AME0009

Effects of carbon fiber stacking sequence on torsional stiffness per weight ratio of formula student semi-monocoque chassis structure

Tanic Leunanonchai, Kitchanon Ruangjirakit*, and Surachate Chutima

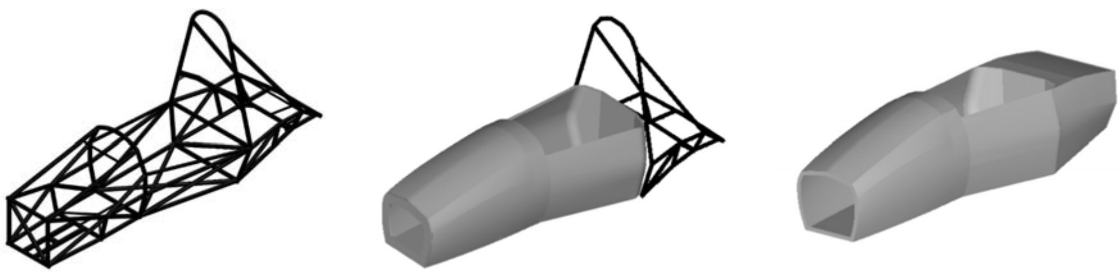
Department of Mechanical Engineering, Faculty of Engineering, King's Mongkut's University of Technology Thonburi 126 Pracha-uthit Rd., Bangmod, Thungkru, Bangkok 10140, Thailand

* Corresponding Author: kitchanon.rua@kmutt.ac.th, +66-2470-9272

Abstract. In the design of Formula Student chassis structure, torsional stiffness and weight are the main factors which affect vehicle's performance. At present, the most popular type of chassis structure is space frame as it is inexpensive and simple. However, the main drawback of the space frame structure is its low torsional stiffness per weight ratio, which could be improved by replacing the steel tubes with sandwich semi-monocoque chassis structure consisting of carbon composite faces and aluminum honeycomb core. Therefore, this research focuses on the effects of different stacking sequences of carbon fiber composite faces that located on both sides of the 15.8 mm-thick aluminum honeycomb core. The responses of semi-monocoque chassis under torsional load are evaluated by Finite Element Code and 3 stacking sequences of carbon fiber considered herein are [0_9/Core/0_9], [F_6/Core/F_6] and [F/0_6/F/Core/F/0_6/F], which F indicates bi-directional fabric and 0 refers to unidirectional fiber. The results suggest that pure bi-directional fabric lay-up [F_6/Core/F_6] gives the highest torsional stiffness per weight ratio which is higher than the [0_9/Core/0_9] and [F/0_6/F/Core/F/0_6/F] lay-ups by 144% and 46%, respectively. Moreover, the torsional stiffness of [F_6/Core/F_6] lay-up increases from the current space frame structure made from AISI 4130 steel by approximately 5 times.

1. Introduction

Formula SAE is the student racing event organized by the Society of Automotive Engineers (SAE) to encourage college and university students to apply knowledge in designing the Formula Student racing car under Formula SAE Rules [1]. To maximize the performance of the vehicle, weight and torsional stiffness are the main factors to consider, as the chassis with high torsional stiffness is able to control the lateral load transfer distribution better than the low torsional stiffness structure [2]. This greatly improves the performance of the suspension system as it works according to the design and helps stabilize the vehicle during cornering. The main types of structure for Formula Student chassis used worldwide can be categorized into 3 groups as shown in Figure 1.



(a) **(b)** **(c)**

Figure 1. Different types of Formula Student racing car structure
(a) Space Frame (b) Semi-Monocoque and (c) Full-Monocoque.

The space frame structure is the most common used structure worldwide as it is the easiest to design and fabricate. However, the main drawbacks are its weight and low torsional stiffness. The full-monocoque chassis, on the other hand, is the lightest structure and also has the highest torsional stiffness. However, it is the most expensive structure and is difficult to design and customize. The compromised structure in terms of torsional stiffness, weight and cost is therefore the semi-monocoque chassis as shown in Figure 1b and is selected to further develop in this research. Another advantage of the semi-monocoque structure is its flexibility to customize compared to full-monocoque structure. The comparison between each chassis type in terms of torsional stiffness, weight and cost is summarized in Table 1 below.

Table 1. Advantages and disadvantages of each chassis type.

