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Design and Fabrication of Composite Monocoque Chassis for Formula Student Racing Car

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Abstract

This study used a combination of analytical, simulation, and experimental methods to design a sandwich-structured composite monocoque chassis. The analytical method, which determined the stiffness value of the composite, depended on the number of layers and the orientation of the fiber angle. The simulation method, based on the finite-element method, was used to validate the stiffness value. The experimental method involved a 3-point bending test that was used to verify the effectiveness of the design produced by analytical and simulation methods. After all model designs were validated through simulation and experimental methods, the next stage was monocoque chassis fabrication. The stiffness and strength were achieved with variations of combined layup orientation angles of 0° and 45°, which could be applied to all panels, regardless of the number of layers. Based on the design results, the processes involved in fabricating the monocoque chassis began with the manufacture of molds and the layup of carbon fiber. Afterward, the prototype was inserted in the oven and the final product experienced finishing to prepare it for use. The fabricated monocoque chassis was used in 2 events in Japan's annual Formula SAE student racing car competition.

Keywords: Monocoque chassis, sandwich-structured composite, 3-point bending, stiffness

1. Introduction

Automobile industries have been using composite materials in developing cars since 1980 [1]. During that time, the McLaren Formula One (F1) team vehicles used a carbon fiber-reinforced monocoque chassis. Its strength and safety were tested during a major car crash, where it saved the life of John Watson at the 1981 Italian Grand Prix held at Monza [2]. Consequently, the use of composite materials was expanded into manufacturing many other components of F1 vehicles [3]. In addition to F1 racing cars, well-known automotive manufacturers such as McLaren, BMW, GM, and Lamborghini now utilize carbon fiber composites in various parts of cars [4].

The main advantage of the composite monocoque is that it significantly increases stiffness without sacrificing weight. Increasing stiffness is essential in improving vehicle handling performance and fuel economy. However, achieving a monocoque chassis depends on the exact number and orientation of layers [5, 6], the manufacturing process [7], and production costs [8].

The design and tilt orientation of carbon fiber, as well as the number of layers, play an essential role in producing a sandwich-structured composite with lightweight and high stiffness. There is a concern that using composites solely based on previous designs does not produce the desired performance. Therefore, the design and manufacturing processes must be combined as a single approach to achieve practical automotive components of vehicles made from composites [9].

Sandwich-structured composite is a class of composite material made by attaching a lightweight core (aluminum honeycomb) between two thin laminate skins. The core is typically a low-strength material of high thickness, providing a sandwich composite with high flexural stiffness at low overall density. The sandwich-structured composites have been utilized on the body of vehicles in student car competitions, such as the student solar-powered cars [10, 11], and student racing cars [12–14].

Several studies explained how the monocoque composite design process was carried out using analytical [15], experimental [12, 13, 16], and simulation methods [11, 17–19]. A combination of experimental and simulation methods was carried out for the suspension connection zone of the monocoque chassis [20]. However, no publications fully explain all the processes from the initial design to the final fabrication. Therefore, this study presents a combination of analytical, experimental, and simulation methods for the design process of sandwich-structured composites. The results can then serve as a guide for fabricating sandwich-structured composites for

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monocoque chassis.

The analytical method, which determined the stiffness value of the sandwich-structured composite, depended on the number of layers and orientation of the fiber angle. A finite-element method of the simulation was performed to validate the stiffness value. Furthermore, the effectiveness of the designs produced by analytical and simulation methods was verified using the experimental method. Design effectiveness is checked by 3-point bending experimental parameters, such as yield load, stiffness, ultimate load, etc.

The design of the sandwich-structured composite consisted of several models that depend on their placement in the monocoque chassis. The model was designed and confirmed through simulation and experimentation before entering the fabrication stage. The fabrication stage started with the mold making and the lay-up process of carbon fiber, after which the prototype was inserted in the oven, and the final product then underwent the finishing stage to prepare it for use. The fabricated monocoque chassis was used in 2018 and 2019 Japan's annual Formula Student engineering competition.

