Mechanical Testing of Composite Materials for Monocoque Design in Formula Student Car

Erik Vassøy Olsen, Hirpa G. Lemu

Abstract**—**Inspired by the Formula-1 competition, IMechE (Institute of Mechanical Engineers) and Formula SAE (Society of Mechanical Engineers) organize annual competitions for University and College students worldwide to compete with a single-seat racecar they have designed and built. Design of the chassis or the frame is a key component of the competition because the weight and stiffness properties are directly related with the performance of the car and the safety of the driver. In addition, a reduced weight of the chassis has direct influence on the design of other components in the car. Among others, it improves the power to weight ratio and the aerodynamic performance. As the power output of the engine or the battery installed in the car is limited to 80 kW, increasing the power to weight ratio demands reduction of the weight of the chassis, which represents the major part of the weight of the car. In order to reduce the weight of the car, ION Racing team from University of Stavanger, Norway, opted for a monocoque design. To ensure fulfilment of the competition requirements of the chassis, the monocoque design should provide sufficient torsional stiffness and absorb the impact energy in case of possible collision.

The study reported in this article is based on the requirements for Formula Student competition. As part of this study, diverse mechanical tests were conducted to determine the mechanical properties and performances of the monocoque design. Upon a comprehensive theoretical study of the mechanical properties of sandwich composite materials and the requirements of monocoque design in the competition rules, diverse tests were conducted including 3-point bending test, perimeter shear test and test for absorbed energy. The test panels were homemade and prepared with equivalent size of the side impact zone of the monocoque, i.e. 275 mm x 500 mm, so that the obtained results from the tests can be representative. Different layups of the test panels with identical core material and the same number of layers of carbon fibre were tested and compared. Influence of the core material thickness was also studied. Furthermore, analytical calculations and numerical analysis were conducted to check compliance to the stated rules for Structural Equivalency with steel grade SAE/AISI 1010. The test results were also compared with calculated results with respect to bending and torsional stiffness, energy absorption, buckling, etc.

The obtained results demonstrate that the material composition and strength of the composite material selected for the monocoque design has equivalent structural properties as a welded frame and thus comply with the competition requirements. The developed analytical calculation algorithms and relations will be useful for future monocoque designs with different lay-ups and compositions.

Keywords**—**Composite material, formula student, ion racing, monocoque design, structural equivalence.

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I. Introduction

BASED on the principle of problem-based learning, student competitions are becoming key elements of the learning process of engineering students worldwide based. Understanding this fact and the implications in acquiring the engineering skills, student teams at the University of Stavanger started the internationally known Formula Student project with the objective of designing and building a single-seat racecar and participating on the competition organized by IMechE (Institute of Mechanical Engineers) at Silverstone, London. So far, the team has designed and built four cars where the first two (in 2012 and 2013) are fuel driven while the last two (in 2014 and 2015) are battery driven.

Among others, the chassis or the frame represents a central component of the car and hence its design and construction plays a key role in racecars. Its weight and stiffness properties are directly related with the performance of the car and the safety of the driver. In addition to carrying all the components of the car, the chassis supports or transfers all the forces that manifest during acceleration, deceleration, and cornering [1]. In addition, a low weight chassis improves the performance of the car because of its direct influence on the design of other components in the car. It further improves the power to weight ratio and the aerodynamic performance. In general, benefits of carbon-fiber based monocoque design of the chassis particularly in the field of racing include the combined strength and toughness. However, the cost of production and the recyclability of carbon fiber technology [2] is often mentioned as the main hindrance for the ongoing effort to replace metal-based chasses with carbon fiber ones. As a result, the competition rules demand that the monocoque frame have strength equal to or greater than the traditional steel space frames that they replace. Particularly, the test samples of sandwich laminate should demonstrate mechanical behaviors better than that of two steel tubulars with specified dimensions [3].

The properties and performance of composite materials depend on the properties of the individual components used to produce the laminate and their interfacial compatibility. Though the representative unit cells are homogeneous and orthotropic, the composite products are inhomogeneous and have anisotropic mechanical properties that demand experimental and/or numerical characterization of mechanical components made of composite materials. Upon observing the desirable properties of composite materials, the last two decades have experienced an exponential growth of number of research activities and publications. To address this issue, Gibson [4] conducted a literature review on mechanics of multifunctional composite materials and assessed the key topics in the area. The review focused on both structural functions such as strength, stiffness, and damping properties and non-structural functions such as electrical, energy storage and damping properties. The combined performance in terms of both structural and non-structural functions of composite materials mainly attracts the research and application of new composites. Composites as structural materials have been widely applied in industrial applications such as automotive [5], [6], aircraft [7], [8], energy [9], [10] and marine or offshore [11], [12] industries. To reflect the amount of research interest, several review articles are reported on mechanical behavior studies [4], [13], FEM (finite element method) modeling and analyses [13]–[16] and modeling machining process [17] of composite laminates.

