DESIGN AND ANALYSIS OF A COMPOSITE MONOCOQUE FOR STRUCTURAL PERFORMANCE : A COMPREHENSIVE APPROACH

A Thesis

Submitted to the Faculty

of

Purdue University

by

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In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Mechanical Engineering

August 2019

Purdue University

Indianapolis, Indiana

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To Rutuja and Saurav

- they have inspired me to be who I am

(that is not true they made me write it)

To my mother and Mun

(The ones who actually inspired it but will never read it)

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Dr. Hamid Dalir for his constant support, motivation and guidance that has helped me to stay focused and committed to the research. I am thankful to Mr Talal Shakfeh for his valuable inputs and endless patience throughout the project. Thank you for taking time out of your busiest days to answer my tiniest doubts. I would also like to thank my faculty advisors Dr Andres Tovar and Dr, Hazim El- Mounayri for their valuable feed backs. I am grateful to all my colleges at Advanced Composite Structures Engineering Laboratory (ACSEL) for all the support and entertainment they have provided me through these two years. I would like thank Mr. Jerry Mooney for his tireless efforts and his help with formatting this document into something that looks professional. I am thankful to Purdue University for opening its doors to me and blessing me with two wonderful years of my life. My family, I am absolutely lucky to have you all in my life, your endless support and faith in me is what has kept me going during some of the toughest phases of my life. I could have never achieved it without you'll. I would like to thank my best friends/ my soulmates Neelu and Ketika, you girls are irreplaceable, my forever 3 am friends. I would like to express my gratitude to my friend/colleague/partner in crime, John. Thank you for challenging me everyday and making me a better person. To Sufia,it took me 5 seconds to befriend you. Thank you for being an amazing honest friend. People like you are rare. To Rachana, if you weren't so crazy I would never be sane. I am blessed to have your never ending energy and your drunk videos in my life.

Lastly caffeine, you have been my companion through endless nights of writing and hard work.

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ABBREVIATIONS

SCCA	Sports Car Club of America
FIA	International Automobile Federation
FEA	Finite Element Analysis
ACP	ANSYS COMPOSITE Pre/Postprocessing
MoS	Margin of Safety
DoF	Degree of Freedom

ABSTRACT

Kamble, Meghana P. M.S.M.E., Purdue University, August 2019. Design and Analysis of a Composite Monocoque for Structural Performance : A Comprehensive Approach. Major Professor: Dr. Hamid Dalir.

Lately numerous studies have been performed to design composite monocoques with high strength and low weight for various student level racing contests. The objective of this paper is to develop an insightful methodology to design and developed a light-weight composite monocoque. The monocoque is designed to pass the mandatory static load tests laid down by the International Automobile Federation (FIA)Formula 3. These Formula 3 tests are considered the baseline of the desired structural integrity of the composite monocoque. The presented design technique emphasises on a monocoque developed for Sports Car Club of America (SCCA) races. The three standard load tests performed on the monocoque are Survival Cell Side test, Fuel Tank test and Side Intrusion test. A sandwich layup of bi-directional woven carbon/epoxy prepreg and aluminium honeycomb is optimized for minimum weight while predicting the unknown properties of layup and ensuring the monocoque doesnt experience failure. The approach intends to achieve minimum weight with high torsional rigidity and is capable of being used for the design and analysis of any kind of formula type composite monocoque.

1. INTRODUCTION

1.1 Composite Materials - General Overview

A composite material is generally defined as a combination of two or more materials which result in better properties than the constituent material. Each constituent maintains its chemical, physical and mechanical properties. Two of basic constituent groups are the matrix and reinforcement. Composite materials have gained popularity due to the high strength to stiffness ratio. For example, a fibre reinforced carbon fibre is up-to five times stronger than 1020 grade steel and still has one fifth of the total weight of steel. As a result, carbon fibre has found applications in various industries like aerospace, defence, marine etc [1] The continuous homogeneous phase is the matrix. Matrix can be polymer, metal or ceramic with low, intermediate and high strengths and stiffness respectively. Though, ceramics have the highest stiffness they are also very brittle. Ceramics are usually used when the motive is to increase the toughness more than the strength and the stiffness. In polymer and ceramics where the bond between the matrix and the fibres is very strong, the matrix transmits loads to the fibres using shear loading at the interface of the matrix and fibres. As per the application the matrix can be chosen. The matrix performs an important task of keeping the fibres intact in a certain orientation. More importantly it also makes sure that the fibres are protected from abrasion.

