m^2$)	Panel width (m)	*EI* ($N\text{-}m^2$)
Vertical side	1	2000	0.33	4600
Total monocoque	6	12000	1.20	16800

Next the $[F/O_3/F/core/F/O_3/F]$ honeycomb sandwich configuration was evaluated for suitability for the front bulkhead support region. Using data from the previous flexural testing shown in Table 1, EI values for the front bulkhead region were calculated based on a linear relationship. Table 3 shows a comparison of calculated *EI* values that satisfy equivalency requirements.

Monocoque Attachments to Steel Components

As specified by Formula SAE rules, the main hoop and rear frame structure must be mechanically attached to the monocoque with two 8 mm Metric Grade 8.8 bolts bolts at 4 points, for a total of 8 bolts. Also each point must withstand a 30 kN load in any direction. In order to determine the worst-case loading for the roll hoop attachments, two load cases were considered: out-of-plane perimeter shear loading and in-plane pin shear loading. These tests and their results are described in detail in a previous work [6].

For added strength, inner backing plates of metal were bonded to the monocoque. The backing plates were made of 3 mm thick steel plate with a bonding area of 14.8 cm^2. This added approximately 15 kN of additional in-plane load capacity (West System 105 resin thickened with colloidal silica has been tested to have a shear strength of approximately 10 MPa [15]), and provided some degree of “graceful degradation” in place of a rapid, catastrophic failure.

In order to comply with the rules, each attachment point between the main roll hoop and the monocoque consisted of a 28-ply monolithic, quasi-isotropic laminate of woven carbon/ epoxy fabric supported on the inner side by a bonded, 3 mm thick steel backing plate. At each attachment point, this resulted in out-of-plane strength and in-plane strength in excess of the 30 kN requirement.

Safety Harness Mounting Points

The proposed safety harness design included lap belts attached to eye bolts mounted to the monocoque frame that were required to meet equivalency requirements of 13.0 kN for the lap restraints and 6.5 kN for the anti-submarine belts. As detailed in the collision systems paper [7], the first attempt involved screwing the eye bolts into steel inserts embedded in a representative honeycomb sandwich $[F/O_3/F/Core/F/O_7/F]$ as shown in Figure 8. However this configuration did not meet the 13.0 kN requirement. Therefore, a “through bolt” configuration was tested. For this test, a 3 mm thick circular backing plate 38 mm in diameter was placed on the outside skin of the honeycomb structure. The harness mount eye bolts passed through the entire structure and the backing plate and was held in place by a nut as shown in Figure 9.