2. Method

Sandwich-structured composites were designed to perform efficiently at an optimal weight without losing strength and rigidity. This design enabled the composite to withstand shock, vibration loads, and bending. A simple sandwich-structured composite consisted of 3 parts, two skin carbon fibers and one core from the aluminum honeycomb, which were joined together using adhesive films, as shown in Figure 1.

The core was the filler of a sandwich-structured composite. Adding it increased the thickness without a significant mass, so the composite attained good stiffness. The resulting sandwich-structured composite cores required good flexural strength and high interlaminar shear strength without sacrificing weight. Aluminum honeycomb made from 5056, 5052, and 2024 series aluminum alloys were the main core often used as composites in the aviation and automotive industries because it offered high rigidity and significant weight reduction if properly manufactured.

The properties of aluminum honeycomb and carbon fiber were shown in Table 1. The skin material used in this study was carbon fiber XPREG XC110 with two different densities, namely 210 g/m^3 and 416 g/m^3. The core material was an aluminum honeycomb with a density of 83.3 kg/m^3. The dimension of the 3-point bending specimen used was 500 mm×275 mm with a distance of 400 mm between the two supports.

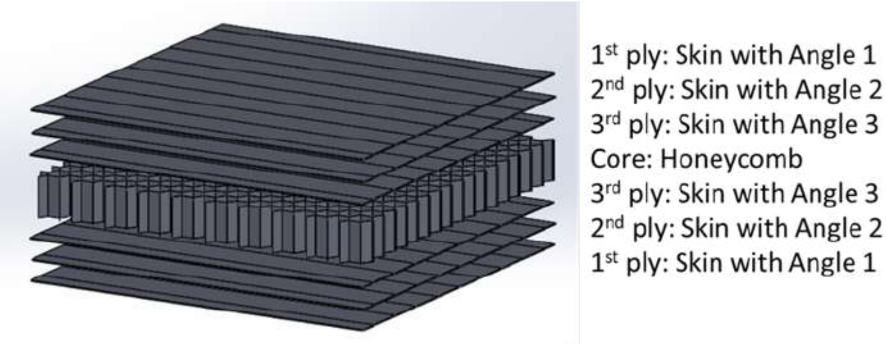


Figure 1. Illustration of a sandwich-structured composite panel.

Table 1. Material properties of skin and core.

Material	Symbol	Description	Value	Dimension
Lamina	E_1	Youngs Modulus, 1-axes	55.1	GPa
Lamina	E_2	Youngs Modulus, 2-axes	55.1	GPa
Lamina	ν_{12}	Poisson's Ratio	0.042	-
Lamina	G_{12}	Shear Modulus	4.21	GPa
Lamina	F_{1t}	Tensile Strength, 1-axes	521	MPa
Lamina	F_{2t}	Tensile Strength, 2-axes	521	MPa
Lamina	F_{12}	Shear Strength	132.6	MPa
Core	G_L	Shear Modulus, L Direction	445	MPa
Core	G_W	Shear Modulus, W Direction	240	MPa
Core	F_L	Shear Strength, L Direction	2.48	MPa
Core	F_W	Shear Strength, W Direction	1.45	MPa

There were several possible design variations of a monocoque chassis that used carbon fiber regarding fiber direction and stacking sequence. Therefore, it was important to find the most efficient variation. The initial orientation of the specimen was based on the general theorem of carbon fiber, which stated that when the carbon fiber was in the loading direction, thus having maximum stiffness and a higher ability to withstand the load. To ensure the final weight of the chassis was significantly reduced, the minimum number of layers that produced high stiffness was used for composite fabrication.

In this study, the 13 stacking sequences of laminates depended on the placement of the panels in the car. This was because the number of layers and their orientation were required to determine the stiffness value at each location. The stiffness was determined by the 3-point bending test, which was carried out using analytical, simulation, and experimental methods.