The objective of the work partially reported is article to characterize the mechanical behavior of composite laminates used for construction of monocoque chassis through mechanical testing. The monocoque chassis is design for Formula Student racecar and hence the mechanical tests are to qualify the laminates according to the competition rules. The article is subdivided into six sections. The following section (Section II) briefly presents the backgrounds of chassis design for racecars with focus on Formula Student racecars. Upon presenting monocoque design requirements in Section III, the article introduces the used test equipment, materials, and methods in Section IV. Section V and VI present the discussion of test results and the conclusions drawn from the study respectively.

II. Brief Theoretical Backgrounds

Two forms of chassis design are commonly used in racecars; namely, space frame and monocoque design (Fig. 1). The space frame design and construction is based on the triangulation principle where metallic tubular bar elements, that transfer load only in pure tension and compression, are welded together to form a truss structure.

The space frame design is favored by many Formula Student teams due to its simplicity to design, construct, and integrate to other components in the car [1]. It also provides high torsional stiffness, which is an important performance criterion of chassis in racecars. This property is achieved by either constructing a structure that has high areal moment of inertia or constructed from strong or high mass density materials. In both cases, the space frame chassis design is known to be heavy, which is undesirable. The monocoque design, on the other hand, represents an innovative chassis design approach in the racecar field that combines high performance with an efficient manufacturing process [18] and low in weight. It is a panel formed design without a solid frame structure that is dimensioned to support the drive force and the external dynamic loads from the suspension system and the aerodynamics. In monocoque design, materials such as aluminum, composites, and steel are used to construct the chassis. Because of the attractive properties such as high stiffness and strength-to-weight ratios, however, the monocoque design of racecars, including that of Formula Student, adopt composite laminates. The additional novelty of this design is the possibility to combine low weight with high torsional rigidity. In addition, the production process is less skill demanding, though complicated and expensive in terms of material costs.

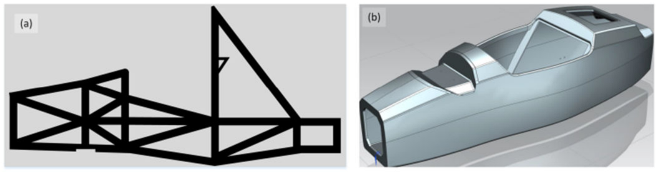

Fig. 1 Two common chassis designs (a) space frame, (b) monocoque

The FS (Formula Student) competition rules demand that the chassis fulfills the triangulation principle in order to increase the torsional rigidity. Design by triangulation principle involves provision of a diagonal element to the structure consisting of four members (Fig. 2 (a)) in order to split the section into two triangular sections. As illustrated in Fig. 2 (b), the space frame design rigidity is secured by a diagonal element while panels of monocoque chassis in Fig. 2 (c) serves as stiffeners of the structure, acting similar to and even better than a diagonal stiffener of a space frame. Furthermore, the chassis should enable a desirable rolling moment distribution for a good balance of the car in diverse driving conditions and it must be able to absorb high impact energy that can increase the likelihood of drivers surviving a crash without injury [19]. While metallic monocoque chasses provide the required energy absorption by deformation, composite materials absorb energy by failure. However, the production process of monocoque chassis is not so skill demanding, the effective design, analysis and production of composite laminates requires understanding of the basic theories of composite materials. Such theories are nowadays widely available in many textbooks and the open literature [15], [20], [21] and thus not covered in this article.

