Robust Vehicle Development for Student Competitions using Fiber-Reinforced Composites

Nikhil Sethi, Prabhash Chauhan, Shashwat Bansal, and Ranganath M. Singari

Abstract This paper presents a study of composite materials used in aerospace and automotive student competitions. The rationale for our research mainly arises from the increasing use of composite material technology in graduate-level student competitions. Moreover, the operational and financial constraints for research and development in student competitions are often more stringent than in the actual industry, and rigorous tradeoffs are conducted before choosing the appropriate material for the vehicles. Vehicles for three primary student competition teams corresponding to each of the authors are developed and compared to find common ground among use cases of composite material technology. The competitions included are namely Seafarer AUVSI SUAS, Shell-Eco Marathon, and Formula Student. An in-depth analysis of the material use-cases, properties, and the vehicle fabrication process is followed. The research is concluded by giving critical observations on points like optimization and sustainability.

Keywords Composites · UAV · Formula student · AUVSI SUAS · Supermileage vehicle

1 Introduction

Material science is an ever-evolving field of research with no boundaries. One of the recent entrants in its scope is fiber-reinforced composite materials. Fiber-reinforced composites, specifically carbon fiber-reinforced plastics (CFRP), are substituting conventional materials in the industry because they offer massively better strength-to-weight ratio. A study of various types of CFRP composites shows how versatile these materials are. Various arrangements of fiber planes can give the user access

N. Sethi (✉) · P. Chauhan · S. Bansal · R. M. Singari
Delhi Technological University, New Delhi, Delhi 110042, India
e-mail: sethi.nirvil@gmail.com

R. M. Singari
e-mail: ranganathdce@gmail.com

R. M. Singari et al. (eds.), *Advances in Manufacturing and Industrial Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-8542-5_6

to a vast amount of applications ranging from the development of commercial super mileage vehicles to well-balanced, high-performing aerospace, and motorsport vehicles. Such prototyping and testing the material for its applicability before its production are a widely acknowledged industry practice. Research at various levels, from core researchers, industry practitioners to college graduates is important for innovation to succeed.

The present study exploits the varied experiences of multiple authors to present a review on fiber-reinforced composites, their properties, and their applications. In particular, the applications of composite materials in the automotive (Eco-Marathon), racing (FSAE), and aerospace (AUVSI SUAS)-related student competitions are covered in the current work. The cycle of development is also given a closed loop by highlighting the various methods of composite disposal and assessing the effects of the same on the environment.

2 Literature Review

In this section, an analysis of previous work conducted by other teams in similar student competitions is carried out. The competitions are taken part by teams from all over the world. As a consequence, the different student teams are often offset in their goals and developmental strategies owing to the variable amount of funding, developmental team size, technical support, research capacity, etc. These factors (in reference to the motive of this paper) affect the composite type, the production process, and the overall finished quality of the vehicle.

For instance, in [1], the authors use a combination of carbon fiber and Kevlar while employing a vacuum infusion process to develop the vehicle fairing. The mold was made through hot wiring foam. New research in fabrication methods also gives rise to advanced lighter frames, especially important for UAVs such as the case in [2], in which the authors use a hollow carbon fiber fabrication method. Some teams with well-established research facilities and significant funding also make use of autoclaves and pre-preg carbon fiber to develop their vehicles [3]. A particularly interesting use case of laminated bamboo fiber composite is used in a supermileage car in [4]. While not being the strongest of all materials, the paper presents a critical analysis of strength and composition.

Only the vehicle body is not limited to composite materials. In [5], exhaustive use of fiber composites for wheel rims and other small parts is documented for the motorsports vehicles. In [6], a chassis designed using composite materials is supported by rigorous structural analysis for multiple deflection cases. In [7], the authors have made an attempt to document the production of the control systems in an FSAE vehicle which includes its pedal box. Considering the degree of risk the regime of motorsports possess, authors in [8] have made an attempt to understand the applicability of composite fibers in the toughest form of racing, F1.

3 Materials

Prior to underlining the types of materials used and their properties, it is necessary to develop a rigorous classification of the various engineering materials and see where composites lie in the hierarchy (Fig. 1, using Refs. [9, 10]).