Chassis Types	Torsional Stiffness	Weight	Cost
Space Frame	★	★★★	★
Semi - Monocoque	★★	★★	★★
Full - Monocoque	★★★	★	★★★

★★★ High ★★ Medium ★ Low

John Christensen [3] has conducted a comparative study between a space frame structure, a semi-monocoque and a monocoque structures using Finite Element Method. The space frame chassis used in this study weighed 32 kilograms and the torsional stiffness was 744 Nm/degree. The monocoque chassis consisted of aluminum core and carbon fiber face in which the type of the stacking sequences was [T_2/F_2/Core/F_2/T_2] where T represents 0/90° twill fabric and F represents ±45° bi-axial directions was used. The results showed that the weight of full-monocoque chassis could be reduced by 23 kilograms while the weight of the semi-monocoque chassis could be reduced by 18 kilograms. In addition, the torsional stiffness was between 4,000 and 10,000 Nm/degree. Another conclusion drawn from this research is that the torsional stiffness of the Formula Student racing car depends on many factors such as type of the material, shape of the chassis and the stacking sequences.

Another study by Leonard Hamilton et al. [4] studied different design of a semi-monocoque structure which complies with the FSAE 2012 rules. The results from experiment and finite element method of 2 lay-ups were compared. The first stacking sequence was [$F/0_3/F/Core/F/0_3/F$] which is used at the front bulkhead support and the second stacking sequence was [$F/0_7/F/Core/F/0_3/F$] that is used at the side impact zone, where F indicates bi-directional fabric and 0 represents unidirectional (UD) fiber. The results suggested that the weight of the semi-monocoque structure could be reduced by up to 53 % compared with the conventional space frame structure and the torsion rigidity of the semi-monocoque chassis was 2000 Nm/degree which increased by 43%.

It could be deduced from the previous studies that the chassis with high torsional stiffness can potentially improve the performance of Formula Student car and also the weight of the chassis needs to be reduced. Therefore, in this research, the stiffness per weight ratio is used as an indicator to evaluate structural performance of 3 different stacking sequences, namely [$0_9/Core/0_9$], [$F_6/Core/F_6$] and [$F/0_6/F/Core/F/0_6/F$], used for faces of the sandwich structure, where F represents plain weave fabric, 0 represents unidirectional fiber at 0° with respect to x-axis of the global coordinate, and the subscript represents number of layer. The 3 stacking sequences have the fiber orientation of balanced-symmetric and cross-ply laminate which act as quasi-isotropic, where shearing-stretching-coupling, bending-stretching-coupling and bending-twisting-coupling do not occur. In order to determine the thickness of the sandwich structure, the FSAE Rule is used as a reference. The FSAE Rule has specified Monocoque Equivalency Rules of 3 zones such that the flexural stiffness (EI) of the monocoque panel is equivalent to the steel tube structure. These 3 zones are 1.Side Impact zone, which the EI equals to 3 baseline steel tubes, 2. Front Bulkhead zone, which the EI equals to 2 baseline steel tubes, and 3.Front Bulkhead Support zone, which the EI equals to 6 baseline steel tubes. In the design of this research, the thickness of the aluminum honeycomb core is fixed while the face thickness can be varied. The face thickness is computed such that the EI passes all requirements of each zone according to the aforementioned FSAE Rule.

2. Laminate Selection of Sandwich Structure

According to the 2016 FSAE Formula Student rules, the flexural stiffness of the sandwich panels ($D_{sandwich}$) must be equal or higher than the flexural stiffness of the steel frame evaluated from a 3-point bending test. The sandwich honeycomb structure as shown in Figure 2 that consists of faces and a core is relatively popular for automotive structure as it exhibits lightweight property, provides smooth surface and gives high out-of-plane and shear stiffnesses. The flexural stiffness of the sandwich structure can be calculated from equation 1 with parameters shown in Figure 3 below.

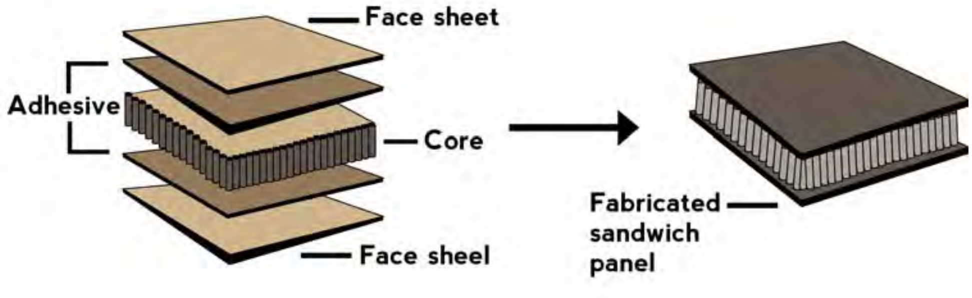


Figure 2. Sandwich structure with honeycomb core.