Based on Figure 2, the analytical method used Equation (1) to determine panel stiffness. The geometric value of the sandwich beam and the E_f value needed to get panel stiffness were obtained from Equation (2). The value of E_f depended on E_x, which was obtained by substituting the values of A_{xx}, A_{xy}, and A_{yy} derived from Equation (3). The Q_{ij} needed to find A_{ij} was obtained from Equations (4) – (6).

$$\frac{W}{\Delta} = \frac{24E_f btd^2}{L^3} + \frac{4bhG_L}{L} \tag{1}$$

$$\overline{E}_x = \frac{1}{h}\left[A_{xx} - \frac{{A_{xy}}^2}{A_{yy}}\right] \tag{2}$$

$$A_{ij} = \sum_{k=1}^{n} {Q_{ij}}^k (z_k - z_{k-1}) \tag{3}$$

$$\overline{Q}_{xx} = U_1 + U_2 \cos 2\theta + U_3 \cos 4\theta \tag{4}$$

$$\overline{Q}_{xy} = U_4 - U_3 \cos 4\theta \tag{5}$$

$$\overline{Q}_{yy} = U_1 - U_2 \cos 2\theta + U_3 \cos 4\theta \tag{6}$$

Furthermore, U_1 to U_4 values were obtained through Equations (7) – (10). The values of Q_{11}, Q_{12}, and Q_{66} required to get U_1 to U_4 were obtained through Equations (11) – (14).

$$U_1 = \frac{1}{8}(3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}) \tag{7}$$

$$U_2 = \frac{1}{2}(Q_{11} - Q_{22}) \tag{8}$$

$$U_3 = \frac{1}{8}(Q_{11} + Q_{22} - 2Q_{12} - 4Q_{66}) \tag{9}$$

$$U_4 = \frac{1}{8}(Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66}) \tag{10}$$

$$Q_{11} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \tag{11}$$

$$Q_{22} = \frac{E_2}{1 - \nu_{12}\nu_{21}} \tag{12}$$

$$Q_{12} = \frac{\nu_{12}E_1}{1 - \nu_{12}\nu_{21}} \tag{13}$$

$$Q_{66} = G_{12} \tag{14}$$

A finite element-based software was used in performing the simulation method. The geometry of the 3-point bending specimen was first created using the CAD software and then exported to the FEM software. In the mesh formation stage, the mesh size was set to 10 mm for a quadrilateral-type mesh. The laminated material was produced by determining the specifications of the fabric, such as thickness, material type, and modulus. Furthermore, the Rosette was used to determine the direction of composite thickening and the orientation of the laminate layup. The part to be made into a laminate was determined using the oriented selection sets. Meanwhile, it was necessary for the support and loading of the 3-point bending specimen to be adjusted during the modeling stage, as shown in Figure 3. The value of deflection that occurred, which was derived from the simulation results, was then processed to obtain the stiffness of the composite panel.

