Fabrication and Structural Equivalency Analysis of CFRP Nomex Core Sandwiched Panels for FSAE Race Car Chassis

Muhammad Yaqoob[1]
University of New South Wales at the Australian Defence Force Academy

Composites sandwich structures have been increasingly used in applications where high strength and stiffness to weight ratio is required to reduce weight for energy saving and optimum performance purposes. Aim of this project was to manufacture a sandwich panel with carbon fibre reinforced plastic (CFRP) skins and a Nomex honeycomb core using the wet layup method and to test it against the requirements specified in FSAE Rules for side impact and front bulkhead monocoque structures of car chassis. Investigations were made into different skin thicknesses to choose best skin thickness for the sandwich panel to improve its weight and characteristics. Tests conducted on sandwich panels were shear perimeter test and three-point bending test. From previous work and testing, shear perimeter test was found as a limiting case out of the two tests. Results showed that selected material passed both tests and was far above the baseline material and Aluminium honeycomb sandwich panel which were tested last year. From results it was established that shear perimeter strength of sandwich panel depends upon skin thickness whereas, energy absorbed by the panel during testing process is dependent upon the thickness of the core. Failure modes of CFRP-Nomex sandwich panels were quite different than Aluminium sandwich panels. In shear perimeter test, CFRP layers in each skin failed individually which was evident from kinks in the graphs. Results also indicated that CFRP material is weaker in compression than in tension.

Contents

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[1] FLG OFF, School of Engineering & Information Technology, ZEIT4500

I. Introduction

In the past few decades, an increased trend has been seen in replacing conventional materials like metals, ceramics and woods by composites [1]. Composite materials offer numerous advantages over conventional materials. Composite materials can be difficult and costly to produce and process, but they provide better weight saving solutions when compared to conventional materials. [5, 6].

Composites sandwich structures have been increasingly used in applications where high strength and stiffness to weight ratio is required. The typical sandwich structure/panel comprises of a low-density core and two thin face sheets. Face sheet material can be metallic, or a fibre reinforced composite laminates and typical core material used is metallic or aramid honeycomb structure, polymeric foam or balsa wood. [3, 10]. Sandwich structures with advantageous properties can be manufactured using a light weight core with shear rigidity and solid skins with significant in-plane compressive and tensile load bearing properties. Such a structure provides a combination with very high level of bending stiffness and reduced weight. These properties make sandwiched composite panels of great interest in applications where weight reduction is required for energy saving and optimum performance like aerospace, automotive and motorsports industries [2, 4].

II. Aim

Aim of this thesis was to manufacture a sandwich panel with carbon fibre reinforced plastic (CFRP) skins and a Nomex honeycomb core using the wet layup method and to test it against the requirements specified in FSAE Rules for side impact and front bulkhead monocoque structures of car chassis.

III. Background

A. Formula SAE and UNSW Canberra Involvement

The Society of Automotive Engineers (SAE) designed a competition to challenge teams of undergraduate and graduate students to conceive, design, fabricate, develop and compete with small formula style vehicles [35]. The competition was called Formula SAE (FSAE) and first held in 1978.

UNSW Canberra has been taking part in FSAE Competitions since 2003. Since then, the Academy Racing Team has been designing and manufacturing a car based on a steel monocoque chassis. In 2016, two final year students Matthew Walker and Nicholas Hood investigated the replacement of the steel monocoque chassis with an aluminium honeycomb panel chassis. Their design was implemented in 2017 and resulted in weight reduction of FSAE vehicle. There is prima facia evidence that further the weight reductions can be made by using CFRP-Nomex sandwich panels for a monocoque chassis.

B. FSAE requirements and Structural Equivalency Spreadsheet

The FSAE rules specify a set of requirements against which teams must manufacture suitable material for their cars chassis [9]. A team may choose any material for car chassis but needs to satisfy FSAE requirements for that material by performing tests listed in FSAE rules. Teams electing to comply these requirements are also required to submit a Structural Equivalency Spreadsheet (SES). SES is the means by which a team “must demonstrate that the design is equivalent to a welded frame in terms of energy dissipation, yield and ultimate strengths in bending, buckling and tension” [9, 35]. SES is Microsoft Excel workbook created by FSAE International made up of different worksheets. Specifications, physical properties of alternate design are entered into the SES and results generated can be compared with baseline material. In case of this project, alternative design material was CFRP Nomex honeycomb sandwich panel and tests performed were three- point bending test and shear perimeter test.

Table 1: Tests Required and Properties Measured

Test	Measured Property
Laminate testing (3-point bend)	Flexural rigidity
	Flexural Strength
	Energy absorption
Perimeter shear testing	Perimeter Shear strength

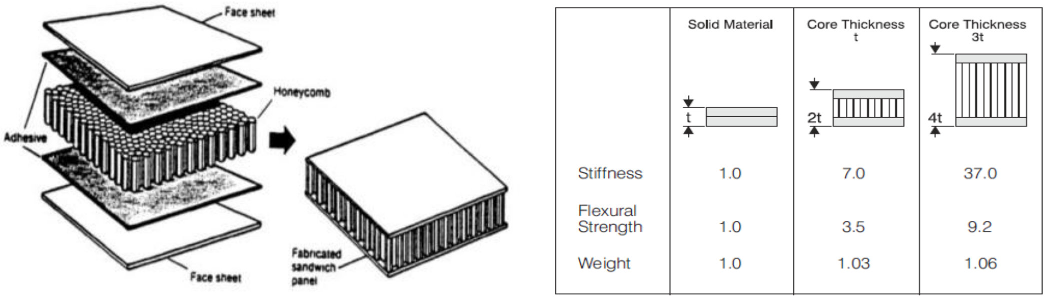
IV. Literature Review

For the scope of this project extensive literature review was conducted to understand and learn about characteristics, fabrication techniques of CFRP Nomex core sandwich panel and its individual components. The FSAE rules and testing procedures to be performed on test samples were also studied.