1.2 Classiifcation of Composites

The reinforcement phase is usually the reason for the an-isotropic behaviour of the composite material. These are bonded or embedded in the matrix. The two major classifications of composites are the Fibre Reinforced Composites and the Particle

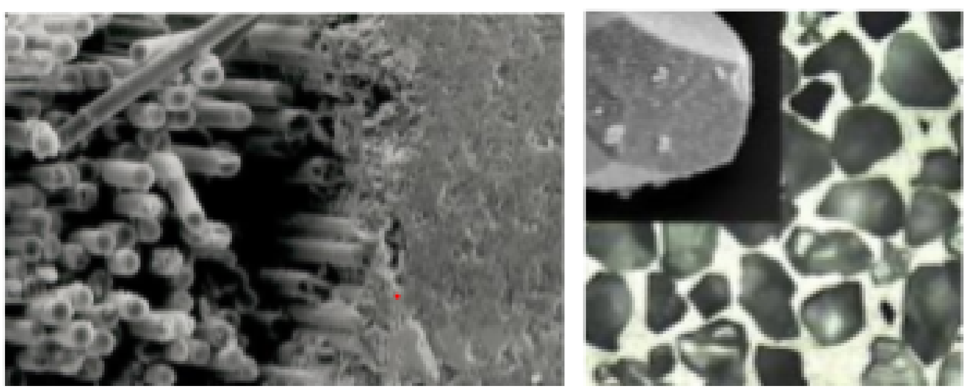
Reinforced Composites. The fibres comparatively have greater value of length than the diameter and used to reinforce the matrix. Some of the fibre materials are glass, carbon, aramid, boron, ceramics and hemp. They also come in different forms like, unidirectional, woven, mat etc. This, ratio of length to diameter is the aspect ratio which varies greatly and are further classified as

Short Fibre Reinforced (less than 2mm)

Long Fibre Reinforced (2to 30 mm)

Endless Fibre (greater than 30mm)

Particle Reinforced Composites: These have particles of a certain material dispersed in matrix of a certain material. Matrix materials are thermosets, thermoplastics, metals, ceramics. They are of shapes and sizes, spherical, ellipsoidal, polyhedral etc. These are less stiff than the continuous fibres. However, they are cheaper than the fibre reinforced variety.



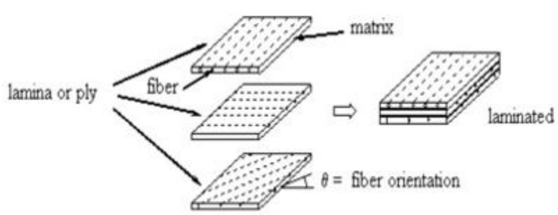
(a) Carbon fiber Epoxy (b) Ceramic Aluminium

Fig. 1.1. Types of Composite Materials; [1]

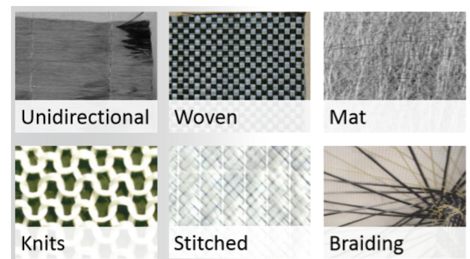
1.3 Stack-up/ Ply Orientations

A single sheet of composite is usually referred as a ply/layer. When a stack of such layers is joined together it is referred to as a lay-up or the stacking sequence.

Individual layers are stacked up in a way that the laminate as a whole is stiff in all directions. A unidirectional composite (0) is stiff in 0 direction buy weak in 90. This is due to the fact that the fibres carry loads in 0 but the weak matrix carries most of the load in 90. Thus, the fibre carries the longitudinal tension and compression loads, while the matrix makes sure that the fibres dont buckle/collapse in compression and distributes the loads among the fibres in tension so that they are stabilized. It is evident that the orientation of the fibres in the composite sheet directly affects its mechanical properties. A well balanced quasi-isotropic laminate carrying loads in all directions has a stack-up with fibres in 0, +45 /-45, +90/-90 directions [2].



(a) Composite material anatomy [1]



(b) Fibre reinforcement forms [3]

Fig. 1.2. Composite Materials

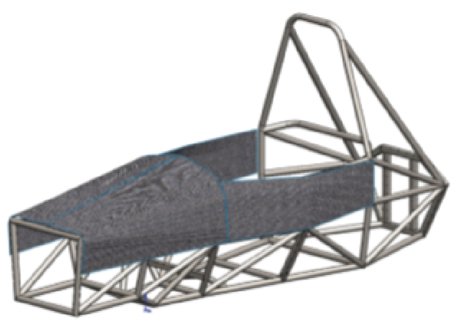
2. REVIEW OF LITERATURE

The study provides a basis to design a semi monocoque with an intention to be part of future SCCA races. SCCA is a non-profit organization, incorporated in the state of Connecticut. In total there are 28 classes that compete in SCCA Club Racing Major events. One of the categories is the Sports Racing Category which has purpose-built road racing cars that can be full body carbon fibre monocoques [2] . A composite monocoque in the SCCA races has to be up to FIA or International Federal of Automobile formula 3 guideline and standard.

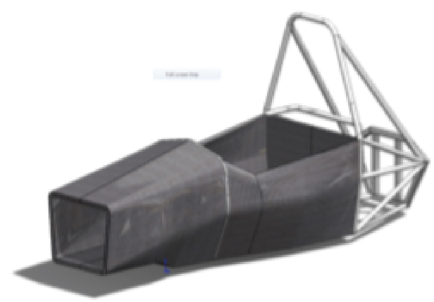
In the event of a crash the designed monocoque is expected to act as a survival cell and protect the driver. This protection is achieved by making sure the monocoque passes a few static load tests imposed by FIA. These tests define the stiffness and strength requirements of the monocoque. They also help spectators safety and assist in making sure that no team has an unfair advantage over the other. Using FEA analysis the behaviour of the chassis is observed under various load conditions. Under a given load, performance is evaluated to identify the area where more reinforcement is required. The technique presented is a reliable approach through a sophisticated analysis to develop formula racing monocoque that passes the Formula 3 static load tests while maintaining a high rigidity and minimum weight.