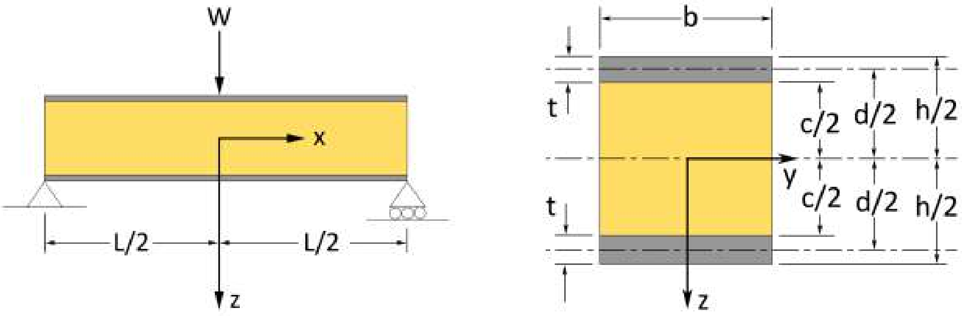
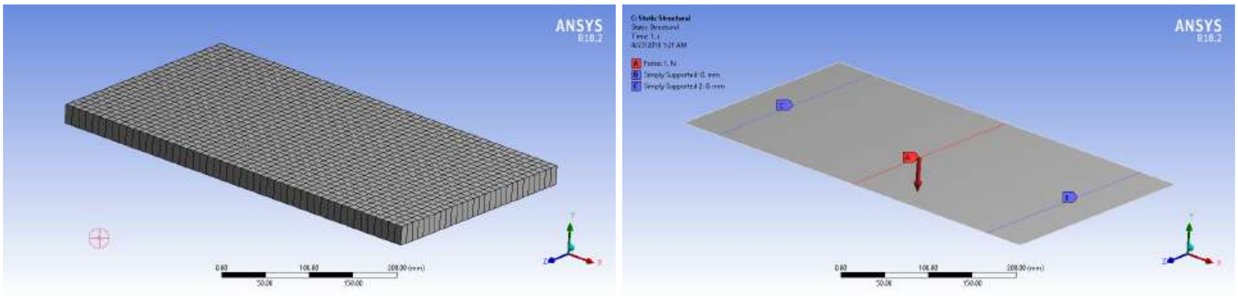


Figure 2. Composite models for analytical methods: (a) three-point bending, (b) sandwich-structured [15].



(a)

(b)

Figure 3. Simulation process: (a) meshing, (b) supports placement and 3-point bending simulation loading.

In the experimental procedure, the specifications of certain equipment were based on the American Society for Testing Materials (ASTM) D2344 standard, short-beam strength of high-modulus fiber-reinforced composite materials. The 3-point bending test was used to determine the stiffness of the sandwich panels used to replace the standard FSAE space frame. From the results of the simulation and analytical methods, experiments were carried out on specimens that were proven to have high stiffness, as shown in Figure 4. The experimental results were in the form of Force F versus displacement graphs. The experimental results were calculated using equations to determine the stiffness values. The result of the experiment was a sandwich-structured composite specimen that could be used for cars.

The fabrication process of the monocoque chassis consisted of 3 steps. The first step was to create a positive model and a master model. The positive model was created using a CNC machine, which used a fiberglass material to obtain a solid model similar to a car's shape. The master model was made as a mold for the monocoque chassis. The second step involved installing an aluminum honeycomb as the core and creating a monocoque chassis using the layup method with a predetermined number of layers and layup orientation. After the layup process was completed, the third step was to insert the layup and the master model in the oven for a heating vacuum process according to the temperature determined by the material.

3. Results and Discussion

Before fabricating the monocoque chassis, the design of the sandwich structures must meet the required standards for stiffness and strength. For this reason, the results from analytical, simulations, and experimental methods were required to be further analyzed. Table 2 showed the stiffness values of the analytical and simulated panels for several variations. As the layup orientations increased at an angle of 45°, the stiffness value decreased.

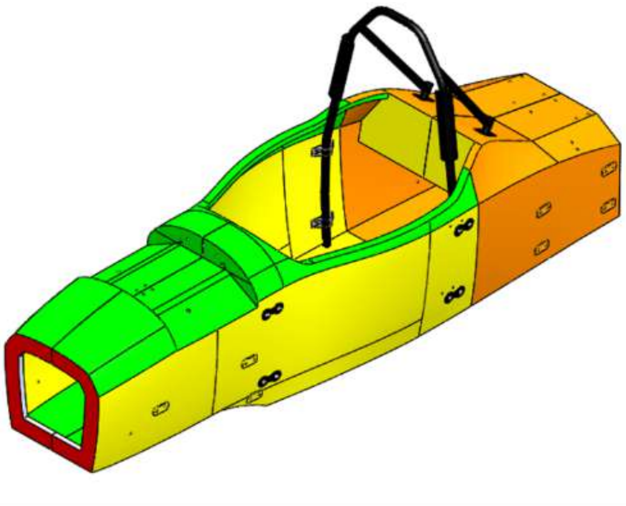
Figure 4. Specimen setup for 3-point bending experiment.