A. Sandwich Panel Theory

The concept of sandwich panel is to form a sandwiched structure by bonding thin, dense, and strong face sheets to a thick, light weight core using suitable adhesive [11]. Low density core improves flexural rigidity of sandwich structure without compromising weight constraints [12]. Each component of structure by itself is week and flexible in different directions but when bonded together, it becomes a strong, stiff, and light weight structure. For the scope of this project, CFRP/Epoxy were used as face sheets and light weight Nomex honeycomb core as a core material [11, 14].

It is assumed that bending modulus of skins is much greater than that of core and bending modulus of core E_C is assumed as zero. This assumption leads us to the conclusion that there will be uniform shear strength throughout the core thickness. Outer surfaces of skins will have highest bending stress and it will be zero in the middle. It is also interesting to see in Figure 1 how significantly stiffness and flexural strength increase by increasing core thickness with very little addition of weight [13].



	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Fig 1: Honeycomb Sandwich Panel Construction and Strength Characteristics [11, 13]

Basic formula for bending stiffness of sandwich structure is given below with assumption that there is uniformly distributed bending stress across thickness of skins, uniformly distributed shear stress across thickness of core and E_C and moment of inertia I_0 of core are negligible.

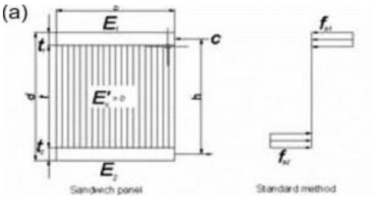


Fig 2: Sandwich Structure

$$Bending\ Stiffness = \frac{E_1 t_1 E_2 t_2 h^2}{E_1 t_1 \lambda_1 + E_2 t_2 \lambda_2}$$

Where E_1 and E_2 are the moduli of elasticity of the face1 and face 2 respectively, h is the distance between the centre line of the two faces and λ is a constant value which varies for different materials. [11, 12, 14]

Last year Aluminium sandwich panels with two core thicknesses of 20mm and 30mm and skin thickness of 0.5 mm each were tested for FSAE requirements. Both panels failed the tests, but thicker panel had higher bending stiffness and gave better results in terms of energy absorption. This year Aluminium sandwich panel with core thickness of 20mm and skin thicknesses of 1mm and 0.8 mm was tested, and it passed the shear perimeter test as thicker skins were used and shear perimeter strength depends upon the skin thickness.

B. CFRP, Matrix Materials and Their Properties

Fiber composites are seen as attractive alternative for metals due to their high specific strength, stiffness and excellent fatigue behavior. CFRP is used more commonly in structural applications than any other high-performance fiber composites due to their overall high specific strength and stiffness properties [22,25]. The mechanical properties of carbon fiber composites can be varied by choice of carbon fibers. Polyacrylonitrile (PAN) based carbon fibers are low cost, have higher failure strains and have overall good mechanical properties. Pitch based carbon fiber composites have superior stiffness and thermal properties [26]. Carbon fiber reinforcements can be manufactured in variety of forms which also affects the properties of overall composite system. These forms range from short chopped mats through a variety of woven fabric products to unidirectional tapes.

Matrix systems used with carbon fibers can either be thermosetting or thermoplastic. Thermosetting matrices undergo chemical change when cured. They have low strain to failure, low viscosity, and low fracture energy unlike thermoplastic matrices [23]. They also have high resistance to solvents and offer high moisture absorption. The advantages of thermosetting matrices over thermoplastic matrices are that they require relatively low processing temperature, are formable to complex shapes, resistant to creep and offer good fiber wetting. The disadvantages are long processing time and restricted storage life i.e. requires refrigeration [22,24]. For this project, thermosetting epoxy resin was selected as matrix material. Epoxy resin are class of compounds that contain two or more epoxide groups per molecule. Epoxy resins offer high reactivity and better cross-linking which translates into higher composites stiffness and glass transition temperatures. They offer low viscosity during curing which gives good wetting of the fibers. They are not prone to voiding and have good thermal and dimensional stability [23]. Epoxy matrices are normally used for applications where upper limit for temperature is 180-200 ^{O}C.

C. Honeycomb Cores, Materials and Their Properties

Honeycomb sandwich panels offer excellent fatigue resistance and shear rigidity and presence of core in the structure plays an important role. Honeycomb core can be manufactured by using any thin flat sheet of material. Materials which are used in manufacturing of honeycomb core are generally divided into two categories, metallic and non-metallic. Metallic materials include aluminum, stainless steel, and titanium whereas non-metallic cores include Kraft paper, Nomex, carbon fabric and fiberglass. For non-metallic cores, Nomex T-722 and 412 are used to make commercial and specification grade honeycomb respectively [11, 20]. Non-metallic cores are normally resin dipped and become very strong after cured. Most common resin used is phenolic resin whereas for high temperature applications, polyimide resin is used [19]. Other non-metallic cores include rigid foam and balsa wood cores but they offer inferior mechanical properties as compared to Nomex honeycomb core.

The commonly studied honeycomb properties are bare and stabilized compressive strengths and compressive modulus [9, 11]. Bare compressive strength is compressive strength without skins whereas stabilized compressive strength is with skins bonded on both sides. Stabilized compressive strength value is normally used for design purposes. For energy absorption applications crush strength is required which is roughly half of bare compressive strength. Other honeycomb properties include L and W plate shear strengths and moduli. L and W shear strengths are shear values along length and width direction respectively. L shear strength is roughly twice of W shear strength. The compressive properties and moduli do not change significantly with increase in thickness, but shear properties do. [11,21].