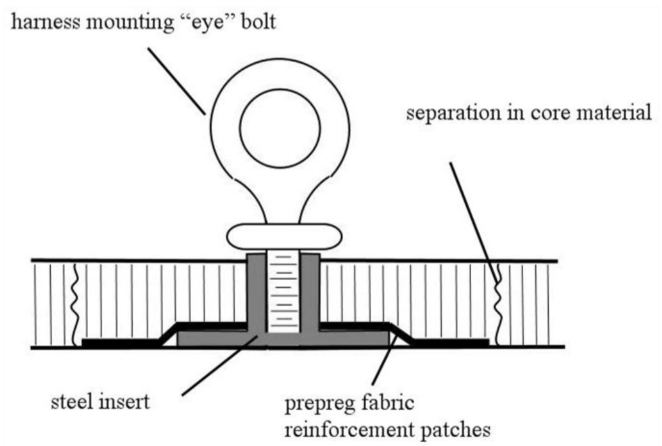


Figure 8. Schematic of harness mount concept

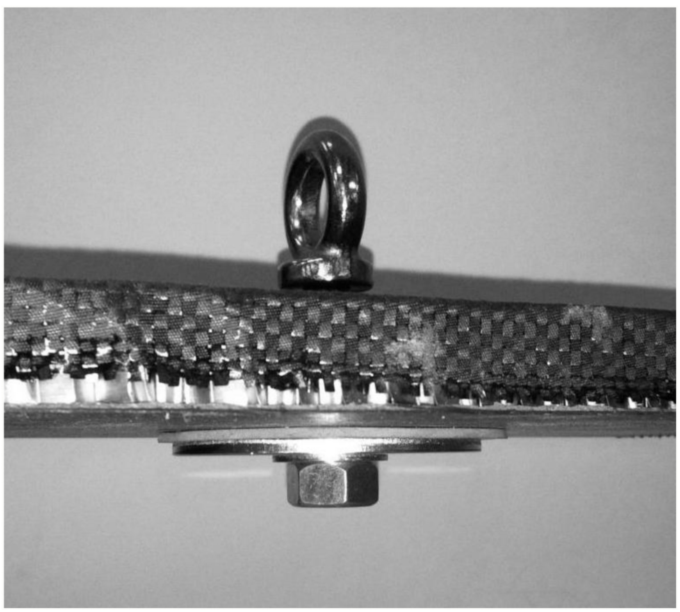


Figure 9. Through-bolt configuration for harness mount

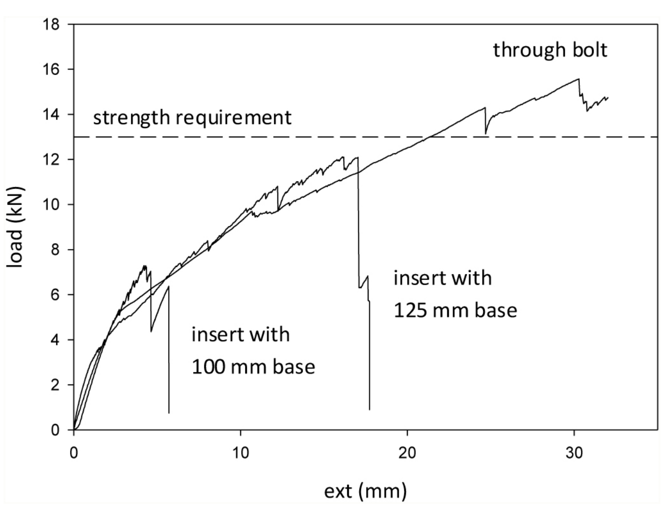


Figure 10. Harness mount tensile results

The through bolt method proved capable of meeting the test requirement and experienced a gradual and predictable failure mode. The back plate slowly deformed as the eye bolt pulled it and the surrounding skin into the core material. The outer skin [F/O_7/F] never sheared before the test was terminated. The only failure was crushing of the core material. Based on these results, the through bolt technique was chosen for the lap belts and the steel inserts were used for the anti-submarine belts.

CONSTRUCTION TECHNIQUES

Mold Construction

A female fiberglass mold was fabricated for the monocoque cockpit layup. First a high density (288 kg/m^3) foam male plug was milled using a Solidworks™ drawing of the cockpit similar to the one shown in Figure 2. Then the milled plug was coated with Duratec™ and wet sanded to a smooth finish. Next a wooden divider panel was made to match the upper and lower centerline of the plug. Using this divider to create a flange area, two female fiberglass mold halves were laid up and cured. Figure 11 shows a photo of the finished plug with the wooden divider and end pieces attached. The final mold was gelcoated and had a wide flange with several holes for easy assembly and disassembly.

Figure 11. Finished plug with wooden dividers ready for mold fabrication

Prepreg Layup

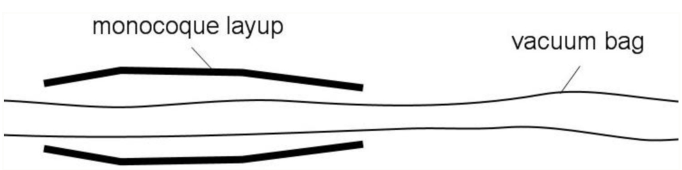
The following paragraphs detail the construction process used for the 2012 frame. These procedures include lessons learned from the 2011 car.

The layup process was completed in three separate steps; outer skin layup, core insertion and finally inner skin layup. Each of these three steps are described in the following paragraphs.

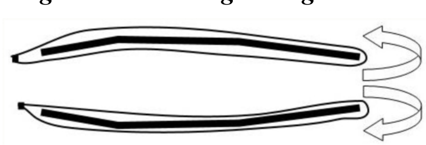
To begin the layup process the mold halves were bolted together and treated with the release agent Frekote™. An external wooden support frame was bolted to the mold to prevent warping and provide stability during the layup. Four large paper patterns were cut to represent the floor, sides, side impact region and top of the cockpit. These patterns were used to aid in cutting the carbon fiber prepreg material required for the outer skin.

First one fabric layer and three unidirectional layers were laid into the mold. All pieces were hand laid into the mold taking special care to work out air bubbles and prevent "bridging" across all features. In the side impact region, four additional unidirectional layers were applied. Lastly a fabric layer was used to cover all of the unidirectional tape, thus providing biaxial stiffness on both sides of the composite skin. The majority of the outer skin consisted of [F/O_3/F] and the side impact regions were [F/O_7/F]. Finally ten fabric "patches" were applied to reinforce the monocoque attachment points as required by the test results.

The importance of the final fabric stiffening layer cannot be overstated. In an earlier layup this fabric layer was omitted [F/O_3] and the results were catastrophic. Upon removal of the outer skin from the mold for inspection, the skin buckled and cracked along the direction of the unidirectional fibers in several areas. This damage occurred even with the most careful handling and rendered the outer skin unusable. In the next attempt, the final fabric layer was used and this prevented skin buckling. It is recognized that the need this fabric layer could be avoided if the outer skin and core were laid up together. However, for novice fabricators, it is critical to inspect the layup between each process. Additionally, the extra fabric layer enhances the torsional rigidity of the finished monocoque.