3.1 *Glass Fiber-Reinforced Polymer*

It is similar to CFRP with the exception of thin glass strands being used as the fibers. It has been used heavily as a reinforcement fiber. It consists of silica, alumina, calcium oxide, and boron oxide in varied proportions to get specific properties. It is a particularly lost-cost fiber and has vast applications in numerous fields, i.e., civil construction, automotive, marine, sporting goods, etc. [11]. Glass fiber is mainly used as reinforcement as it increases tensile strength, impact resistance, heat and chemical resistance, and dimensional stability. The use of glass fiber has the disadvantages of high viscosity of the melt, low surface quality, and damages to the tool and structure due to abrasion. It is readily available in the industry as continuous fiber rovings, chopped strands, and staple fiber [11]. It has a lower strength-to-weight ratio than carbon fiber but is much cheaper in comparison.

3.2 *Fiber-Metal Laminates (FML)*

FMLs are a class of metallic materials which are made by sandwiching layers of composite fiber strands among several thin metal layers with epoxy as the matrix.

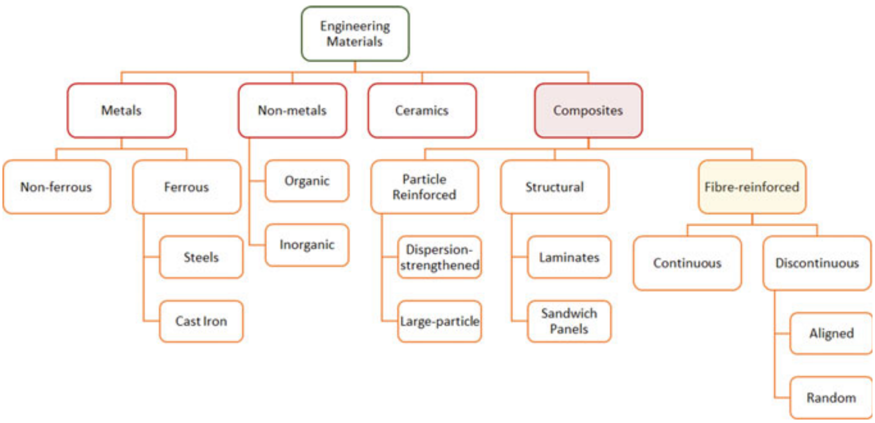


Fig. 1 Classification of materials

Some common FMLs are:

- Aramid-reinforced aluminum laminate (ARALL), based on aramid fibers
- Glass-reinforced aluminum laminate (GLARE), based on high-strength glass fibers
- CentrAl, which surrounds a GLARE core with thicker layers of aluminum
- Carbon-reinforced aluminum laminate (CARALL), based on carbon fibers.

3.3 Metal Matrix Composites

MMCs are relatively new composite materials which are made by dispersing a reinforcing material into a matrix of another metal. This material can be either metal or nonmetal. Compared to other reinforced metals, these composites have a high specific strength, greater stiffness, good wear resistance, and high operating temperatures. Their properties can also be tailored for individual applications.

3.4 Ceramic Matrix Composites (CMC)

It is a new type of material that has ceramic fibers embedded in a ceramic matrix. These are also known as CFRCs. The use of ceramics as reinforcement enhances the fracture toughness of the whole system while still exhibiting high strength and Young's modulus that is characteristic of the ceramic matrix.

3.5 Aramid Fiber

Aramid fiber is made of aromatic polyamides. They characteristically consist of large phenyl rings that are linked together by amide groups. The fibers are straight and rigid, having a high melting point and exhibit insolubility [12]. Aramid fibers are spun to make high-performance fibers like Kevlar and Nomex.

3.6 Kevlar

These are aramid fibers which have benzene as the rings in long molecular chains. The fibers have an excellent strength-to-weight ratio, high thermal stability, and high cutting resistance. The fibers have poor resistance to abrasion. Kevlar has been heavily used in knife proof armor and bulletproof vests for the past 25 years [13].

3.7 Nomex

Nomex is a high-performance aramid fiber and is also known as meta-aramid. Nomex is very low flammability and is self-extinguishing in nature. The fabric acts as a barrier to heat and fire and feels like normal textiles and is comfortable in use [14]. It is heavily used in making heat resistant garments and fabrics.

3.8 Carbon Fiber-Reinforced Polymer

It is a strong and light fiber-reinforced plastic containing strands of carbon fibers. CFRPs are expensive to produce but are commonly used in places where high strength-to-weight ratio and stiffness are essential, such as aerospace, superstructures of ships, automotive, civil engineering, sports equipment, and an increasing number of consumer and technical applications. Pure carbon fiber is characteristic of containing at least 92% carbon in it [15]. Carbon fiber is manufactured by the controlled pyrolysis process.