D. Skin-Core Bond in Honeycomb Sandwich Structures

Skin-core bond plays vital role in structural integrity of any sandwich construction. The inter-laminar shear strength and flatwise tensile strength largely depend upon the quality of adhesive bond between skin and core. In honeycomb structures, cell walls provide small area for bonding with skins. Formation of adequate fillet size has been recognized as primary goal of manufacturing of sandwich panels [32]. Quality of bond and structural strength becomes dependent on shape of adhesive fillet at the interface between skin and cell wall. High density honeycomb cores with smaller cell size provide relatively larger cell wall area for bonding and produce panels with higher flatwise tensile strength due to greater fillet area per unit panel area [34]. Grove at el. Showed that higher de-bonding was obtained with bigger adhesive fillet size [2,32,33]. It is also important to know that size of adhesive fillet increases with increase in cell size of core due to availability of larger amount of adhesive [2,34]. A schematic diagram of typical adhesive fillet is shown below.

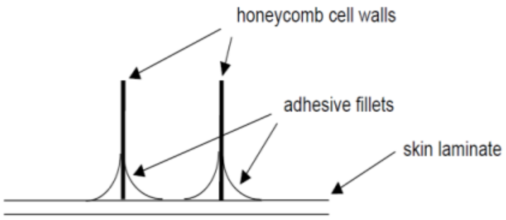


Fig 3: Location of Adhesive Fillet Between Honeycomb Cell Walls and Skin Laminate in Sandwich Construction [32]

V. Design and Fabrication of Sandwiched Panels

For this project, wet layup method was used to manufacture CFRP skins in the Composite Laboratory at SEIT UNSW Canberra and then skins were bonded to Nomex honeycomb core using epoxy adhesive to form sandwich panels. The relevant literature review for wet layup method has already been discussed in detail in the initial project report. Apart from literature review, analytical and experimental methods were used to determine to suitable skin thickness for sandwich panels.

A. Wet Layup Method

Different methods can be used for fabrication of CFRP skins which includes hot press, autoclave, and wet layup method depending upon the size and shape of sample to be manufactured. For the scope of this project, samples required to be manufactured were of size 500 X 275 mm and 100 X 100 mm. Larger samples could not be manufactured using hot press equipment in SEIT Composite lab due to size limitations. Due to complexity and lack of operating staff available, autoclave method was also ruled out. Thus, wet layup fabrication method was chosen for fabrication of required size samples. Apart from availability and size limitations, another main reason for choosing wet layup method was that it can be used to fabricate samples of complex shapes and design which will allow Academy Racing Team to manufacture chassis sized structure using prepregs at SEIT Composite Lab.

Wet layup is one of the oldest, simplest, and most commonly used method for fabrication of fiber reinforced composites. This method involves impregnation of dry fibers with suitable resin [29]. Resin selection is based upon different factors including compatibility with fibers, tensile strength, glass transition temperature, chemical resistance and cost [28,29]. Quantity of resin applied to fibers is usually varied between 40% to 60 % by weight. After impregnation of plies with resin, plies are stacked into required configuration [27,30]. Resin impregnated fibers are consolidated by using vacuum bagging method and then left to cure for few hours at room temperature [31].

The disadvantages of wet layup process observed during manufacturing phase were that it did not deliver consistent results in terms of skin thicknesses. Variation in thickness was observed across different skin samples fabricated. Possible reasons for that can be human errors i.e. application of unequal resin amounts to fabric cloth and errors during consolidation process i.e. different amount of pressure applied and curing time for different samples. Results with better consistency can be achieved by carrying out wet layup and consolidation process with more careful approach.

B. Fabrication of CFRP Skins

For the scope of this project, test specimen of two sizes 500 X 275 mm and 100 X 100 (3-4 samples each size) were required to be manufactured for three-point bending test and shear perimeter test respectively. After carrying out engineering analysis and shear perimeter test on 100 X 100 skin samples[2], it was decided to use four layers of carbon fabric in all skins to be used in sandwich samples. Using four layers of carbon fabric gave us skin thickness of 0.96-1 mm.

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[2] The detailed discussion of shear perimeter test on 100 X 100 skin samples is given in the Testing Section of the report.

A bigger mold was prepared for samples of 500 X 275 mm but mold configuration was kept same for both sample sizes. The only difference was that Mylar sheet was used for smaller samples to obtain better surface finish. Resin impregnated plies were consolidated by using vacuum bagging method and then left to cure at room temperature for few hours. The mold configuration was kept as follows:

- Aluminium plate as rigid base
- Mylar sheet to produce a high-quality surface finish and as a release surface
- Layers of the reinforcing fibers and the matrix forming the test sample
- Perforated release film to allow excess resin to move away from the test sample
- Breather cloth to allow consistent pressure distribution across the sample
- Vacuum bag material

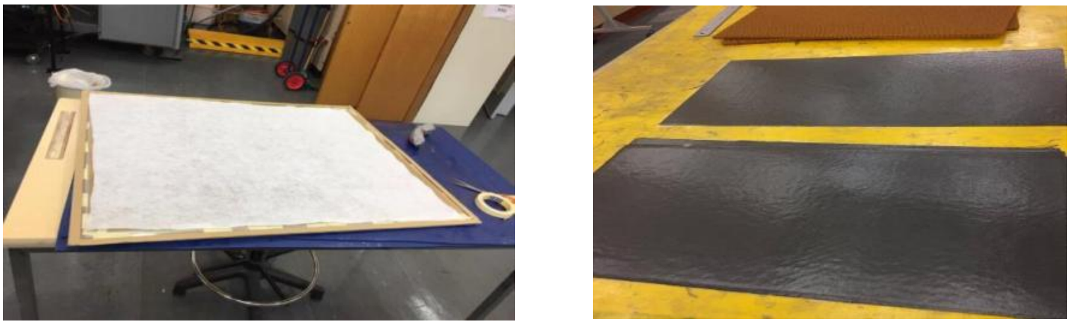

Fig 4 (L) to (R): Picture of Mold Frame and Fabricated CFRP Skins (500 X275 mm)