Since the main target is to reduce weight while increasing structural strength, the use of composites materials becomes the most applicable choice, this introduces the main challenge in conducting any analytical study that involves composites due to the nature of the ingredients used as well as the diversity of options they come in. A monocoque in simple terms is a system where the external skin supports all the systems loads. The monocoque comprises of the driver cell, suspension elements and fuel tank. The engine is directly attached to the back of the monocoque unit by a composite or an aluminium plate and then is connected to the gearbox assembly.

It is then further connected by the rear suspension components. The central unit has wing structures, underbodies and cooling ducts attached to it. These units i.e. the chassis, engine and gearbox thus form a structure that carry all the inertial and aerodynamic loads [4]. Thus, a monocoque is of major structural importance [5–8]. One of the easiest ways to accommodate composites in an already existing space frame chassis is to replace steel members with composite shear panels on the top, bottom and sides (Figure 2. 1 a). This method provides appreciable weight savings. A better approach is to develop a steel rear space frame unit and mate it with a composite fore body (Figure 2.1 b). This method significantly reduces weight and also increases the to rigidity of the body over a full steel space frame structure [5]. Construction of a full body composite monocoque is a complex process but it assures to achieve the greatest weight savings and highest stiffness in comparison to designing a semi monocoque or hybrid monocoque while also satisfies all the safety and strength requirements [6]. In any racing sport, limitations are placed on the overall dimensions



(a) Hybrid monocoque



(b) Semi monocoque concept

Fig. 2.1. Concepts of Monocoque [2]

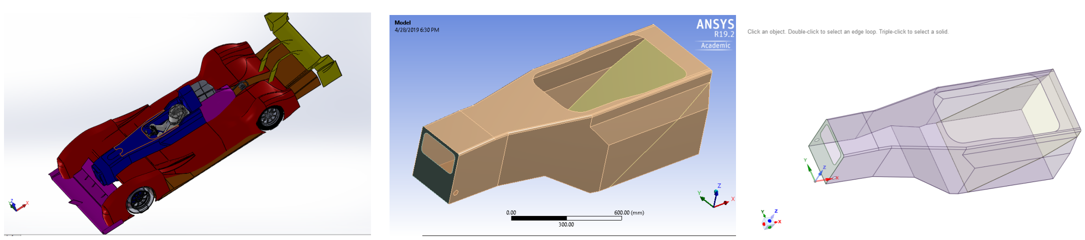
and the envelop of the driver within the cockpit of the car with strict constraints on weight, geometry and the size of the car [9–11]. The race car requires more stringent performance parameters than a regular car. There are a myriad of forces acting on it, like the various forces due to the suspension assemblies, forces due to numerous attachments to the chassis, aerodynamic forces etc. making the design and necessary analysis a complex process [12–14]. A light weight chassis with high rigidity is one of the important factors contributing to success in formula racing. A light weight chassis ensures reduced lap time while high torsional rigidity ensures good handing performance during cornering. About 80 percent of the volume of a Formula racing car is made of composites which include suspension arms, brake discs, crash structures and gear box housing [15, 16].

2.1 Overview of Thesis

A lot of literature is available to design race cars for formula student races and feasibility of the designs are tested. However, there is a very little available literature that guides in designing a composite monocoque that passes the mandatory safety tests by FIA as well as meets the strength requirements, the research will outline the steps taken to perform a detailed Finite Element Analysis (FEA) on composite monocoque using the ANSYS (R19.2) simulation suite. Though the current thesis considers a monocoque specifically designed for SCCA, it takes into account guidelines for Formula 3 races and thus the results and the methodology is of use to anyone who is designing a formula level monocoque

3. CAD MODELLING

An entire solid body of the race car is designed with a number of panels and aerodynamic parts in SolidWorks (Figure 3.1.a) This design usually comes from the aerodynamics team. The design at this point such that it helps the car to produce maximum downforce and less drag. The solid body created for the research was designed keeping in mind the geometric constraint requirements of SCCA races. For the sake of simplicity, the solid model used from the aerodynamics team just incorporates the monocoque shell without the bulkheads, internal stiffeners or metal inserts (Figure 3.1.b). Further, the solid body was edited and defeatured in ANSYS SPACECLAIM DIRECT MODELER (SCDM). The solid body was also converted to shell body in SCDM (Figure 3.1.c). It was noted that the monocoque was symmetric about the length of its body and hence it was decided to perform half body analysis. Thus, taking advantage of the symmetry helped in reducing the model size and the computation time.