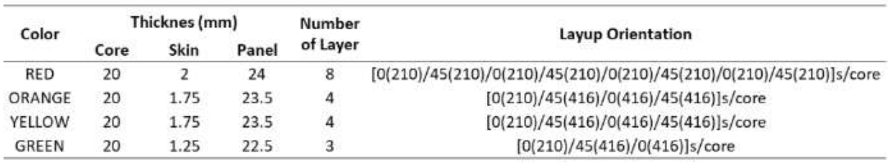
Table 2. Panel stiffness value from simulation and analytical methods.

No.	Number of Layer	Layup Orientation	Panel Stiffness from Simulation (N/mm)	Panel Stiffness from Analytic (N/mm)
1	3 Layer	[0(210)/0(416)/0(416)]s/core	4414	2872
2		[0(210)/45(416)/0(416)]s/core	3476	2323
3		[0(210)/45(416)/45(416)]s/core	2372	1466
4	4 Layer	[0(210)/0(416)/0(416)/0(416)]s/core	6148	4042
5		[0(210)/0(416)/45(416)/0(416)]s/core	5234	3541
6		[0(210)/45(416)/0(416)/45(416)]s/core	4339	2859
7		[0(210)/45(416)/45(416)/45(416)]s/core	3098	1875
8	5 Layer	[0(210)/0(416)/0(416)/0(416)/0(416)]s/core	7872	5226
9		[0(210)/0(416)/45(416)/0(416)/0(416)]s/core	7073	4755
10		[0(210)/45(416)/0(416)/45(416)/0(416)]s/core	6555	4158
11		[0(210)/45(416)/0(416)/45(416)/45(416)]s/core	5709	3374
12		[0(210)/45(416)/45(416)/45(416)/45(416)]s/core	4502	2299
13	8 Layer	[0(210)/45(210)/0(210)/45(210)/0(210)/ 45(210)/0(210)/45(210)]s/core	9655	6591

This study showed that the layup orientation should not only be at 0° or 45° alone because of the strength reduction. A combined layup orientation of 0° and 45° was the variation required to meet the desired stiffness and strength specifications. This applied to all panels, regardless of the number of layers. The layer variations selected for each panel were applied to different positions in the car, as shown in Figure 5.