C. Skin-Core Bonding and Cutting of Sandwich Panels

Total of 16 CFRP skins with four plies per skin were manufactured in Composite Lab at SEIT, 8 skins for 500 X 275 mm and 8 skins for 100 X 100 mm test samples. Once all skins were fabricated, next step was to bond the skins to Nomex honeycomb core to form sandwich panels (test specimen). Adhesive used to bond the skins with core was Loctite EA 9309 Epoxy Aero Paste Adhesive. It was important to apply adhesive on CFRP skins in such a way that adequate adhesive fillets are formed after bonding as quality of bond and structural strength becomes dependent on shape of adhesive fillet at the interface between skin and cell wall. Bonded sandwich panels were required to cut into 500 x 275 mm and 100 x 100 mm test samples for testing purposes. Cutting of sandwich panels were carried out at SEIT using diamond saw which uses water to avoid heating effects on cutting edges.

Table 2: Epoxy Adhesive EA 9309 Properties

Epoxy Adhesive (EA 9309)	Viscosity (Pa.s)	Peel Strength (N/25mm)	Tensile Strength (MPa)	Compressive Strength (MPa)	Poisson Ratio	Glass Transition Temp (°C)
Mixed (Cured)	12	396	31	43	0.38	53

Note: For further details see Appendix A

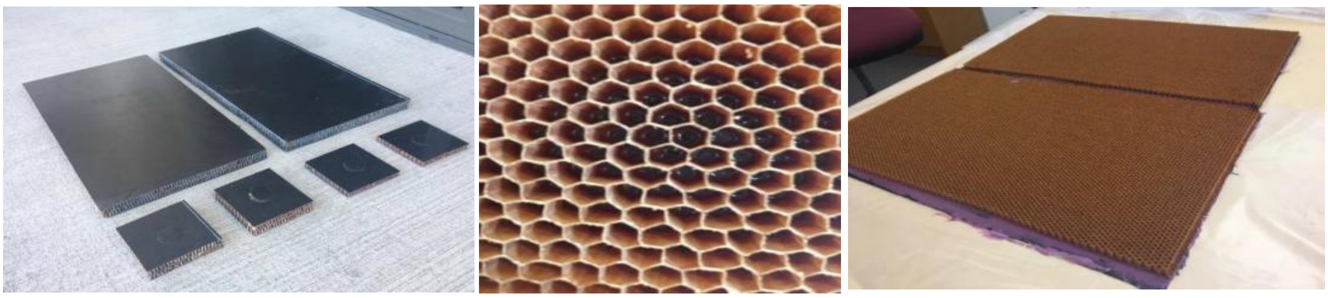

Fig 5 (L to R): Single and Double Core CFRP-Nomex Sandwich Panels, Depiction of Formation of Adhesive Fillets and Boding of CFRP Skins to Nomex Honeycomb Core

VI. FSAE Requirements and Testing of Sandwich Panels

The FSAE rules specify a set of requirements against which teams must manufacture suitable material for their cars chassis [9]. The FSAE requires three-point bending and shear perimeter tests to be conducted on sandwich panels IOT to satisfy FSAE requirements for side impact structure and front bulkhead structure of monocoque chassis of the racing car. Detailed discussion of FSAE requirements for both tests can be found in the Appendix D.

Table 3: Tests Required and Performance Requirement

Rule/requirement/car location		**Test Type**	**Performance requirement**	
			Property	**Value**
Side impact structure	Side impact zone	Bending	Buckling modulus	3 baseline steel tubes
		Bending	Energy absorption	2 baseline steel tubes
		Shear Perimeter	Minimum shear force	7.5 kN
	Floor	Bending	Buckling modulus	1 baseline steel tube
Front bulkhead	Support	Bending	Buckling modulus	1 baseline steel tube
		Shear perimeter	Perimeter shear strength	4 kN
	Bulkhead	bending	Buckling modulus	Baseline steel tubes

[9]

A. Shear Perimeter Test

It was decided to conduct shear perimeter test because smaller samples were easy to manufacture and from engineering analysis and previous work it was determined that shear perimeter test was the limiting case. Shear perimeter test was required to be conducted to measure force required to push 25 mm diameter flat punch through the flat test sample. In order to pass the test, force required to push 25 mm diameter flat punch, is 7500 Newtons for side impact structure and 4000 Newtons for front bulkhead structure. Two batches of sandwich samples were tested of dimensions 100X100X12 mm and 100X100X22 mm. Test specimen were not clamped to the fixture and fixture supported entire test specimen except for 32 mm diameter circle coaxially aligned with the 25 mm diameter punch as mentioned in FSAE rules. [7, 35].