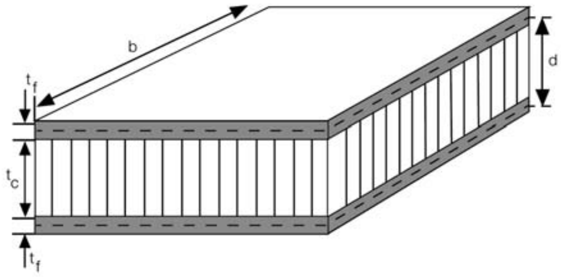


Figure 3. Honeycomb sandwich panel.

$$D_{Sandwich} = \frac{E_f b t_f^3}{6} + \frac{E_f t_f b d^2}{2} + \frac{E_c b t_c^3}{12} \tag{1}$$

Where

D	=	Flexural Stiffness (Nm^2)
E_f	=	Modulus of face material (Pa)
t_f	=	Face thickness (m)
t_c	=	Core thickness (m)
d	=	Average thickness of sandwich panel (m)
b	=	Width of sandwich panel (m)

In this research, the sandwich structure with Carbon Fiber Reinforced Plastic (CFRP) faces and honeycomb core is selected by which three different stacking sequences of CFRP are considered as show in Table 2.

Table 2. Stacking sequences of CFRP used in this study [5, 6].

Lay-up	Face thickness, t_f (mm)	Core thickness, t_c (mm)	Average sandwich thickness, d (mm)
$[0_9/Core/0_9]$	1.125	15.800	16.925
$[F_6/Core/F_6]$	1.800	15.800	17.600
$[F/0_6/F/Core/F/0_6/F]$	1.350	15.800	17.150

It can be shown that all 3 stacking sequences of CFRP used in this study are balanced and symmetric, which yields $B_{ij}=0$, cross-ply ($A_{16}=A_{26}=B_{16}=B_{26}=D_{16}=D_{26}=0$) laminate. This suggests that the coupling effects as shown in the ABD matrix (Figure 4) are eliminated.

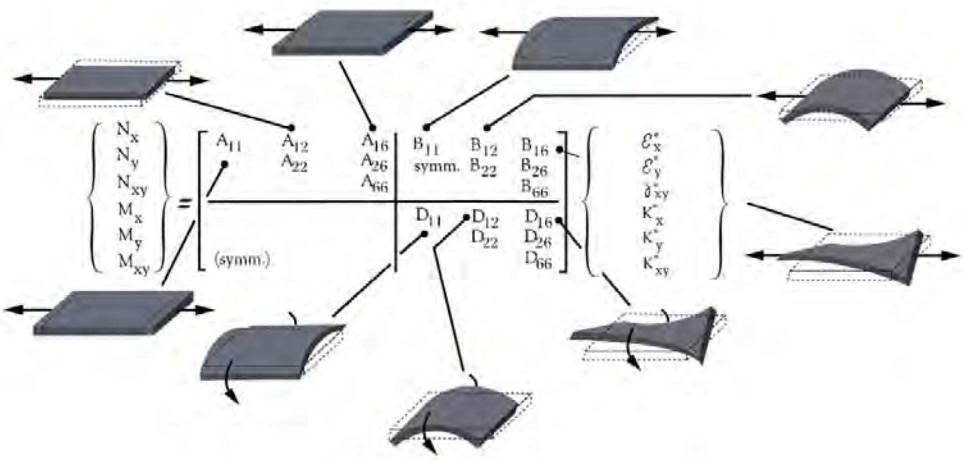


Figure 4. ABD matrix of composite structure.

3. Torsional Stiffness Analysis

Semi-monocoque chassis in this research was designed in accordance to 2016 FSAE Rules. The semi-monocoque chassis can be separated into 4 main parts, which are main hoop, front bulkhead, front bulkhead support and side impact as shown in Figure 5. The torsional stiffness as well as the strength of the chassis were evaluated using finite element analysis through Hyperworks ver. 14 package. The material properties of the CFRP faces, aluminum honeycomb core and the steel tube used in the finite element analysis are shown in Table 3, Table 4 and Table 5, respectively.