(a). passing the vacuum bag through the monocoque



(b). sealing the vacuum bag back on itself

Figure 12. Cross-section schematic illustrating double bagging technique. For clarity, only the monocoque and vacuum bag are pictured.

Figure 13 shows a picture of the sealed layup going into the autoclave. The curing process included an 8 hour debulking period at 28 inHg and room temperature to remove voids from the layup followed by a 2 hour cure at 127°C [9]. Note that the autoclave was only used for heat and vacuum as the part was not cured under applied pressure.

Figure 13. Vacuum bagged layup going into the autoclave

The next step involved laying in the core material. The paper templates were used to rough cut the film adhesive and core and these pieces were laid into the cured outer skin. The film adhesive was cut away from the reinforced monocoque attachment points to enable easy removal and trimming of the core material. This was necessary as these points will become the 28-layer monolithic regions as required by the previous testing. Foaming adhesive was used to join the core sections and the layup was double vacuum bagged. This time the vacuum was set to 15 inHg to avoid crushing the core material. Cure time was 2 hours at 127°C. Upon removal from the autoclave, the core was trimmed in preparation for the inner skin layup.

Prior to laying in the inner skin, aluminum "hard points" with helicoil inserts were pounded into the core for attaching critical components such as the brake pedal mount, shock mounts and steering column mounts. This was a required improvement over the 2011 design in which these critical components were only bonded to the finished monocoque rather than being bolted in place. One of the required safety checks at the competition includes braking hard enough to lock all four wheels from a moderate speed. During this test, the brake pedal mount broke away from the monocoque floor due to a failure of the secondary bond (in the 2011 car). While the car safely came to a stop, extensive redesign was required to mechanically attach a new brake pedal mount to the floor. This precluded the team from competing in three of the four driving events. In 2012 all attachment points were bonded and bolted for added strength and ease of repair.

The inner skin layup was the last step in the monocoque fabrication process. Reinforcement patches were placed over roll hoop and suspension attachment points to complete the monolithic structure. Then the core was covered by a layer of film adhesive, bi-directional fabric, three layers of unidirectional tape and a final layer of bi-directional fabric.

After working out any major air bubbles, the whole structure was vacuum bagged for the final time. Another debulking period was required but in order to prevent collapsing the core, a reduced 15 inHg vacuum was applied for 16 hours before a 2 hour cure at 127°C [9]. After the cure, the monocoque was removed from the mold, trimmed and finished with clearcoat.

TEST RESULTS

The 2012 monocoque structure was tested to evaluate weight savings and torsional rigidity around the longitudinal axis of the vehicle. High torsional frame rigidity is desirable because it permits a wide range of individual axle suspension stiffness values which lead to fine tuning of handling characteristics. [16]

First torsional rigidity was measured and compared against a previous (2010) Formula SAE vehicle which had a traditional steel space frame construction. To accomplish this test, both vehicles were fixed by the front suspension mounting points to a welding table. Then an aluminum pole was attached to the rear frame in the vicinity of the rear suspension mounting points. Using weights, a known torque was applied to the vehicles while angular deflection was measured using a digital inclinometer. Test results showed that the monocoque vehicle torsional rigidity was 2000 N-m/° while the 2010 vehicle's value was 1400 N-m/°. Thus the overall improvement was 43%. This test was considered operationally representative since it is the torsional rigidity between the suspension mounting points that is so critical in vehicle handing.

To measure the weight savings, the 2010 Formula SAE vehicle was disassembled. All components that were replaced by the monocoque forebody were placed on a large industrial scale. These parts included the body panels and steel space frame components located forward of the roll hoop. The total mass of these parts was 30 kg. In contrast, the monocoque forebody (including the required steel front hoop shown in Figure 2) weighed only 14 kg, a savings of 53%.

Additionally, drivers who had driven both the steel and monocoque cars clearly preferred the handling qualities of the monocoque car. This was largely due to the increased stiffness, lighter weight and subsequent “surefooted” handling.

SUMMARY/CONCLUSIONS

In summary, the objectives of this study were successfully met. The student design team designed a carbon fiber reinforced plastic monocoque frame to replace the traditional steel space frame for a small open wheeled racecar. Candidate sandwich structures and attachment methods were tested against requirements set forth by the Formula SAE competition rules. In all cases, strength and stiffness requirements were met or exceeded and a viable monocoque frame was constructed by undergraduate students using simple construction techniques. Fabrication lessons learned included the need to use a fabric layer on both sides of the unidirectional tape to prevent buckling of the standalone outer skin. Also, vacuum bagging such a large part is difficult but can be effectively done using a double bagging technique. Critical components must be mechanically fastened to the monocoque rather than simply bonded in place. Ultimately, the monocoque frame for the 2012 vehicle was 53% lighter than the steel frame components it replaced and the complete vehicle torsional rigidity was increased by 43% to 2000 N-m/°.