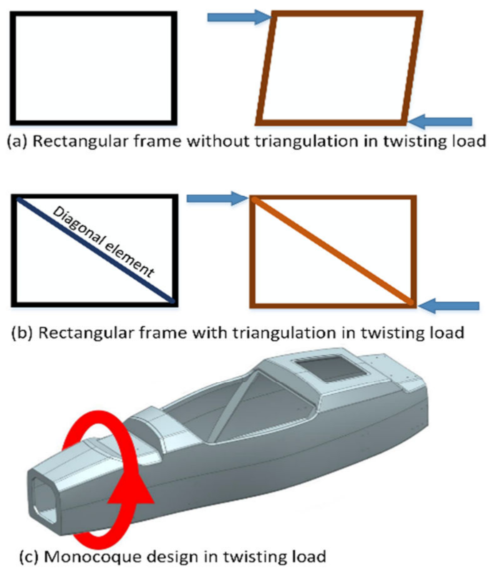

Fig. 2 Principle of triangulation and monocoque design in torsion

III. Monocoque Design Requirements for FS Competition

In order to ensure the safety of the driver, the FS regulations state a series of requirements on the monocoque design, construction, and test of the material. Violation or lack of fulfillment of these requirements can result in missing competition points or, in the worst case, disqualify the car from participating in the competition. Thus, the teams should provide documentation of the test results of the monocoque material for each defined zone of the car body. This documentation is provided in an Excel sheet; also called Structural Equivalence Sheet (SES), which is designed to demonstrate that material of the monocoque structure has equivalent performance with a welded frame in terms of energy absorption, ultimate strength, bending, buckling, etc. An extract of this sheet is shown in Table I. The table shows list of the rule descriptions against the rule numbers in the first and second column and the evaluation criteria are listed on the right hand columns. To get the SES approved, each relevant criterion for each rule description should indicate a green background, which is an indication that the values are better than the pre-defined reference values.

TABLE I
Extract of the Structural Equivalence Sheet

Rule No.	Rule Description	Design Description and/or Material Used	Steel Tube and Laminate Composite Equivalency Parameters								
			EI/Safety Factor	Area	Yield	UTS	Yield as Welded	UTS as Welded	Max Bending Load at UTS	Max deflection at max baseline load	Energy absorbed during bending
T3.11	Main Roll Hoop Tubing		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.12	Front Roll Hoop Tubing		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.13	Main Roll Hoop Bracing Tubing		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.13.6	Main Hoop Bracing Support - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.14	Front Hoop Bracing - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.19	Front Bulkhead - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.20	Front Bulkhead Support - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
T3.25	Side Impact Structure - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
T5.4	Shoulder Harness Bar		341	206	217	182	368	221	435	29	554
T3.21.6	Impact Attenuator Anti-Intrusion Plate		PA								
T3.37	Front Hoop Bracing - Monocoques		166	NA	705	589	###	717	319	##	614
T3.32	Front Bulkhead - Monocoques		###	NA	224	187	380	228	720	7	340
T3.33	Front Bulkhead Support - Monocoques		141	NA	616	515	###	626	270	71	520
T3.34	Side Impact Structure - Monocoques		178	NA	NA	NA	NA	NA	NA	NA	NA
T3.37	Main Hoop Bracing Support - Monocoques		264	NA	###	967	###	###	508	38	977
T3.35	Main Hoop Attachment - Monocoques		PA								
T3.36	Front Hoop Attachment - Monocoques		PA								
T3.37	Hoop Bracing Attach. - Monocoques		PA								
T3.38	Impact Attenuator Attachment -Monocoques		PA								
T3.41	Safety Harness Attachment - Monocoques		PA								
EV3.4.2	Accumulator Attachment										
EV3.4.4	Accumulator Protection		105	NA	446	373	756	454	202	95	389
EV4.2.2	Tractive System Protection		105	NA	462	386	783	470	203	95	390

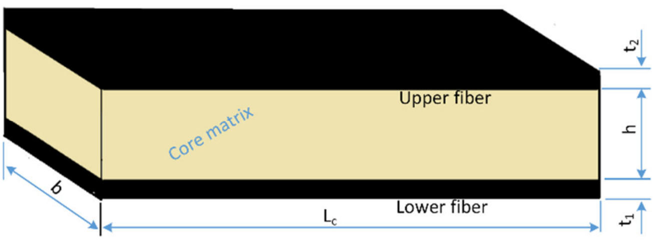

Fig. 3 Dimensional parameters of composite laminate

The most critical requirement is stated for the laminate that is used for the side impact panel beside the driver. For this part of the monocoque, the rules state that two reference steel tubulars are tested using the same setup and the laminate should, among others, endure maximum load, have higher bending stiffness and absorb higher energy when deformed to 12.7 mm. Theoretically, these parameters for the reference steel tubular are calculated using the relations given in (1).