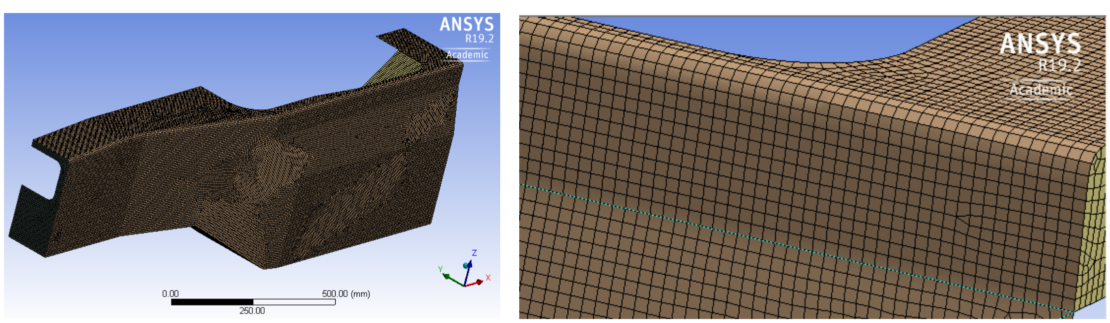
(a) Chassis with aerodynamic (b) Full solid body (c) Full Shell Monocoque

Fig. 3.1. Moncoque Design Phases

4. MESHING

In any FEA analysis the mesh density or the finite element size has a tremendous impact on the computation time. It also hugely affects the accuracy of the results. Coarse elements lead to less accurate results yet but usually reduce the computation time. This method of meshing is helpful in scenarios when the objective of the analysis is rough estimation of results. This is helpful in scenarios when the objective of the analysis is rough estimation of results [17].

Finer the mesh more accurate are the results at the cost of increased computation time. One has to then make a decision about the size of the mesh and the computation time according to the objective of the analysis. If the objective is to find the deflections under certain loads, then a coarse mesh will be considered good enough as long as in it captures correctly the geometrical features of the modelled parts. The present analysis is aimed to achieve the most accurate possible results and hence a high order mesh of SHELL 181 elements was generated in ANSYS Design Modeler (Figure 4.1) using face meshing and body sizing techniques. The half monocoque model generated had 42509 elements and 43492 nodes.



(a) Generated fine mesh (b) Zoomed in mesh

Fig. 4.1. Mesh

5. FABRIC CREATION AND LAYUP SELECTION

A woven prepreg was chosen for the analysis obtained from a local supplier. Woven composites easily conform to a complex geometry than unidirectional, they were thus chosen over unidirectional composites. As a weave fabric is equivalent to two unidirectional composites (0, 90) one layer of weave can replace two unidirectional layers thus reducing the ply layup time and also show notable improved damage resistance [18]. The 2x2 twill weave prepreg used for the analysis was RC 200T SE 84LV from GURIT. Some of the material properties of the chosen composite taken of GURIT to define the material in ANSYS are listed in Table 1. One of the major difficulties while performing a composite material analysis is the fact that the data sheet obtained from the supplier often has insufficient data necessary to define the selected prepreg in any FEA software. This is evident in the current data sheet used as well. Engineers usually are certain about a few properties and the rest are usually assumed as the mathematical calculations to find out all the required input properties are complex and time consuming. The results produced eventually are then less accurate. In order to define a material completely and accurately, a designer requires nine material properties, Youngs Modulus X, Y, Z directions, Shear Modulus in XY, YZ, ZX directions and Poissons ratio in XY, YZ, ZX directions.

With an intention of overcoming this short coming ANSYS Material Designer was used to design a 2x2 twill weave (Figure 5) and later the nine properties were obtained. ANSYS Material Designer uses composite homogenization and rule of mixture equations. The composite microstructure at its sub surface may have matrix voids, fibre matrix dis-bond, fibre- coating interphase etc. Defining such a microstructure geometrically and materially is impractical. Thus, homogenization is important for the purpose of characterization. A representative volume structure (RVE) is the complex microstructure of the chosen composite that is simplified or idealized.

5.1 Initial Set-up in Material Designer

The homogenization in Material designer starts at modelling the RVE and defining the material properties of the constituent materials. The required properties of the resin epoxy used was taken from the data sheet and fed into the software (Poissons Ratio, Youngs Modulus).However, the data sheet has Youngs Modulus defined for the carbon fibre prepreg but not carbon fibres alone. the principle is to input the individual ingredients

Table 5.1.
Isotropic Properties of Carbon Fiber and Resin

Material	Density	Youngs Modulu's	Poisson's Ratio
Dry Carbon fibre	1800	140	0.3
Resin Epoxy SE 84LV	1160	3.9	0.35