The finite element model of the Formula Student racing car is shown in Figure 6. In the monocoque area, the element was selected to be 4-noded shell element (Quad 4) whereas in the rear frame area, the element was selected to be 2-noded beam element (Bar2).

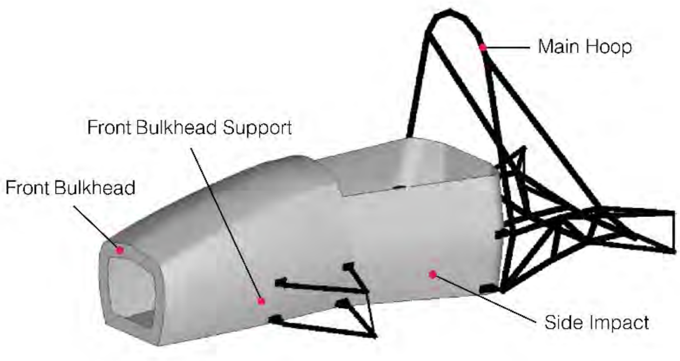


Figure 5. Monocoque structure with rear space frame.

Table 3. Mechanical property of CFRP face.

Facing Material	UD Carbon Tape (0°) Epoxy	Woven Carbon Epoxy
Fiber volume fraction (v_f)	0.6	0.55
Longitudinal modulus (E_1), GPa	135	70
Transverse modulus (E_2), GPa	10	70
In-plane shear modulus (G_{12}), GPa	5	5
Major Poisson's ratio (ν_{12})	0.3	0.1
PLY Thickness (t_f), mm	0.125	0.3
Weight per PLY , kg/m^2	0.19	0.45
Longitudinal Tensile Strength (F_{1t}), MPa	1500	600

Table 4. Mechanical property of aluminum honeycomb core.

Material	CR III 5056 Hexagonal Aluminum Honeycomb
Density (ρ), kg/m^3	50
Compressive Strength (σ_T), MPa	2.8
Compressive Modulus (E_c), MPa	669
Shear modulus (G_c), MPa	310

Table 5. Mechanical property of AISI 4130 steel [7].

Material	Steel AISI 4130
Tensile Strength, Ultimate (UTS), MPa	670
Tensile Strength, Yield , MPa	435
Poisson's Ratio (ν)	0.29
Modulus of Elasticity (E), GPa	205
Shear Modulus (G), GPa	80

The chassis was fixed at the rear A-arms (no translation and rotation for all 3 axes) while the front A-arms are free. The couple forces of 1,000 N were applied at the front A-arms as shown in Figure 6. The assumptions for this analysis are that the front A-arms are rigid, which means that the deformation is not permitted, and the monocoque and the rear frame are connected through rigid link.

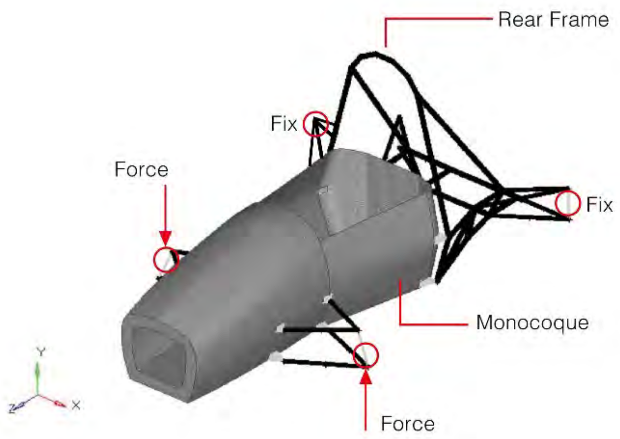


Figure 6. Finite element model for torsional stiffness analysis.

The torsional stiffness can be calculated from equation 2

$$K_T = \frac{Ft}{\tan^{-1}\left(\frac{y_1 + y_2}{t}\right)} \quad (2)$$

Where

K_T	=	Torsion Stiffness (Nm/degree)
F	=	Couple force (N)
t	=	Width at the load point (m)
y_1	=	Deflection at left A-arm (m)
y_2	=	Deflection at right A-arm (m)

4. Result & Discussion

The results of each stacking sequence are compared as shown in table 6.

Table 6. Finite element analysis results of three lay-ups.