$$\begin{aligned} &\text{Flextural rigidity} &: EI = \frac{200\,000 \cdot n\pi\left(D^4 - d^4\right)}{64} \\ &\text{Bending stiffness} &: G_s = \frac{F_{s2} - F_{s1}}{y_{s2} - y_{s1}} \\ &\text{Absorbed energy} &: U = \sum_{i=0}^{n}\left(y_i - y_{i-1}\right)\cdot F_i \end{aligned} \quad (1)$$

where, E = 200 000 MPa - Modulus of elasticity of steel, I (mm^4)– moment of inertia of a tube, D (mm) - outer diameter D of the tube, d (mm) - inner diameter of the tube, n = 2 – number of tubes, F_{s1} (N) – Force at no deflection, F_{s2} (N) – Force at beam deflection of 12.7 mm, y_{s1} = 0 mm, y_{s2} = 12.7 mm – reference beam deflection, y_i = beam deflection at load F_i.

In classical mechanics, the force-displacement relation of a simply supported beam with symmetrical load is given as:

$$y = F \cdot L^3 / 48E \cdot I \quad (2)$$

Based on this equation for beam deflection, the Modulus of elasticity for a composite laminate sample (Fig. 3) is calculated as in (3):

$$E = \frac{G_c \cdot L_c^3}{48 I_c (y_{c2} - y_{c1})} \quad (3)$$

and the gradient of the force-deflection relation (G_c) and moment of inertia (I_c) of the composite laminate are calculated from (4) and (5) respectively.

$$G_c = \frac{F_{c2} - F_{c1}}{y_{c2} - y_{c1}} + S_c \quad (4)$$

$$I_c = \frac{b \cdot (h + t_1 + t_2)^3 - h^3}{12} \quad (5)$$

where F_{c1}, F_{c2}, y_{c1} and y_{c2} are as defined in (1), but valid for the composite laminate. The parameter S_c in (4) stands for the setup compliance of the test rig. It serves as a compensation for the possible unreliability of the test setup. The other dimensional parameters of the composite laminate are as illustrated in Fig. 3.

IV. Test Equipment, Materials and Methods

Diverse mechanical tests were conducted to ensure that the used composite material fulfills the strength and energy absorption requirements of the monocoque structure for the FS competition. The primary tests reported in this article consist of 1) 3-point bending test, 2) perimeter shear test and 3) energy absorption test.

A. 3-Point Bending Test

The 3-point bending test was conducted using Instron 5980 universal test machine. Conducting this test, which can be modelled as a beam simply supported at the ends and carrying a load at its beam center, is relatively simple. As a result, several tests can be conducted at low effort to find the material characteristics such as bending stress, strain and rigidity (in terms of elastic modulus in bending). The test setup and dimensions used in this experiment are given in Fig. 4.

In total, 64 bending tests were carried out by varying the parameters such as type of carbon fiber, core material thickness, core material density, lay-up, etc. The selected densities and thicknesses of the PVC core material used in the test are also given in Table II.

Among the conducted tests, 26 of them were on Hexcel type carbon fiber while the rest 38 were on Toray type. The carbon fibers were delivered by Hexcel Corporation and Saertex respectively.

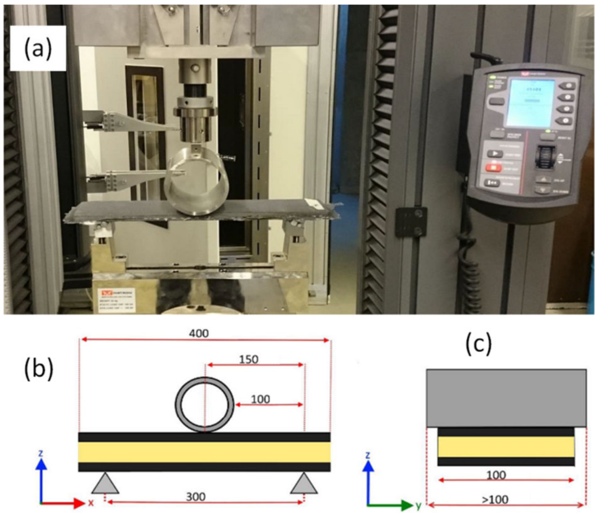

Fig. 4 (a) Test setup for the 3-point bending test, (b) and (c) sample dimensions in front and side views respectively

TABLE II
DENSITIES AND THICKNESS OF PVC CORE MATERIALS USED IN THE TESTS

Designation	H80	H100	H130	H200
Density (kg/m^3)	80	100	130	200
Core material thickness (mm)	15	5.6	5.6	5.6
			11.2	11.2
			25	25

The main differences between these fibers are the orientation of the windings and the weight per unit area (m^2). To make further investigation of the fiber materials, both types were studied using scanning electron microscopy (SEM) and the obtained images are shown in Fig. 5.