REFERENCES

1. Formula SAE competition rules available at: http://students.sae.org/competitions/formulaseries/rules//, 2012.

2. Adams, H., “Chassis Engineering”, Penguin Putnam, New York, 1992.

3. Formula SAE competition results available at: http://students.sae.org/competitions/formulaseries/results/, 2012.

4. Sloan, J., “Formula 1 team accelerates design to track speed”, High-Performance Composites, http://www.compositesworld.com/articles/formula-1-team-accelerates-design-to-track-speed, 1 May 2008.

5. McDonald, M., Joyce, P., and Hamilton, L., “Designing Composite Suspension Arms for a Formula SAE Vehicle,” SAE Technical Paper 2011-01-1262, 2011, doi: 10.4271/2011-01-1262.

6. Forero, C., McDonald, M.C., Joyce, P.J. and Hamilton, L.J., “Production of a Composite Monocoque Frame for Motorsports Application (Design and Testing), presentation at SAMPE 2012, Baltimore, MD, 2012.

7. Hamilton, L.J., Joyce, P.J., Dodds, L., Hugh, A., “Production of a Collision Protection System for a Composite Monocoque Racecar Frame, presentation at SAMPE Tech, Charleston, SC, 2012.

8. Datasheet for Hexcel 5056 Aluminum Honeycomb OX-core can be found at: www.hexcel.com/Resources/DataSheets/Honeycomb-Data-Sheets/CR3_us.pdf

9. Datasheet for Cytec CYCOM 5215 prepreg can be found at: www.cytec.com/engineered-materials/products/Datasheets/CYCOM%205215.pdf

10. Bitzer, T., “Honeycomb Technology”, Chapman & Hall, London, 1997.

11. Black, S., “Improved core materials lighten helicopter airframes”, High-Performance Composites, pp. 56-60, May 2003.

12. Datasheet for Cytec FM-300-2 film adhesive can be found at: www.cytec.com/engineered-materials/products/Datasheets/FM 300-2.pdf

13. Hexcel Corporation. "HexWeb Honeycomb Sandwich Design Technology." Duxford, Hexcel Composites, 2000. http://www.hexcel.com/NR/rdonlyres/80127A98-7DF2-4D06-A7B3-7EFF685966D2/0/7586_HexWeb_Sand_Design.pdf

14. Daniel, Isaac M. and Ishai Ori, "Engineering Mechanics of Composite Materials", Oxford University Press, New York, pp. 378-383, 2005.

15. Coker, J., "Epoxy Tests and Comparison", http://www.jcrocket.com/adhesives.shtml, accessed 5 May 2010

16. Bastow, D., Howard, G. and Whitehead, J.P., "Car Suspension and Handling, 4th ed., SAE International, Warrendale, PA, p. 63, 1993.

Contact Information

Leonard J. Hamilton
ljhamilt@usna.edu

APPENDIX

APPENDIX A

Table A1. Monocoque Equivalency Rules

Test	Requirement
Laminate testing (0.2 x 0.5 m flat specimen in three point bend test)	Bending: equivalent to one steel tube[1] Ultimate strength: equivalent to two steel tubes[1]
Side impact (0.33 m tall impact zone)	Impact zone EI = 50% of EI for three steel tubes[1] Total side $EI = EI$ for three steel tubes[1] Perimeter shear test[2] = 7.5kN
Front bulkhead	Perimeter shear test[2] equivalent to 1.5 mm thick steel plate Monocoque $EI = EI$ for two steel tubes[2] about lateral and vertical axis
Front bulkhead support	Perimeter shear test[2] = 4.0 kN Total monocoque $EI = EI$ for six steel tubes[1] Vertical side $EI = EI$ for 1 tube[1]
Monocoque attachments (to steel components)	30 kN in any direction
Safety harness mounting points	Shoulder and lap belts: 13 kN in any direction Anti-submarine belts: 6.5 kN in any direction
Impact attenuator mounts	Equivalent to four 8 mm Grade 8.8 bolts

[1]Baseline steel tubes replaced by monocoque are 25.4 mm outer diameter and 1.65 mm wall thickness and have a minimum yield and ultimate strength of 305 MPa and 365 MPa respectively. Minimum Young's modulus = 200 GPa.

[2]Force required to push a 25.4 mm diameter steel rod through a flat plate of equal design

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper.

SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
Printed in USA