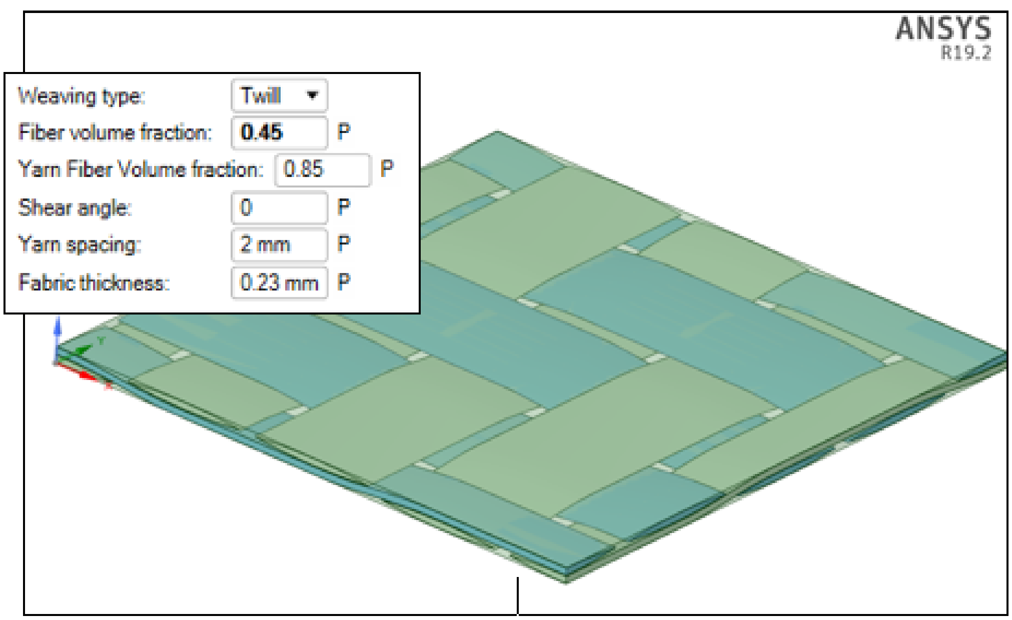


Fig. 5.1. Geometric Information of Fabric.

The isotropic properties (in our case it is the resin properties and the carbon fibre bulk properties), then define the geometrical information of the fabric as shown in the next figure.MD will then create a representative unit of the fabric (including 3D solids of the fabric twill and the surrounding resin), this sample will then be meshed (Figure 5.2) and automatically used in a series of 6 FE runs where MD applies a unit of tension or compression load individually in multiple directions to measure the overall stiffness of the sample and mathematically derive the nine orthotropic constants.

Since the individual ingredient are isotropic material, the properties needed to run the simulation are: Density, 1 Youngs modulus and 1 Poissons ratio for each material. The supplier data sheet gave these three properties for the resin material only, the properties for the plain carbon fibre were not included. However, two Youngs moduli (E1 and E2) of the cured ply were provided, therefore the approach taken here was to use these E values as target parameter and run the MD analysis iteratively by changing the plain carbon fibre inputs until the target E1 and E2 are reached, below are the predicted 9 orthotropic properties in Figure 5.2.

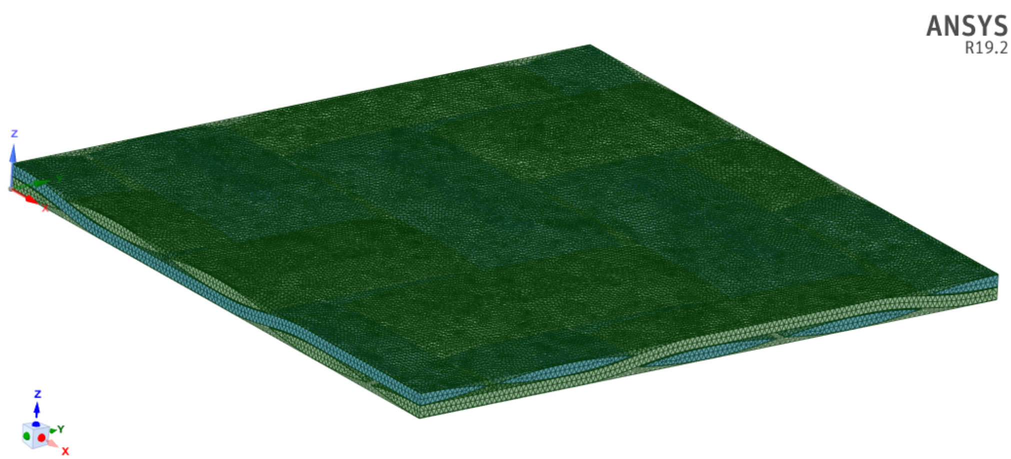


Fig. 5.2. Woven Composite Meshed In ANSYS Material Designer.

Table 5.2.
Final Orthotropic Properties of Carbon Fiber Prepreg

Material Property	Units	Values
Youngs Modulus X-Direction	GPa	60.10
Youngs Modulus Y-Direction	GPa	1.088
Youngs Modulus Z-Direction	Gpa	18.78
Poisson's Ratio XY	-	0.22607
Poisson's Ratio YZ	-	0.30326
Poisson's Ratio XZ	-	0.30635
Shear Modulus XY	GPa	19.25
Shear Modulus YZ	GPa	4.63
Shear Modulus XZ	GPa	4.62

5.2 Stack - up Selection

When a designer has to engineer layered composites that task involves complex definitions that comprise material properties, various thicknesses etc. Without proper FEA support that helps to set up the model one may lose a lot of time before actual failure analysis are done. Hence before committing to a final layup preliminary analysis was done to see how the laminate properties were. This helped to understand how well the fibres are distributed over the monocoque. It was noted that a symmetric stack-up of [(0, 90)/ (+45, -45)/(90, 0)]s performed well over a [0/90] S. Laying up 6 layers over a monocoque is in itself a time-consuming task. Hence, to experiment with some layup the static load tests were performed using the symmetric layup of [(0, 90)/ (+45, -45)/(90, 0)]s. The stack up was chosen in a manner to guarantee good fibre distribution in all the directions over the monocoque body. Each ply at thickness of 0.23 mm bringing the chassis thickness to 1.38 mm was tested for the selected tests with an intention of checking for failure.