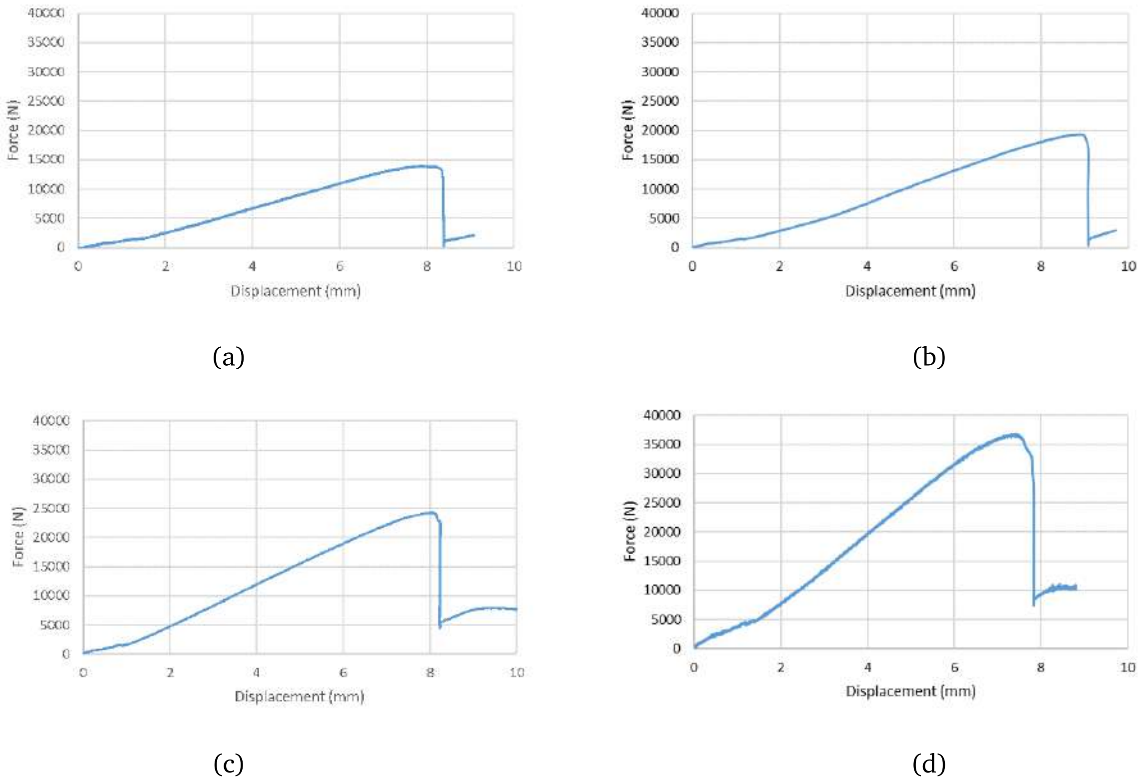
The test specimens for the 3-point bending experimental method were manufactured. Furthermore, the experimental results for the entire specimen were illustrated using a graph of load versus deformation (displacement), as shown in Figure 6. In determining the stiffness value of each panel, it was necessary to calculate the gradient, which was regarded as the stiffness, using at least three points on the graph. Figure 7 showed that panels with more layers had greater stiffness values, which corresponded to the analytical and experimental results.





Color	Thicknes (mm)			Number of Layer	Layup Orientation
	Core	Skin	Panel		
RED	20	2	24	8	[0(210)/45(210)/0(210)/45(210)/0(210)/45(210)/0(210)/45(210)]s/core
ORANGE	20	1.75	23.5	4	[0(210)/45(416)/0(416)/45(416)]s/core
YELLOW	20	1.75	23.5	4	[0(210)/45(416)/0(416)/45(416)]s/core
GREEN	20	1.25	22.5	3	[0(210)/45(416)/0(416)]s/core

Figure 5. Location and layup orientation of panels in monocoque chassis.



(a) (b)

(c) (d)

Figure 6. The results of the 3-point bending experimental method on the panel: (a) 3 layers, (b) 4 layers, (c) 5 layers, (d) 8 layers.

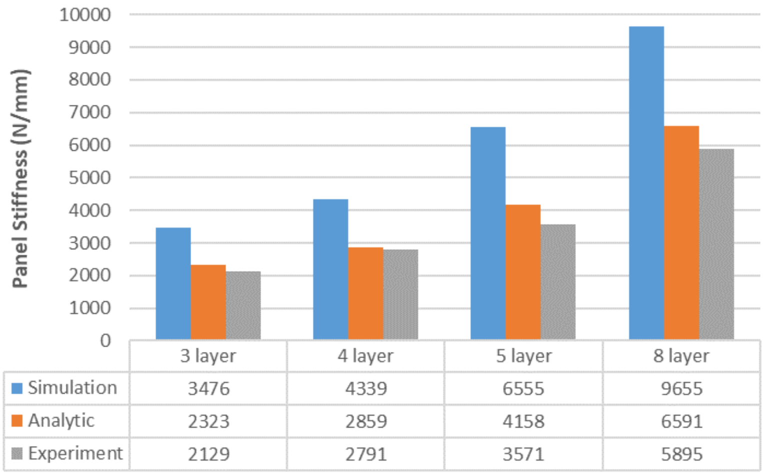


Figure 7. Comparison of panel stiffness values from simulation, analytical, and experimental methods.