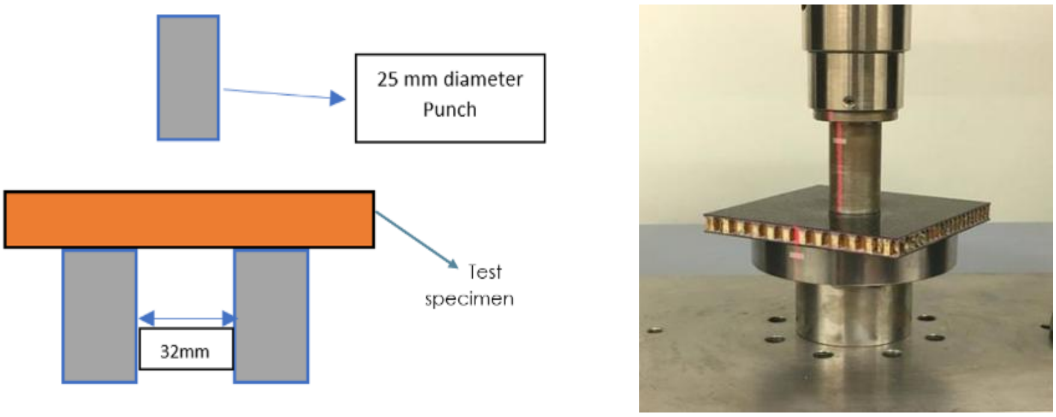

Fig 6: Shear Perimeter Test Assembly

The shear perimeter test was carried out on 50 kN Shimadzu Machine in Shimadzu Testing lab at SEIT. Laser equipment was used in test setup to measure deflections due to application of force for accuracy of results. The test was carried out under quasi-static loading conditions. The stroke rate was kept from 0.75-1 mm/min for all test samples.

1. *Shear Perimeter Test on CFRP Skins:*

As mentioned above, to determine suitable thickness for CFRP skins to be fabricated for actual test samples, shear perimeter test was conducted on two batches of CFRP skins samples of thickness of 0.50-0.52 mm, 0.75-78mm and 0.96-1.00 mm (2, 3 and 4 layers respectively). Both batches, A and B were fabricated using same techniques and same materials. The test conducted on skin samples not only helped to validate the engineering analysis but also allowed to observe the behaviour of CFRP skin and its failure modes during testing process.

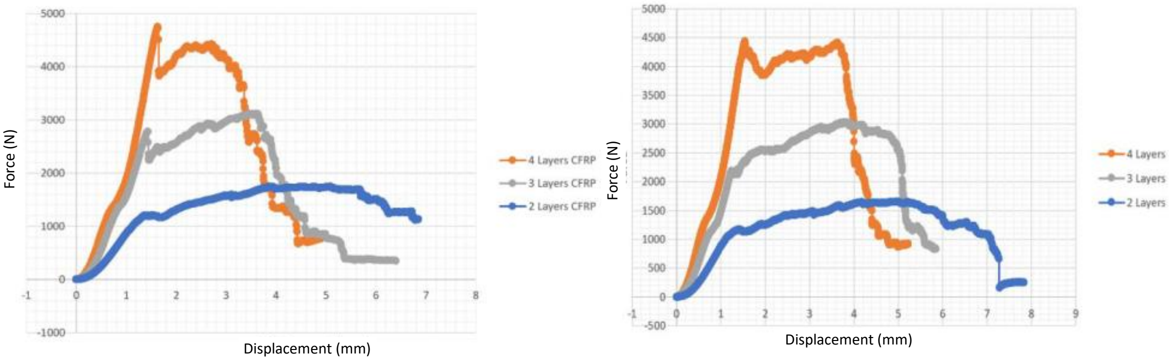

Fig 7: Shear Perimeter Test Graphs for CFRP Skin Samples

As expected, test specimen with 4 layers/plies achieved maximum force before failing which can be seen in the graphs provided above. It is important to mention that peak load (force at failure point) for thinner (0.96 mm) and lighter CFRP skin was observed approximately at 4800 N as compared to 1 mm aluminum skin whose peak force was observed at 4400 N. It was also observed that maximum force achieved by each sample increased almost linearly with adding a layer to the test sample. The kinks in the graph represent failing of each layer individually with increasing force. Skins with different skin thickness had different failure modes as it can be seen that thinner samples were less stiff and absorbed more energy as compared to stiff thicker samples. As core does not contribute significantly towards the shear force in the shear perimeter test and shear force largely depends upon skins of sandwich panel. So, it was decided to fabricate sandwich panels with skins having 4 layers/plies which can meet 7500 N of maximum force requirement.

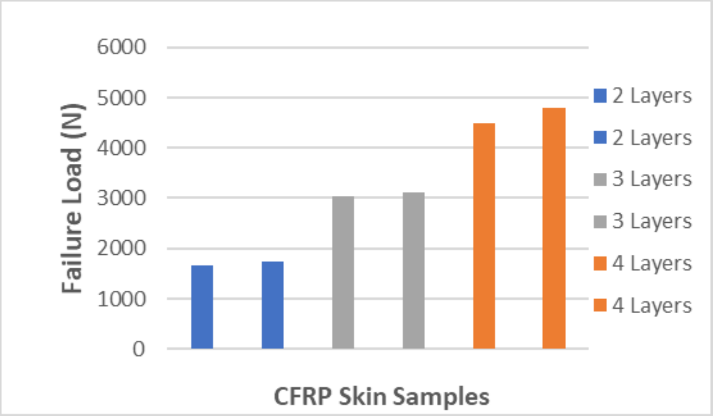

Fig 8: Shear Perimeter Test Results Showing Peak Load for CFRP Skin Samples

2. *Shear Perimeter Test on Sandwich Panels*

During the early phases of project, it was decided to use a 20 mm thick Nomex honeycomb core with density of 72 kg/m3 and cell size of 3.2 mm. Detailed properties of selected Nomex honeycomb core are given in Appendix C. The core was ordered during early weeks of Semester 1 but supplier was unable to deliver the required core on time, so it was decided to use Nomex honeycomb core available in SEIT Composite Lab which was only 10mm thick and less dense than the selected core. Keeping in mind that core thickness does not affect the test results significantly, it was decided to initially test the sandwich panels with 10mm core. Core thickness does not affect the peak load in the shear perimeter test, but it does contribute significantly towards the flexural rigidity of sandwich panel which is an important property for three point bending test. According to FSAE rules, sandwich panels for both tests should be fabricated by using same method and should be identical apart from their aerial dimensions. So, later on shear perimeter test was also conducted on double core sandwich panels where two 10mm cores were bonded together by placing a single CFRP layer between them to form a 20mm thick core.