PAN carbon fiber—Polyacrylonitrile CF contains 68% carbon. It is polymerized by inhibitors like azo compounds or peroxides. Virgin textile PAN is not suitable for production as it takes a long time in stabilization and undergoes uncontrolled oxidation. Most of the commercially available carbon fiber used in the industry is provided by TORAY and HEXCEL groups.

Carbon Fiber Patterns
Unidirectional—This is the simplest pattern with only unidirectional fabrics. It is used when almost all the force is coming from a single axis.

1×1 Pattern—It is the easiest pattern looking like checkboxes also known as plain weave pattern which is the most standard pattern (Fig. 2).

2×2 Twill—This pattern is elastic and good for different shapes as the weave is loose. It is the most popular pattern and widely used in production (Fig. 3).

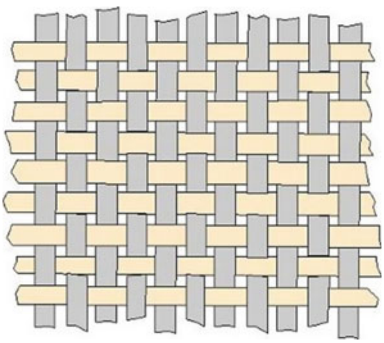


Fig. 2 1 × 1 Pattern

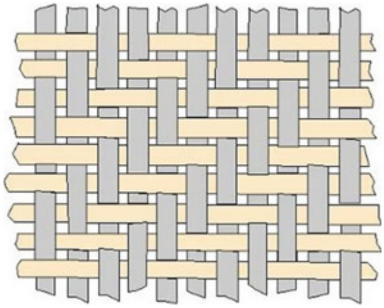


Fig. 3 2 × 2 Twill

Triaxial Pattern—Triaxially woven fibers have much better shear resistance, stain resistance, and bursting resistance. The resulting fabrics do not easily crimp and are structurally better than rectangular woven fabrics.

Carbon Fiber Grades

MSI (million pounds per square inch)—This grade is based on tensile modulus which is a measure of stiffness. 33MSI is the most commonly used carbon fiber. 42MSI fiber is known as intermediate modulus fiber. Fibers with MSI 55 or higher are known as high modulus fibers and are costly and dense [15].

nK Fibers—This denotes the bundle sizes that fiber is available in 1, 3, 6, 12, 24, and 50 K are the commonly available ranges. These bundles are woven into fabrics although this has little to do with the quality of fiber.

GSM (grams per square meter)—Often, carbon fiber is sold with pre-impregnation of epoxy. This is commonly known as pre-peg. Pre-pegs are unidirectional, which means they have to be spread out-the thickness of which is indicated by GSM number.

4 Case Studies: Student Competitions

4.1 Seafarer AUVSI SUAS

The Student Unmanned Aerial Systems (SUAS) competition organized by the association of unmanned vehicle systems international which is one of the largest international competitions for autonomous UAVs. The competition entails the development of an autonomous aerial system capable of performing a complex mission centered around a humanitarian/civil scenario. The airframe used for the UAS covers a major part of the system and must be optimized and tuned to specific mission requirements.

The performance/operational requirements that drive the design and process are highlighted in Table 1. To avoid digressing from the scope of the paper, only the fabrication and structural constraints that propel the choice of material are discussed (Fig. 4).

Table 1 Design requirement

Parameter	Objective	Threshold
GTOW	<21.5 kg	<27.5 kg
Load factor	≥2	>1.5
Turning radius	<30 m	<45 m
Wind tolerance	>10.28 m/s	>7.7 m/s

Fig. 4 Exploded CAD

Fig. 5 Removal from the mould

Owing to a short takeoff distance, high payload-to-empty weight ratio, a small turning radius, and consequently a high wing loading [16], the airframe needs to be strong enough to sustain the loads while being light enough to meet the operational requirements.

After the development of the CAD and rigorous structural analysis on ABAQUS, a fuselage featuring a monocoque shell was proposed. For initial testing, sandwiched laminates of carbon fiber, glass fiber, and balsa sheet were made, and their strengths were experimentally determined which would be further used for wing and tail skins. The results favored 200 GSM glass fiber and balsa sheets with a 45° orientation owing to the much greater load transfer capability and shear strength. The calculations for the wing spar gave the load and bending moment as the output for the selection of the length and cross section. The wing spar was built using 400 GSM unidirectional

Fig. 6 Render of the UAS

CF and balsa wood. It was further tested for structural strength with a maximum cantilever loading of 76 kg (factor of safety = 2). All the molds were manufactured using CNC cut medium density fiber boards.