Lay-up	$[0_9/Core/0_9]$	$[F_6/Core/F_6]$	$[F/0_6/F/Core/F/0_6/F]$	Space Frame
Weight, kg	23.5	29.7	25.7	34.6
Left Deflection (y_1), mm	3	1.23	1.8	6.49
Right Deflection (y_2), mm	3	1.22	1.8	6.49
Angle, degree	0.29	0.12	0.17	0.64
Torsional Stiffness (K_T), Nm/degree	3894	9536	6490	1800
Longitudinal Maximum Stress, MPa	94	35	74	-
Transverse Maximum Stress, MPa	13	10	18	-
In-plane Maximum Shear Stress, MPa	45	18	41	-

It can be observed from Table 6 and graphically shown in Figure 7 that the deflection of semi-monocoque chassis under couple forces are very small. In addition, the maximum stresses of all lay-ups are below the tensile strength of the sandwich structure; therefore, the semi-monocoque structure could be used safely under torsional load.

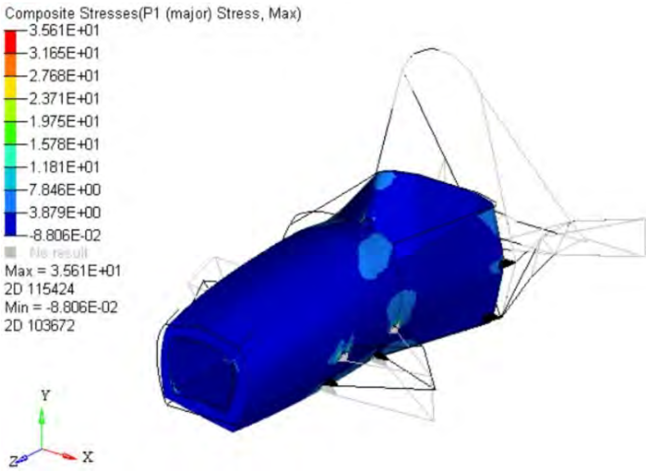


Figure 7. Maximum stress under couple force of [F_6/core/F_6] lay-up.

All 3 stacking sequences of CFRP face in this research are balanced, symmetric and cross-ply laminate to prevent the shearing-stretching coupling, bending-stretching coupling and bending-twisting coupling. This makes the face to exhibit the quasi-isotropic or isotropic-like behavior. According to the ABD matrix of each lay-up as shown in Table 7, the [F_6/core/F_6] provides the maximum torsional stiffness as the D_{66} entity is maximum. The [0_9/core/0_9] lay-up, on the other hand, provides maximum resistance to tension or compression force in fiber direction as the A_{11} entity is maximum while the D_{66} entity is the lowest; hence, the torsional stiffness is minimum. This is because there are no fiber in the transverse direction to resist the torsion. The [F/0_6/F/Core/F/0_6/F] lay-up

provides slightly less torsion compared to the [F_6/core/F_6] lay-up as there are less fibers in the transverse direction, 4 layers compared to 6 layers.

Table 7. ABD matrix analysis of each stacking sequences**.**

Lay up	ABD Matrix
$[0_9/\text{Core}/0_9]$	$\begin{bmatrix} 3\times10^5 & 9.4\times10^3 & 0 & 0 & 0 & 0 \\ 9.4\times10^3 & 3.1\times10^4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.5\times10^4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.1\times10^7 & 4.7\times10^5 & 0 \\ 0 & 0 & 0 & 4.7\times10^5 & 1.6\times10^6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8.8\times10^5 \end{bmatrix}$
$[F_6/\text{Core}/F_6]$	$\begin{bmatrix} 2.6\times10^5 & 1.6\times10^4 & 0 & 0 & 0 & 0 \\ 1.6\times10^4 & 2.6\times10^5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.1\times10^4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.9\times10^7 & 1\times10^6 & 0 \\ 0 & 0 & 0 & 1\times10^6 & 1.9\times10^7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.4\times10^6 \end{bmatrix}$
$[F/0_6/F/\text{Core}/F/0_6/F]$	$\begin{bmatrix} 2.9\times10^5 & 1.1\times10^4 & 0 & 0 & 0 & 0 \\ 1.1\times10^4 & 1\times10^5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.7\times10^4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\times10^7 & 6.6\times10^5 & 0 \\ 0 & 0 & 0 & 6.6\times10^5 & 7.4\times10^6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1\times10^6 \end{bmatrix}$

The comparison of torsional stiffness per weight ratio of 3 different lay-ups are shown in Figure 8. From Table 6, although the $[F_6/\text{Core}/F_6]$ lay-up is the heaviest, it provides the highest torsional stiffness. Therefore, this lay-up provides maximum torsional stiffness per weight ratio among other lay-ups. As a benchmark, the torsional stiffness of the conventional AISI 4130 steel frame chassis is 1,800 Nm/degree and the weight is 34.6 kilograms; therefore, the torsional stiffness and the weight of $[F_6/\text{core}/F_6]$ lay-up are greater than the steel frame by 429% and 14.16%, respectively, making the torsional stiffness per weight ratio of the semi-monocoque structure higher than the space frame by approximately 5 times.