As it can be seen in graphs provided below, that both single and double core sandwich panels passed the shear perimeter test by meeting the 4 kN peak load requirement for front bulkhead structure and 7.5 kN peak load requirement for side impact structure. From test results CFRP skin samples and sandwich samples, it was evident that skin thickness of sandwich panel largely affected the peak loads. It can be established that greater the skin thickness of test specimen, greater peak load it would be able to withstand before complete failure. It is also valuable to mention that where core thickness does not affect the peak load significantly, but it does affect the amount of energy absorbed. Greater the core thickness, more amount of energy sample would be able to absorb as can be seen in the graphs provided below. Fairly similar failure modes were observed in all test specimen. Local buckling of CFRP skin was observed as plunger started to punch through the sample. After the test was completed, cracks were observed along the +, - 45^{O} and 90^{O} on the test specimen which can be seen in figure 9. Apart from failure in the skin, there was breaking and crushing of core as well during the testing process. It was deduced that the panel can be further strengthened by replacing the core with high density having smaller cell size. It is also important to mention that there was no de-bonding of skin and core and delamination of any kind in the skins during testing process which demonstrates the good quality of manufacturing process of sandwich panels.

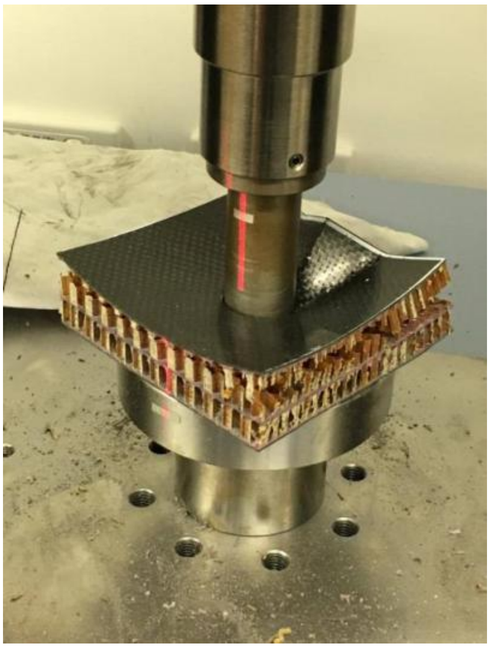

Fig 9: Failure Modes in the CFRP- Nomex Sandwich Panel during Shear Perimeter Test

CFFR-Nomex honeycomb sandwich panels behaved differently during test as compared to Aluminium honeycomb sandwich panels. Layers/plies in each CFRP skin of failed individually which is evident from the kinks in the graph where in case of aluminium sandwich panel, there was a one smooth peak (without kinks) before skin on top failed. Also, in case of CFRP-Nomex sandwich panel, high concentration of shear stress was around the punch which explains why plunger was able to cut through the test specimen. Notice also that the highest force peak was prior to the failure of the back skin. It was observed that a wad of collapsed material (face skin and core) spread the shear stress around the plunger which allowed the highest force peak to be achieved.