The interfacial adhesion in a laminate of composite materials highly depends on the type of the core material. Due to the attractive strength properties and availability on market, in contrast with their reasonable prices, Epikote 235 type Epoxy resin was) of a laminate consisting of HexForce 43245 and selected for the monocoque production. A microscopic image (in SEM Epikote 235 (Fig. 6) shows that the fibers are completely impregnated by the matrix (PVC core). This is expected to enhance the mechanical interlocking between fiber and matrix.

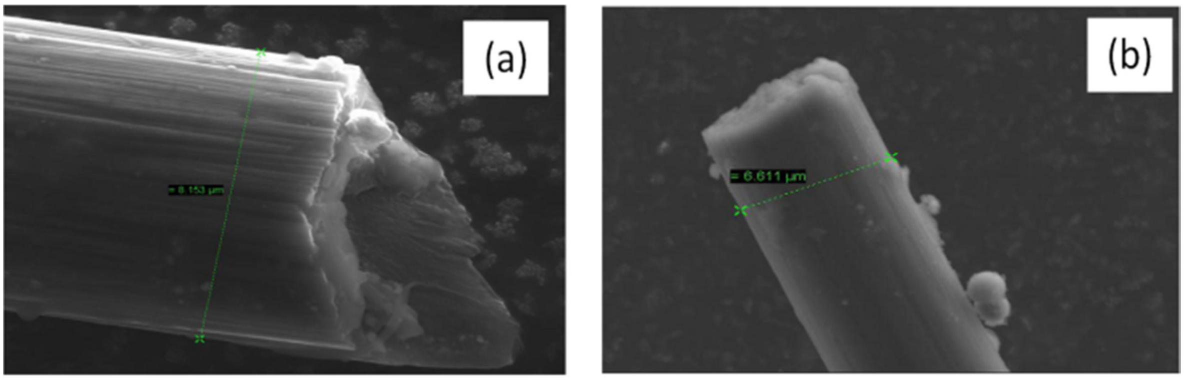

Fig. 5 SEM images of (a) Hextow AS4C and (b) Toray T700 fibers

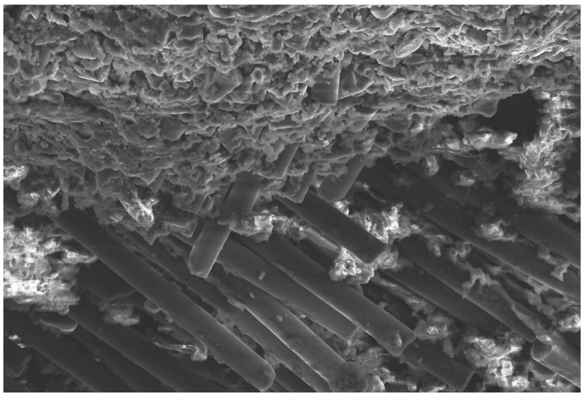

Fig. 6 SEM image of a laminate

B. Perimeter Shear Test

Conducting perimeter shear test of composite laminate used in the monocoque design is a requirement of the competition rule. Thus, the target is to find out the maximum force (F_{max}) that can penetrate the upper (outer) fiber of the laminate (Fig. 7). In particular, perimeter shear test is an important test required for the side impact laminate in order to protect the driver from possible penetration of objects in case of a collision. The test was conducted on Instron 5980 press machine by forcing a cylindrical extruder of 25 mm diameter through the test sample at a rate of 20 mm/min. To ensure complete penetration of the test sample during the test, an aluminum plate with a symmetrical hole of 32 mm was placed beneath the test sample (Fig. 7).