6. LOAD APPLICATION AND BOUNDARY CONDITIONS

6.1 Load Application Using Deformable Loading Technique

The methodology of the tests performed and the results obtained are discussed below in detail. The required force is applied as a remote force in ANSYS. The remote force is applied using Deformable loading/Remote Load methodology in ANSYS. It is an implicit multi point constraint with one independent node(master) and several (slave)dependent nodes. The force is distributed to the slave nodes as forces proportional to the distance of the master node from the centre of gravity of the slave node times the weighting factor. A remote point is created in the space as defined by the user (Figure 6.1). A region is scoped over the geometry created in ANSYS where the load is expected to be distributed. Using constraint equations, the remote point distributes the load between the nodes of the area scoped. Constraint equations are created using translational degrees of freedom of slave nodes (Figure 6.2). Constraint equations are converted to distributed forces during the solution over the slave nodes.

6.2 Boundary Conditions

Boundary conditions are applied on the monocoque for all the static tests performed are in a way so as to represent the actual constraints the monocoque faces when the front and rear suspension is mounted on it. 1) Black Square - The front circular edge has the front suspension mountings. Translation and rotation are allowed only in Y axis at the circular edge, all other DOFs are fixed. 2) Blue Edges - Symmetric body conditions are applied by allowing translation of the symmetric