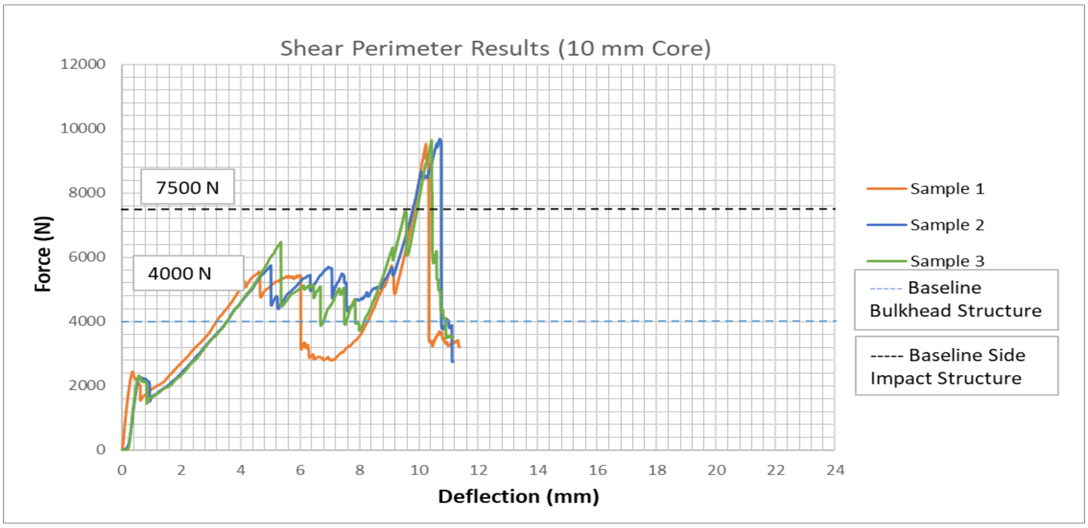

Fig 10: Shear Perimeter Test Results for Single Core CFRP-Nomex Sandwich Panels

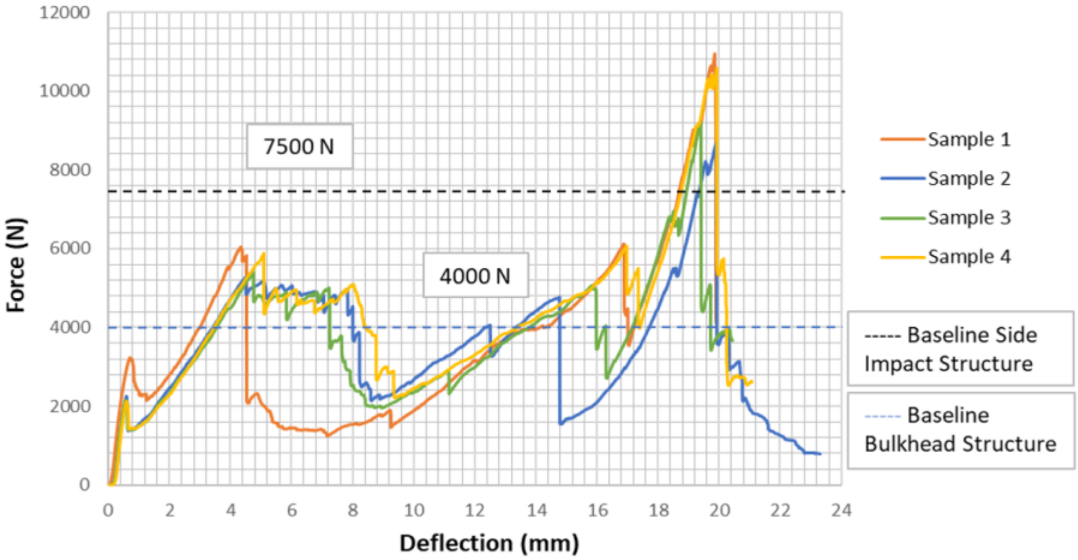

Fig 11: Shear Perimeter Test Results for Double Core CFRP-Nomex Sandwich Panels

B. Three Point Bending Test

The next test to be conducted was three-point bending test. According to FSAE rules, Teams building material for side impact structure and front bulkhead should build a flat panel of size 500 X 275 mm and perform three-point bending test on the panel. It was required to demonstrate by testing that panel absorbs same amount of energy as three baseline steel tubes will absorb when deflected to 12.7 mm of deflection. For side impact structure and front bulkhead, base line steel tubes have diameter of 25.4 mm and wall thickness of 1.65mm with unit length. Test assembly was set up in a way that load applicator over hanged the test specimen to avoid edge loading. The load applicator used was metallic and 50 mm in radius. No other material was placed between load applicator and specimen as specified in FSAE rules [35, 36].

The three-point bending test was carried out on 50 kN Shimadzu Machine in Shimadzu Testing lab at SEIT. Laser equipment was used in test setup to measure deflections due to application of force for accuracy of results. Metallic plates were used to hold the supporting rollers in the position. None of the test samples were clamped during the conduction of test. The test was carried out under quasi-static loading conditions. The stroke rate was kept from 0.75-1 mm/min for all test samples.

Fig 12: Three-Point Bending Test Assembly

Three-point bending test was conducted on CFRP-Nomex sandwich panels with skin thickness of 1mm (4 layers) and core thickness of 20 mm. The areal dimensions of test specimen were 500x275 mm. Test results were surprisingly good, as it can be seen in the graph that all the test samples were far above the baseline material in meeting the strength and energy absorption requirements. Unlike shear perimeter test graphs, there were no kinks in three-point bending test graphs, rather they were quite smooth and almost linear until the failing point. The failure modes of CFRP-Nomex sandwich panels were quite different to Aluminum sandwich panels. There was no local buckling of skin observed in CFRP-Nomex test specimen unlike Aluminum sandwich panels. In case of Aluminum samples, load applicator left an impression on the skin by permanently deforming the skin and crushing the core whereas, it was not the case in CFRP-Nomex test specimen. However, it was observed that the upper skin was cracked in the middle due to load applicator as CFRP is brittle material. So, it can be established that that CFRP is weaker in compression than in tension as no cracks were observed in bottom CFRP skin of sandwich panels. Again, like in shear perimeter test, skin-core bond was impressive in three-point bending test as well. No dis-bonding was observed during the test in any of the test specimen. Apart from failure in skin, there was also core breakage occurring during the test. Although all test specimen passed but they can further be strengthened and toughened if required by using higher density core.

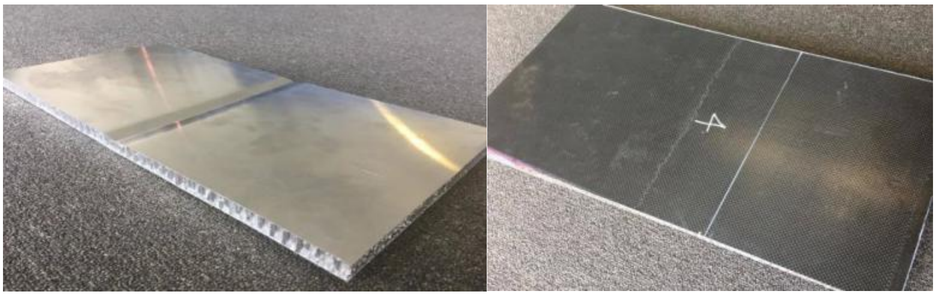

Fig 13: Depiction of Different Failure Modes for Aluminum and CFRP-Nomex Sandwich Panels