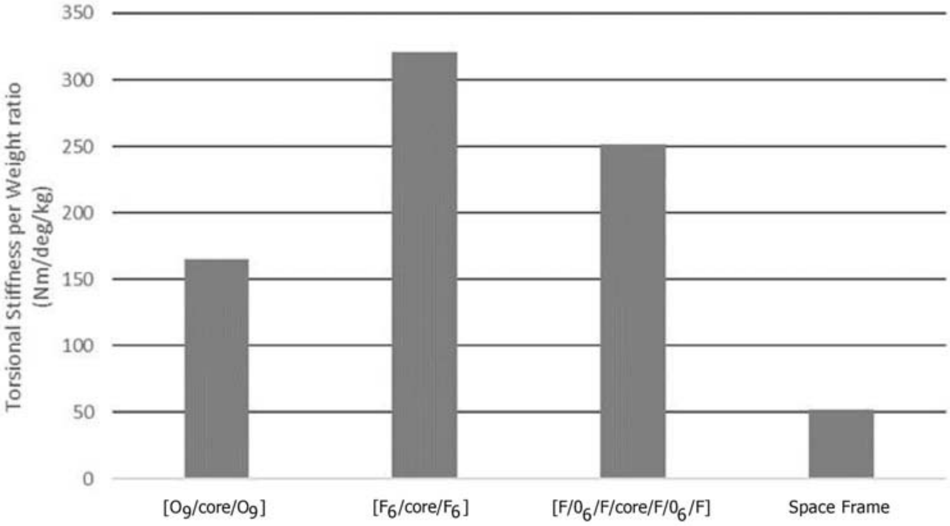


Figure 8. Torsional Stiffness per weight ratio comparison**.**

5. Conclusion

In this paper, the torsional stiffness per weight ratio of the Formula Student racing car semi-monocoque structure was evaluated for three different stacking sequences of the faces of sandwich structure, namely [0_9/Core/0_9], [F_6/Core/F_6] and [F/0_6/F/Core/F/0_6/F]. The structure was analyzed by HyperWork14 finite element code. The results show that the [F_6/Core/F_6] lay-up has the highest torsional stiffness because D_{66} entity in the ABD matrix appears to be the highest among all stacking sequences considered herein. However, the [0_9/Core/0_9] lay-up can handle tension or compression in fiber direction because A_{11} entity has the highest value. Therefore, this lay-up is the least stiff when subjected to torsion. Finally, the lay-up that gives the highest Torsional stiffness per weight ratio is [F_6/Core/F_6] which increases from AISI 4130 Space Frame by approximately 5 times.

References

[1] "FSAE Rule," 15 June 2017. [Online]. Available: http://students.sae.org/cds/formulaseries/rules/.

[2] E. Sampo, A. Sorniotti and A. Crocombe, "Chassis Torsional Stiffness : Analysis of the Influence on Vehicle Dynamic," in *SAE Technical Paper 2010-01-0094*, 2010.

[3] J. Christensen, "Carbon Fibre Monocoque Chassis Feasibility and Manufacturability for FSAE," in *SAE Technical Paper 2015-01-0078*, 2015.

[4] L. Hamilton, P. Joyce, C. Forero and M. McDonald, "Production of a Composite Monocoque Frame for Formula SAE Racecar," in *SAE Technical Paper 2013-01-1173*, 2013.

[5] Performance Composites, "Mechanical Properties of Carbon Fibre Composite Materials, Fibre / Epoxy resin," 20 June 2017. [Online]. Available: http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp.

[6] ZENKERT, D., and BITZER, T.,, "HexWebTM HONEYCOMB SANDWICH DESIGN TECHNOLOGY," 25 June 2017. [Online]. Available: http://www.hexcel.com/user_area/content_media/raw/Honeycomb_Sandwich_Design_Technology.pdf.

[7] ASM Aerospace Specification Metals, "AISI 4130 Steel, normalized at 870°C (1600°F)," 25 June 2017. [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=m4130r.