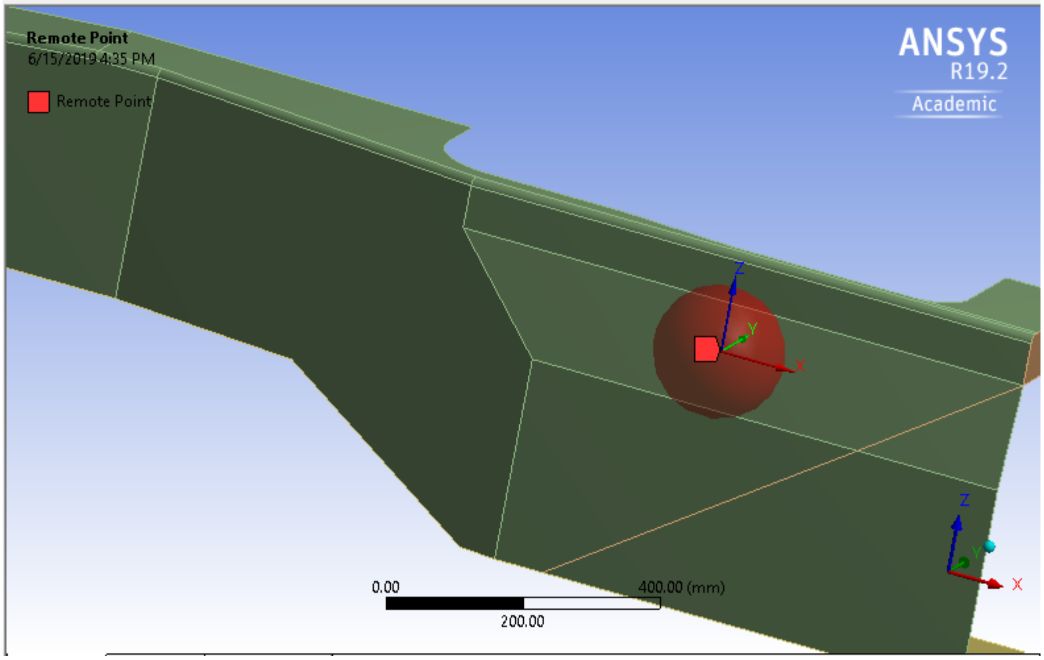


Fig. 6.1. Remote Point Creation

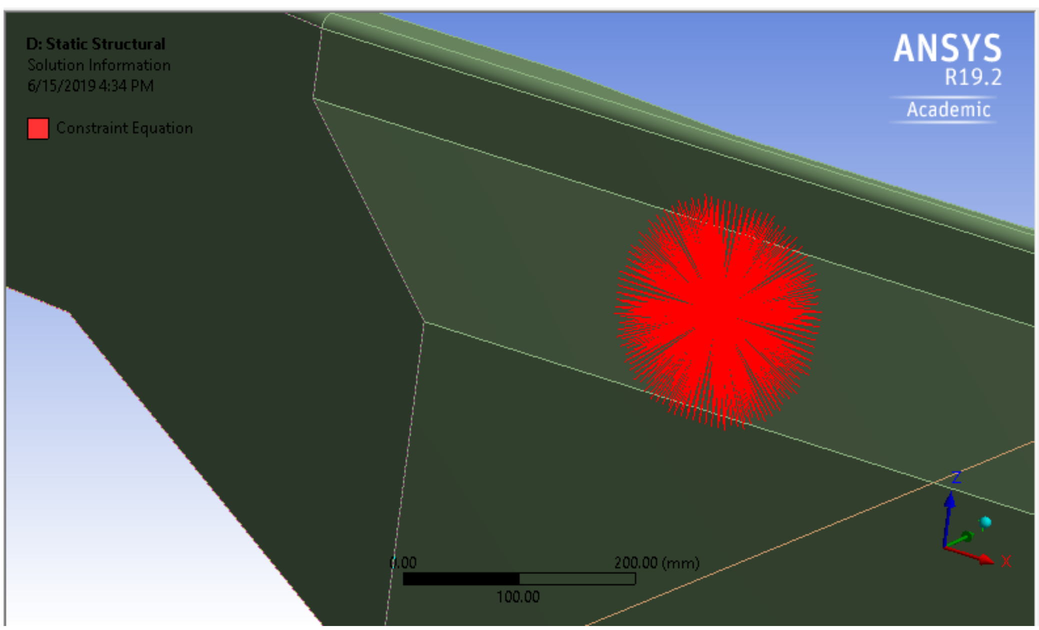


Fig. 6.2. Force Distribution using Constraint Equations

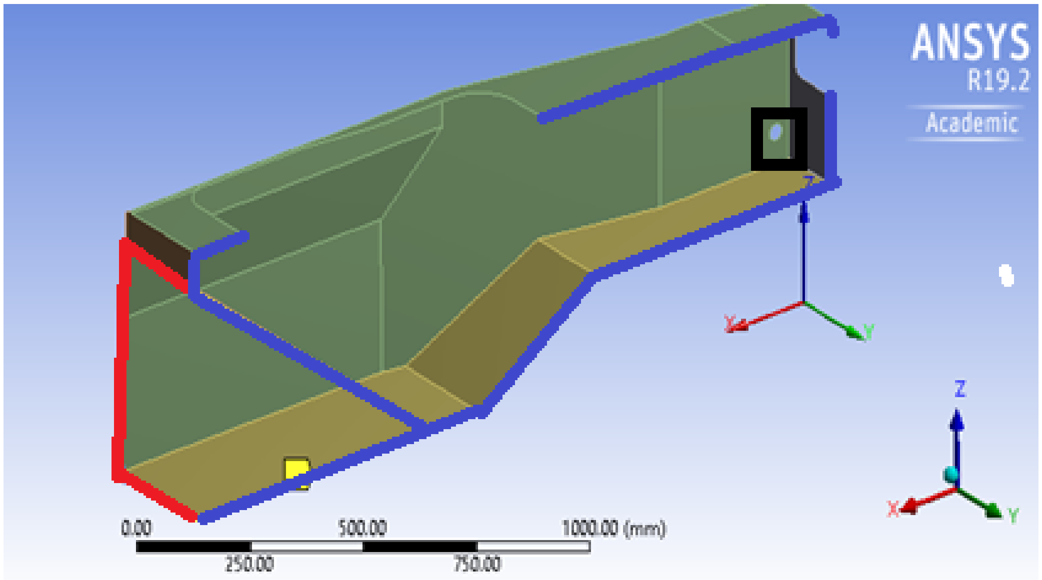


Fig. 6.3. Schematic Representation Of Boundary Conditions Applied On To The Monocoque

edges on X and Z axis while the Y axis translation is fixed. 3) Red Rear Edges - The edges of the chassis at the back is being remotely constrained representing the rear suspension mountings, translation in Z direction is fixed, rotation about X and Z axis is fixed, all other DOFs are free.

6.3 Static Load Test For the Monocoque

According to the FIA FORMULA 3 guidelines, the monocoque is tested for its strength and stiffness requirements by a few tests. In the real world these tests are performed in the presence of a FIA technical delegate who measures the results using equipments verified by the FIA. In order to pass these tests, it is expected that the monocoque shows no structural failure of its inner or outer layers. These tests are discussed in detail below.

6.3.1 Survival Cell Side Test

According to this test as described in the technical hand book, a rubber pad of a certain diameter (20mm) is placed in the cockpit area conforming to the chassis shape. A force of 20kN is to be applied at the centre of the pad through a ball jointed junction in less than 3 minutes. Deflection or elastic deformation of less than 20mm is acceptable in this case. Using deform-able loading technique in ANSYS as explained in section 6.1, a load of 20kN is applied on the side wall of the driver cockpit region on a scoped area of 20mm diameter. The boundary conditions applied are as explained in section 6.2