For a similar competition, with a target to develop VTOL tricopter hybrid UAS, the design of the UAS is accomplished with a similar procedure as done previously in [17] by the author (Fig. 6). Glass fiber and extruded polystyrene (XPS) composite were chosen for the material of the prototype. This was partly because of a critical lack of funding and resources which is a common issue faced by many student teams.

Manufacturing Process

The fabrication of the complex blended wing body geometry was accomplished by hot wiring a block of foam along the three projected sketches on the orthographic planes (to avoid a lot of finishing) and finish it by sanding the extra corners with high grit emery paper. A similar procedure was followed for the wing. The process used for composite manufacturing is the hand epoxy layup and vacuum bagging process. The quantity of epoxy follows a general rule of 1.6 times the composite weight. This value was obtained from previous experience on similar materials.

A ratio of 1:9 for hardener: resin is used in our particular case. The different layers including the separator and breather for a uniform flow of air are placed. This was followed by adding two layers of 100 GSM glass fiber at the top and a layer each of 100 and 200 GSM glass fiber at the bottom owing to the tensile forces at the bottom (for the wing) and belly landing capability for the fuselage. The composites were

Fig. 7 XPS foam bod

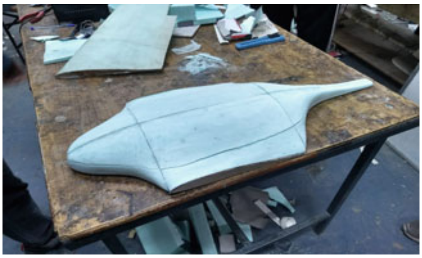


Fig. 8 Vacuum baggng

Fig. 9 Final RTF prototype

cut according to shape and an epoxy layup using hands, and spatula was carried out before placing it on the mold. The vacuum was maintained for 6 h at a pressure of 150 psi with approximately 1 h of curing time.

4.2 Supermileage Eco-marathon

Eco-Marathon organized by Shell is one of the biggest supermileage competitions in the world. The competition requires the development of high mileage vehicles with specific safety and mensuration parameters. Here, only the specifics of material use and fabrication process have been documented. The vehicle was designed considering the competition requirements, i.e., improved driver safety, minimized aerodynamic drag, reduced vehicle downforce, and reduced frontal surface area of the body.

The body was also designed to comply with the following requirements:

- Allow room for multiple drivers to fit in individually.
- Provide space for the working components to operate safely.
- Maintain minimum ground clearance and provide a smooth aerodynamic flow.
- Balance out the frame with the driver and all the components in it.
- Provide a horizontal parting line for easier manufacturing of the body in two parts.

Manufacturing Process

The body was manufactured by the team members using 4 × 4 twill carbon fiber. The construction began with two plugs that were created from chopped glass fiber. The plugs were then sanded and treated with a series of primer coats, paint coats, and finally clear coats to achieve a smooth finish. The smooth male mold was then coated in Gelcoat, a material used to achieve a high-quality surface finish on a composite material. After sanding, mold release agent was applied in the mold, and two layers of carbon fiber were laid inside. The layers of carbon fiber were impregnated with a mixture of epoxy and hardener taken in the ratio of 10:3 respectively by weight (optimum being 65:35 by weight, but this increases the stiffness a lot plus would lead to inaccuracy in measurement) (Fig. 11).

Then, layers of peel ply and breather were kept on top of the layers of laminate. The whole setup (the carbon fiber, epoxy, resin, breather, and peel ply) was connected to a vacuum pump via vacuum lines and a vacuum bag. The vacuum bag was sealed tight in place using butyl tape to the flanges that were provided to the plug. This process of vacuum bagging was done, so that the excess epoxy resin gets absorbed by the breather under atmospheric pressure and also gets a smoother finish on the outside. Reinforcements and flanges were laid into the carbon fiber body during the layup process, utilizing thin, flexible aluminum sheet sandwiched inside carbon fiber as the reinforcement material. The body was allowed to cure five days while letting the pump apply pressure for 5 h.