Based on the results of the 3-point bending test, i.e. those samples that fulfil the requirements from Toray fiber were selected and by combining the other parameters, as discussed in the previous section, 35 samples were tested. The force-deflection profile of the samples under loading is expected to be as illustrated in Fig. 8. Upon obtaining the force F_{max} that penetrates the upper fiber, the value is further used to calculate the shear stress (6) and compare with the value stated in the rule.

$$\text{Shear stress} : \tau = F_{\max} / \pi D t \tag{6}$$

where, D = 25 mm is diameter of the extruder and t = thickness of the upper carbon fiber.

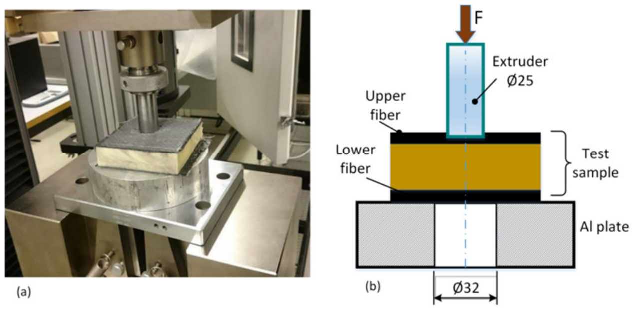

Fig. 7 (a) Test setup of perimeter shear test and (b) Illustration of parts in the setup

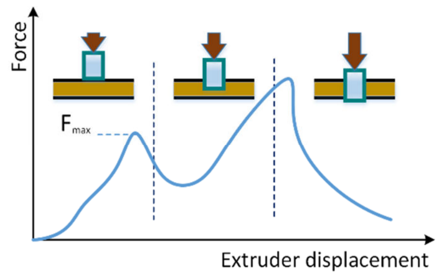

Fig. 8 Force-displacement relation in perimeter shear test

V. Discussion of Results

One of the critical requirements of the competition rules is that the laminate used to construct the monocoque frame should absorb more energy than the reference steel tubes. Thus, a number of tests were conducted on steel tubes commonly used for framed chassis design. Fig. 9 shows the plot of the bending force against deflection of one of the tests conducted on E235 steel. Based on the 3-point bending test results, the absorbed energy can be calculated from the plot of the bending force against the deflection. The test on these reference tubes provided the following values:

- maximum load, F_{max} = 9092 N,
- absorbed energy = 98.2 J,
- bending stiffness, EI = 4.03E+08 Nmm^2 and
- setup compliance, G_s = 6131 Nmm.

The obtained results, in both 3-point test and perimeter shear test, are studied to figure out the influence of selected parameters such as fiber lay-up, core material thickness, and mass density on the key performance criteria – bending deflection, maximum load at specified deflection and absorbed energy. The plots given below (Fig. 10) are extracts from the conducted several tests.

A. Results from 3-Point Bending Test

Influence of the laminate lay-up: To explore the relation between the used fiber lay-up and the stated performance parameters – maximum load, maximum deflection and the absorbed energy – during the 3-point bending test, the test value of selected samples (Table III) of identical mass density H80 were plotted.

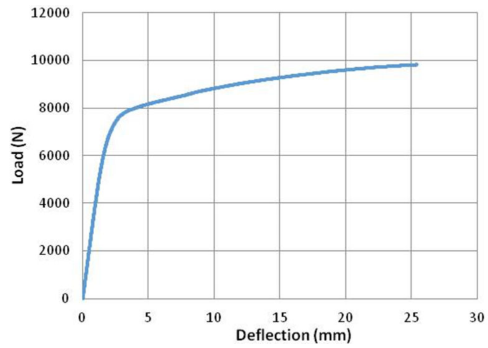

Fig. 9 Plots of 3-point test for reference steel tubes (E235)

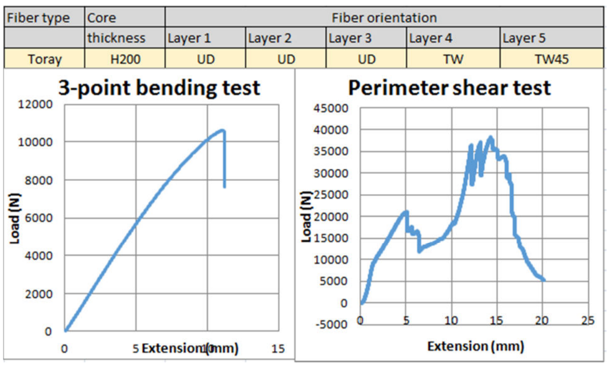

Fig. 10 Plots of 3-point test and shear test for a fiber sample of Toray

TABLE III
LAY-UP AND TEST RESULTS OF SELECTED SAMPLES

Sample nr.	Layer 1	Layer 2	Layer 3	Max. load (N)	Deflection (mm)	Absorbed energy (J)
8	TW90	TW45	UD	2194.8	8.06	10.54
9	UD	TW45	TW45	1996.6	8.90	11.35
10	TW45	TW	TW45	2035.8	10.81	13.45
11	UD	TW90	TW45	2467.8	7.87	11.29
12	TW90	UD	TW45	2141.0	7.75	10.98
18	UD	TW90	TW90	2050.8	8.25	11.69.