A comparison graph between the stiffness values from experimental, analytical, and simulation results was also shown in Figure 7. It was observed that the analytical and experimental methods were in better agreement compared to the simulation method. The major difference was that in the simulation method, the loading was in the form of a line, whereas the loading was in the form of a 100 mm diameter circle in the experimental method. The agreement between the analytical and experimental methods was due to the perfect bonding state between the skin and core, determined by the percentage of resin between them.

After the design of the sandwich-structured composite was validated by analytical, simulation, and experimental methods, the next stage was the fabrication of the monocoque chassis. The result of the first fabrication stage was creating a positive model using machining, as shown in Figure 8, to obtain a master model, as shown in Figure 9. The inner surface of the master model corresponded to the outer surface of the monocoque chassis.

Figure 8. Master model making (a) machining, (b) positive model.

Figure 9. Master model of monocoque chassis.

The next step was to install the carbon fiber and aluminum honeycomb in the master model. The carbon fiber used was the prepreg, which already contained resin. The installation was carried out by attaching the carbon layer to the master model with sticky resin, as shown in Figure 10. Difficulties in the installation were observed when the position of the master model was located above the carbon layer. The attachment of the honeycomb to carbon fiber was shown in Figure 11. The honeycomb was nailed in several places to ensure it stayed in place. Some difficulties were encountered because the honeycomb was frequently detached from its initial position, where the cutting pattern of the honeycomb must be similar to the master model.

The third step was curing using an oven, as shown in Figure 12. During the process, the carbon layer was vacuumed to ensure it was compressed and followed the contours of the master model. The difficulties encountered were the frequent adjustment of the vacuum plastic to prevent it from getting strained or torn, as well as the recurrence of small leaks in the vacuum bagging plastic. Furthermore, finishing processes must be carried out after removing the monocoque chassis from the oven. The finished monocoque chassis assembled with the wishbone could be seen in Figure 13. The final result was a monocoque chassis used in two different FSAE events in Japan.

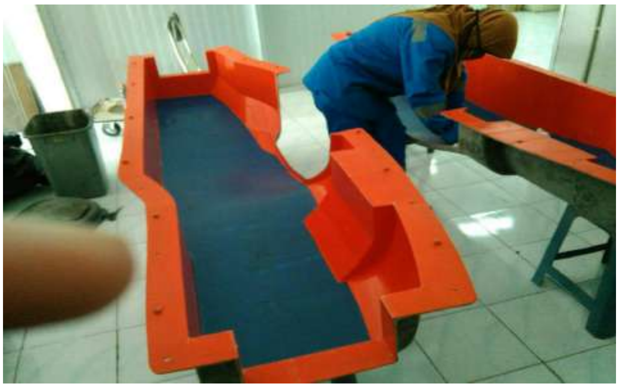


Figure 10. Carbon fiber attachment to the master model.

Figure 11. Honeycomb attachment to master model.

Figure 12. The curing process of the monocoque chassis.

Figure 13. Monocoque chassis after finishing process.

4. Conclusion

The steps for designing and fabricating a monocoque chassis using a sandwich-structure composite were described in this study. The stiffness parameter resulting from the 3-point bending on a sandwich-structure composite panel was determined through analytical, simulation, and experimental methods. The results from the design stage show that the combination of layup orientation of 0° and 45° on 3 layers, 4 layers, 5 layers, and 8 layers had the appropriate stiffness and strength. Based on these results, the monocoque chassis was fabricated, starting with mold making and the carbon fiber layup process, which continued with the aluminum honeycomb installation. Afterward, the prototype was inserted in the oven and the final product experienced finishing to prepare it for use.

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