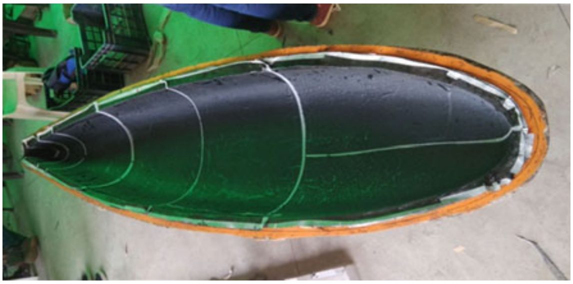


Fig. 10 Impregnated carbon fiber

Fig. 11 Prototype vehicle

4.3 Formula Student FS FSAE

Formula Society of Automobile Engineers (FSAE) is a community of engineering undergraduate and graduate students, monitored by renowned race car design engineers. Student-run teams participate in competitions on a yearly basis all across the globe, where they design and build race cars following a certain set of rules and regulations.

Aerodynamic devices are primarily used in motorsports vehicles to generate negative lift (downforce) and to minimize drag. This gives the vehicle a competitive advantage providing superior control and performance by increasing the traction levels and reducing resistance. Components designed must be lightweight, easy to manufacture, and easy to handle and service. Several theoretical design iterations were modeled to arrive at a successful design.

A **multi-element rear wing** is designed to maximize rear-end downforce enhancing the understeering capacity of the vehicle. This increases the traction levels at the driven wheels, and hence, the capacity to accelerate increases enormously (Figs. 12 and 13).

The **front wing** is designed to achieve satisfactory levels of front-end downforce so as to balance the downforce produced at the rear end. The front wing is also the

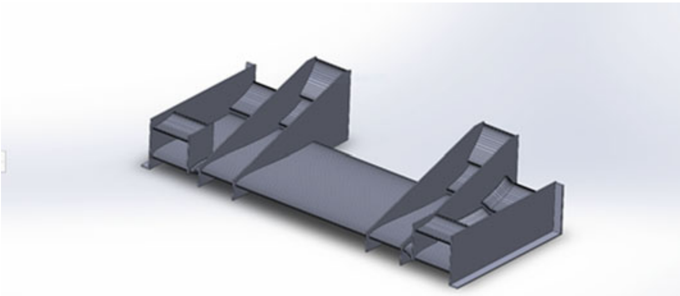
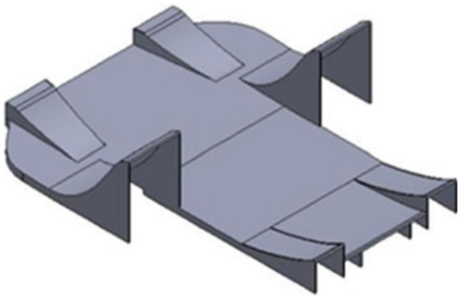


Fig. 12 Front wing

Fig. 13 Undertray



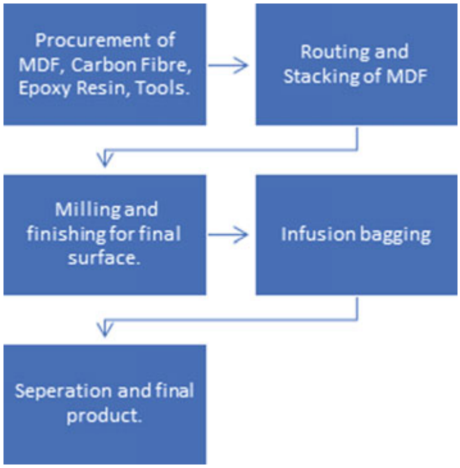


Fig. 14 Production flow Chart

onset of fluid flow in the vehicle, and hence, it also ensures that the other aerodynamic devices receive a clean flow of air.

The **undertray** is composed of three regions. The entry, middle, and the exit. Undertray achieves the goal of providing the maximum amounts of downforce levels with negligible drag penalties. It capitalizes the low pressure, the high-velocity region below the vehicle (Fig. 14).