Closer study of the plots in Fig. 11 reveals lack of clear relationship between the laminate lay-up and the maximum load carried by each laminate. On the other hand, sample nr. 10, the only sample that does not contain UD (unidirectional) fibers, deform highest (about 28% over the average) and absorbed the highest amount of energy. As a result, it may be concluded that UD fibers increase the strength of the laminate, while no clear image is observed from the other lay-up orientations.

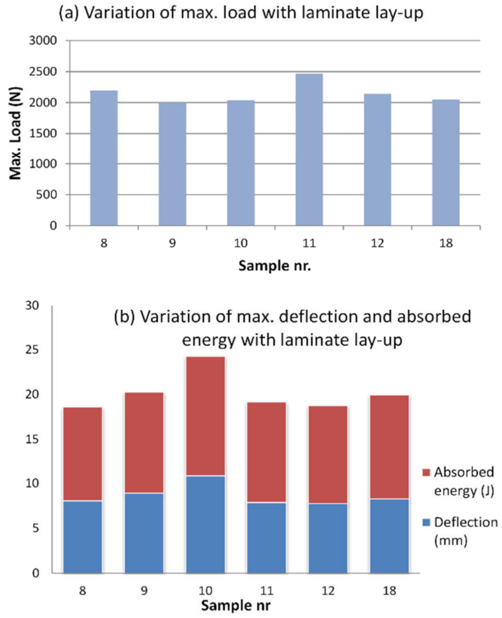

Fig. 11 Variations key parameter as a function of laminate lay-up

Influence of Core Material Thickness: To study the influence of the thickness of the core material, the test results for six samples with identical lay-up and mass density were compared in terms of the key performance parameters (Table IV). To enable better visualization, the results are plotted against the thickness of the core material together with their trend lines as shown in Figs. 12 (a)–(c).

TABLE IV
VARIATION OF PARAMETERS WITH CORE MATERIAL THICKNESS

Sample nr.	Thickness (mm)	Absorbed energy (J)	Max. load (N)	Deflection (mm)
2	11.2	22.70	4357.80	10.33
3	11.2	31.40	4974.00	12.20
4	5.6	36.93	3032.30	23.89
5	25.0	27.78	7772.80	6.95
25	11.2	20.08	4607.60	9,03
26	25.0	17.04	8096.90	5.74

The plot of the maximum load variation indicates that there exists strong relationship between the achieved maximum load and the thickness of the core material. This relation is nearly linear and the trend line shows a small deviation from the measured values. The proportional increment of the loads with the thickness can be attributed to the fact that the moment of inertia increases with an increasing thickness, which makes the sample stronger. Furthermore, larger bending deflections are expected for lower thickness core material. As shown in Fig. 12 (b), the relation between the deflection and the core thickness tends to be non-linear. The variation of the absorbed energy is similar to that of bending deflection, but the measured values are relatively scattered.

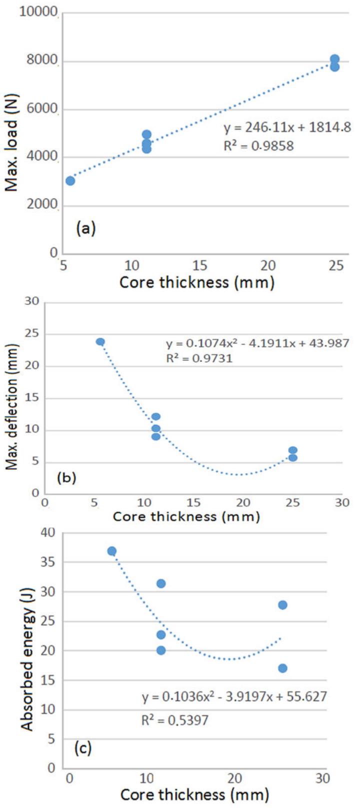

Fig. 12 Plot of performance parameters as a function of core material thickness (a) max. load, (b) max. deflection and (c) absorbed energy