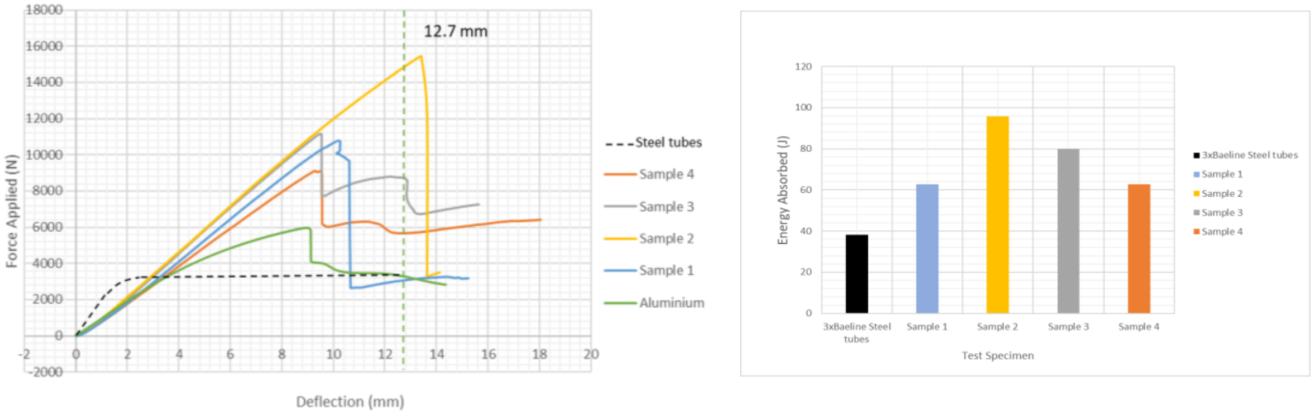

Fig 14: Three-Point Bending Test Results for Double Core CFRP-Nomex and Aluminum Sandwich Panel (L to R) Force-Displacement Graph and Bar Graph Representing Energy Absorbed by Each Sample.

Figure 14 provided above represents the amount of energy absorbed by sandwich panels during three-point bending test. Sample 2 was undoubtedly best performing sample out of all. The reason sample 2 absorbed greater amount of energy was because it was few millimeters wider than rest of the samples which implies that for a given length, width of a test specimen greatly affects the amount of absorbed energy and flexural rigidity. The absorbed energy was determined by calculating area under the curve of force-displacement graph. As mentioned above, core thickness contributes significantly towards the amount of energy absorbed during the test as well as improves the flexural rigidity of sample. That's the reason it was decided to use 20 mm thick core to meet these performance requirements.

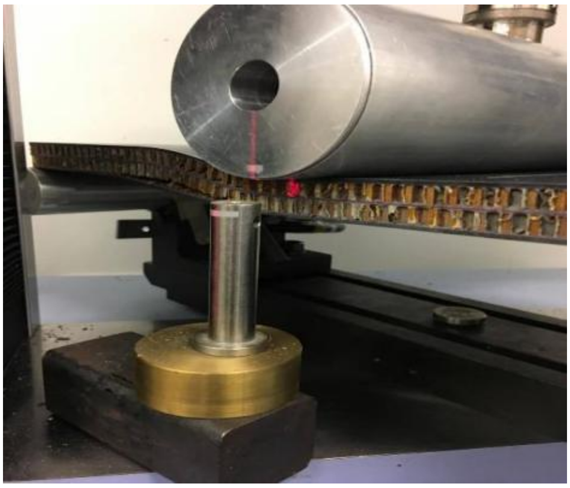

Fig 15: CFRP-Nomex Sandwich Panel Behavior during Three-Point Bending Test

VII. Conclusion

Aim of this project was to manufacture sandwich panels with CFRP skins and Nomex honeycomb core and to test them against FSAE requirements for side impact and front bulkhead structure of FSAE car chassis. All the test samples passed the tests and complied with FSAE requirements. Test results indicated skin thickness largely contribute towards the shear perimeter strength whereas energy absorbed mainly depends upon core thickness of sandwich panel. In the shear perimeter test, shear stress concentration was around the punch which explains why plunger was able to cut through the test sample. In the three-point bending test, CFRP skin being brittle material failed by cracking the middle where load applicator was placed whereas, aluminium skin failed in the ductile manner. As expected, Shear perimeter test came out to be limiting case out of the two tests.

Two main motivations behind this project were to reduce weight for Academy Racing Car by replacing the Aluminium sandwich panel chassis with CFRP-Nomex honeycomb panel and allow Academy Racing Team to manufacture chassis sized structure at SEIT Composite lab using wet layup method. That would allow the racing team to manufacture the car chassis shape which will also account for aerodynamic factors as complex shapes can be fabricated using wet layup method. All the test samples far above in meeting FSAE requirements but unfortunately were heavier as compared to Aluminium sandwich panels which can be seen in the table 4. There are areas which can be investigated to reduce weight of CFRP-Nomex sandwich panels which will be discussed in the recommendations section.

Table 4: Areal Density Table for Aluminium and CFRP-Nomex Sandwich Panels

Panel Type (Skin-core-skin) mm	Areal Density (kg/m2)	Chassis Weight (kg)	FSAE Tests	Time of Testing
CFRP-Nomex (1-20-1)	9.6	27.5	Passed	2017
Al (1-20-0.8)	6.5	18.7	Passed	2017
Al (0.5-30-0.5)	4.4	12.6	Failed	2016
Al (0.5-20-0.5)	3.9	11.2	Failed	2016

Note: Chassis weight were calculated using chassis surface area as 2.87 m^2. Further specifications of Aluminium sandwich panels can be found in the Appendix B.

VIII. Recommendation

This project has been mainly a success apart from weight reduction aspect. So, my recommendations will focus the ways to reduce the weight of sandwich panel. Adhesive used to bond the sandwich panels contributed significantly towards the weight of the panel (approximately 400 g per panel). I would recommend choosing the adhesive more carefully in order to reduce the weight of the panel. Film adhesive or low viscosity adhesives would be good choice. Secondly, I would also recommend choosing one 20mm thick core instead of bonding two 10mm cores together using adhesive. It would also result in weight reduction of the panel. Lastly, I would recommend that this project be revisited using hybrid skin with Carbon-Kevlar combination. Kevlar being much lighter and tougher than carbon would result in weight saving of the sandwich panel. I fabricated hybrid skins at SEIT composite lab but due to time limitations could not perform the tests.

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