Material Selection and Production

Aerodynamic devices are load-carrying units which undergo various kinds of loading during their operation. They cannot fail structurally and cannot be compliant. At the same time, they are supposed to be lightweight. The devices hence must have a strong core, a good surface to have better aerodynamic flow, and easy manufacturability. Fiber-based materials (essentially carbon fiber) are used to meet the required functionality. Carbon fiber provides the desired manufacturability and stiffness at the least weight. 3 k 2 × 2 twill carbon fiber weighing 200 GSM was chosen because of its good drapability, relatively low cost, high strength and stiffness, versatility, and low weight. The body panels of the car were made of a resin-infused single layer of carbon fiber. The endplates of the rear wing and front wing and mid plates of the front wing have been made using flat Rohacell 71 foam as a core between two layers of 2 × 2 200 GSM twill weave CF which improves bending stiffness and gives a pristine surface finish.

Layup of plane parts was done on sheets of glass, so that surfaces have a glass-like surface finish. For the curved contours, molds made of MDF were used. Resin infusion and wet layup vacuum bagging are used as a production process. The resin-to-fiber ratio was kept to 40:60 to achieve satisfactory results.

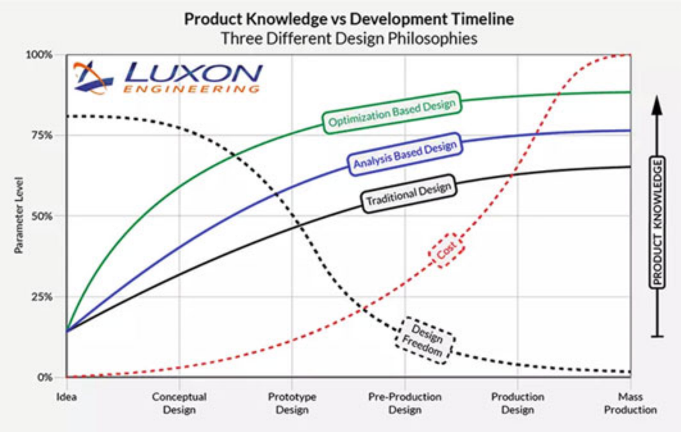


Fig. 15 Production versus design timeline [18]

Fig. 16 Mould preparation

Fig. 17 Glass finishing

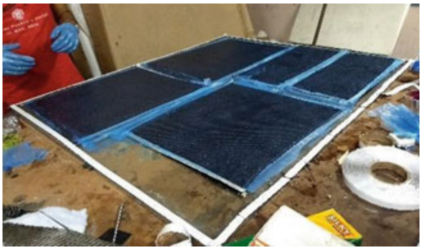


Fig. 18 Final FSAE vehicle

5 Optimization

An extensive literature review and the collective experience of the authors after working for the past four years in such student teams revealed that the pressure for students to meet with both competition and academic deadlines to develop the vehicles as fast as possible leaves the field of design optimization unexplored. Thus, tools and methodologies like structural, topology, and shape optimization are avoided and the method of prototyping and testing is given a higher priority. While this is a viable method which has its own benefits, it often does not comply with how development is carried out in the industry and results in tighter budget constraints.

A key factor besides the strict timelines and pressure is often the lack of proper knowledge and resources to carry out such advanced simulations.

A faculty advisor at such a stage is pivotal in guiding through the process. However, this always leaves scope for biased designs among underprivileged teams. Figure 15 [18] shows how optimization can accelerate the design process and yield better products.

6 Sustainability

In today's world, sustainability plays a major role in determining use of materials for manufacturing and use of technology. Since the EU directive of minimum 85% of the weight fraction should be reusable or recyclable, the use of CFRP composite which is incinerated at end of life cycle is not possible [19]. Efficiency is a major driver in the automobile industry and hence, besides attention to innovation in the propulsion system, weight reduction is also an important field of experimentation. We need to access the life cycle sustainability of CFRP composite.

6.1 Manufacturing

Fabrication involves specialized techniques and tools as well as labor-intensive processes where automation has been difficult to achieve. The process usually involves the use of multiple raw materials and chemical components that are costly and time intensive in nature. Still, the development of manufacturing techniques is underway as the use of carbon fiber and other CFRP materials present an opportunity to move towards sustainable products and manufacturing.

6.2 Material Production

The first steps include material extraction, i.e., fossil fuels from the earth. Carbon fiber is made from organic polymers, which consist of long strings of molecules held together by carbon atoms. Most carbon fibers (about 90%) are made from polyacrylonitrile. CFRPs are produced using chemical-intensive energy consuming methods. Carbon fiber has high energy content compared to the rest of the fibers and is a high cost product [20]. This is a barrier against the use of CFRPs even though it has many useful properties and specifications that help drive innovation and better performance.