Influence of Core Material Mass Density: To study the influence of the mass density of the core material, the test results for 3 pairs of samples (in total six samples) with identical lay-up and core material thickness of 5.6 mm were selected and compared in terms of the key performance parameters (Table V). The selected samples have mass densities of 100, 130 and 200 kg/m^3. The obtained results together with their trend lines are also plotted in Figs. 13 (a)-(c). As depicted in these plots, all parameters tend to increase with mass density of core material, but with a polynomial like function. This, in short, implies that a core material of higher density endures higher loads and absorbs higher energy when deformed.

TABLE V
VARIATION OF PARAMETERS WITH MASS DENSITY OF SAMPLES

Sample nr.	Density (kg/m^3)	Max. load (N)	Max. defl. (mm)	Absorbed energy (J)
43(1)	200	5531.33	15.26	35.19
43(2)	200	5202.81	18.63	50.48
44(1)	130	3924.10	14.80	30.44
44(2)	130	3952.30	15.80	32.97
45(1)	100	2568.00	10.51	17.16
45(2)	100	2872.50	11.03	17.52

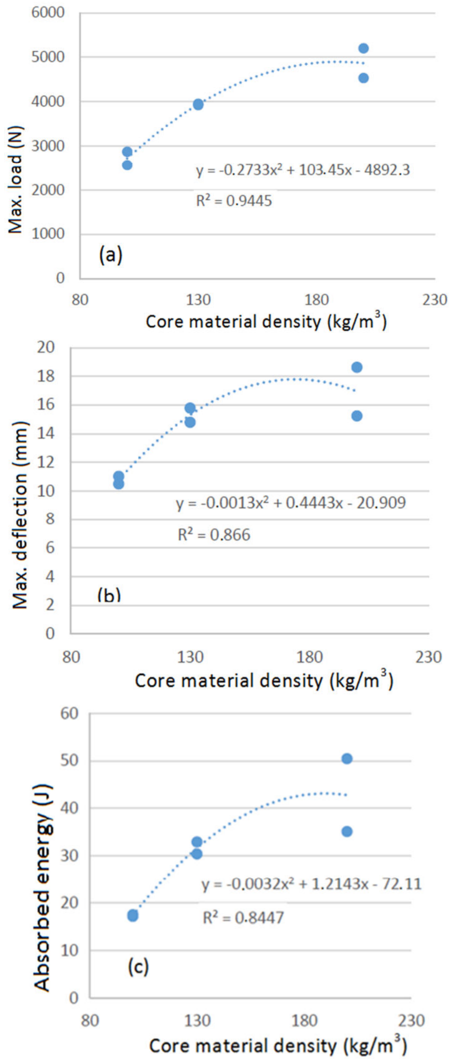

Fig. 13 Plot of performance parameter as a function of core material density (a) max. load, (b) max. deflection and (c) absorbed energy

B. Results from Perimeter Shear Test

Upon identifying, the composite laminate that fulfills the requirements of the competition rules on 3-point bending test, further tests were conducted to figure out if those laminates can also qualify for the perimeter shear test. Fortunately, all of them qualified the test. As stated earlier, only the Toray type fiber was tested. The key results in this test are the first and second maximum loads corresponding to the upper and lower layers of the carbon fiber.

VI. CONCLUSION

Intended to develop an appropriate sandwich structure for a monocoque chassis design, used in a Formula 1 type racecar for international student competition, diverse mechanical tests were conducted and some of the results of these tests are reported in this paper. The stated dimensioning criteria, according to the competition rules, are the maximum load, maximum deflection and size of absorbed energy at failure under 3-point bending test as well as the maximum force required to penetrate the upper layer of the laminate under perimeter shear test. The bottom-line is to get a lightweight laminate and fulfills the strength related criteria described in Section II of the paper.

The analysis of the test results indicated significant influence of the core material thickness and mass density on the dimensioning criteria where thinner core materials with higher density best fit for the purpose. On the other hand, the obtained results are subject to some uncertainties involving how the tests were conducted. These include possible errors in production process of the test samples and the test setup including implementation of the load applicator on downscaled test samples in the 3-point bending test. These and other areas of uncertainties in the test will be subject of further test and verification using more test samples in the next monocoque design.

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