6.3 End of Life

Waste treatment policies aim to limit the impact of waste on the environment by promoting the use of recyclable and reusable materials. CFRPs pose a challenge in this domain as they mostly consist of multiple components that are fused together, and hence, recyclability provides a challenge. Methods like pyrolysis, hydrolysis, chemical recycling, regrinding, and incineration are often used to recycle FRCMs. Also, products are specifically fabricated for custom requirements, hence hindering widespread reusability [21].

7 Conclusion

Student competitions are a great medium for undergraduate-level students to indulge in the experimental side of the course syllabus and explore the industry. Moreover, a competitive environment makes room for innovation and sets the path for aspiring engineers and researchers. Three such competitions were studied in the current work, and the following key points were noted in comparison:

1. A different mission and size of the vehicle drives the optimum mixture of resin and hardener for the epoxy matrix.
2. The manufacturing techniques and range of materials is closely linked to the availability of resources and budget for development. Being from the same university and country, this is very similar for the three teams in our case.
3. The design process can vary from vehicle to vehicle depending on the high- and low-level requirements. However, the testing procedure and timelines are very similar for all teams worldwide. This is primarily attributed to the similar timeline of the college academics and frequency of examinations.

Acknowledgements The authors would like to thank Prof. Ranganath M. Sangari for his continuous support throughout the project. Both the UAVs in Sect 4.1 were manufactured at UAS-DTU laboratory, Delhi Technological University and the authors acknowledge the help of the team members for the same.

References

1. Faron H, Marcinkowski W, Prusak D (2015) Composite bodywork design and creation process in FSAE. Case study AGH racing. Int J Mech Eng (IJME) 4(6):13–20
2. Cornell University Unmanned air systems, Orion Technical Design Report, Seafarer AUVSI SUAS 2019
3. Flow Design Team, University of Split, Technical Design Report, Seafarer AUVSI SUAS 2019
4. Tomar P, Khandelwal H, Gupta A, Boora G (2017) Efficient design of a super mileage low cost vehicle frame using natural bamboo. Mater Today: Proc 4(9):10586–10590
5. Yay K, Murat Ereke I, Fatigue strength of a rim model with FEM using a new approximation technique. SAE Technical Paper Series 2001-01-3339
6. Olsen EV, Lemu HG (2016) Mechanical testing of composite materials for monocoque design in formula student car. Int J Mech Mechatron Eng 10(1)
7. Composite Parts for a FSAE Racecar: Monocoque Chassis, Pedal Box & Aerodynamic Undertray Project Number: P09221 Multi-Disciplinary Senior Design Conference, Kate Gleason College of Engineering
8. Savage G (2003) Composite materials technology in formula 1 motor racing Honda racing F1 team 2003
9. Callister WD, Rethwisch DG (2009) Materials science and engineering: an introduction, 8th edn. Wiley, New York
10. Chapter 4: Metal matrix composites, Advanced Materials by Design, Stati Uniti d'America, Congress. Office of technology assessment
11. Yang HM (2000) Fiber reinforcements and general theory of composites in comprehensive composite materials
12. Ash RA (2016) Vehicle armor in lightweight ballistic composites, 2nd edn.
13. De Araújo M (2016) Natural and man-made fibres: physical and mechanical properties. Fibrous Compos Mater Civ Eng Appl. https://doi.org/10.1533/9780857095583.1.3
14. Hearle JWS (2001) Textile fibers: a comparative overview. Encycl Mater Sci Technol
15. Huang X (2009) Fabrication and properties of carbon fibers. Materials (Basel) 2(4):2369–2403
16. Megson THG (2010) Introduction to aircraft structural analysis
17. Dagur R, Singh V, Grover S, Sethi N, Arora BB (2018) Design of flying wing UAV and effect of winglets on its performance. Int J Emerg Technol Adv Eng 8(3)
18. Luxon Engineering, Design Optimization, https://luxonengineering.com/services-optimization.html. Accessed 24 Nov 2019
19. Duflou JR, De Moor J, Verpoest I, Dewulf W (2009) Environmental impact analysis of composite use in car manufacturing. CIRP Ann-Manuf Technol 58:9–12
20. Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. Compos Part A 40:1257–1265
21. Witik RA, Teuscher R, Michaud V, Ludwig C, Månson J-AE (2013) Carbon fibre reinforced composite waste: an environmental assessment of recycling. Energy Recov Landfill 49:89–99. https://doi.org/10.1016/j.compositesa.2013.02.009