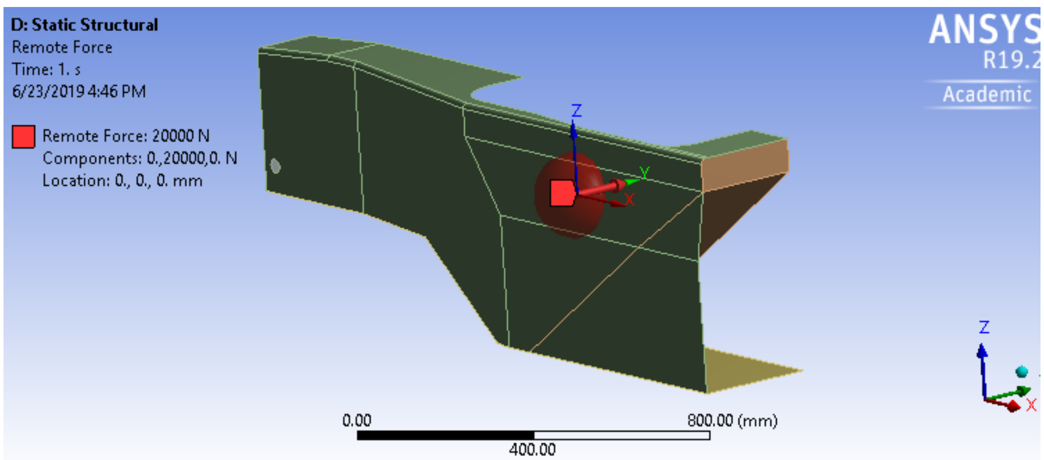


Fig. 6.4. Load Application Survival cell Side Test

6.3.2 Fuel Tank Test

A further static load test is carried on the survival cell from under the fuel tank. A rubber pad of 200 mm diameter is placed at the centre of the fuel tank and load is applied via a ball jointed junction at the centre of the fuel tank. The load applied is of 10kN and must be applied in less than 3 minutes. It is necessary that the no structural failure of the surface of the survival is noticed and a deflection less than 20 mm is allowed. As described in section 6.1 load of 10kN is applied using the same boundary conditions as explained in section 6.2 Since half body analysis is done in the fuel tank test the diameter becomes half and only those nodes are considered Hence the load is divided to half. Hence 5kN that is half the initial load is considered.

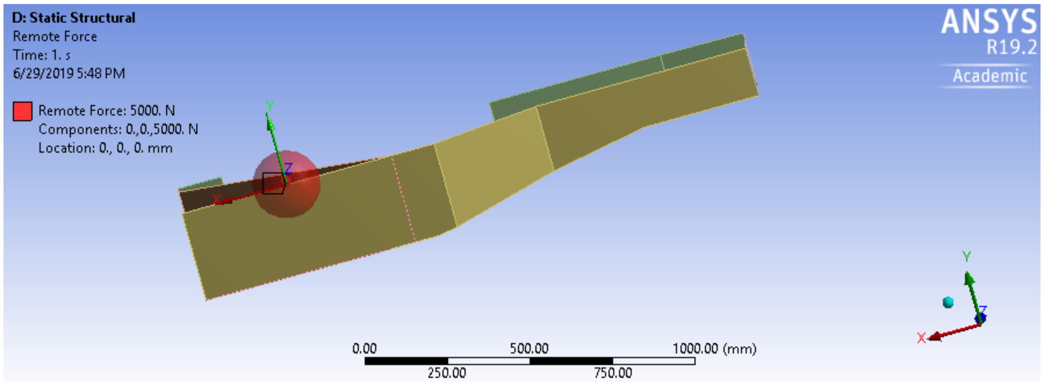


Fig. 6.5. Load Application Fuel Tank Test

6.4 ANSYS Work Flow

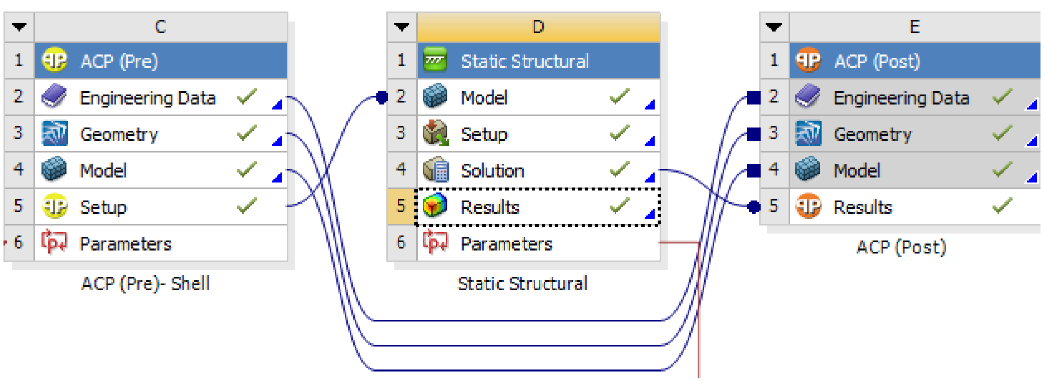


Fig. 6.6. ACP Setup

ACP Pre-processing : Steps involved include defining materials, Importing geometry, meshing and finally laying the fabric up Simulation: Steps include applying loads and boundary conditions and further solving for stresses and deformation PostProcessing : After applying loads the failure analysis is carried out. Once the material is defined which essentially means the material properties and mechanical properties are fed into the software the geometry can be imported. Once it is meshed as per the analysis requirements the composites can be laid up (Figure 6.5). After every layup the green arrows show the fabric direction which helps to understand how the fibres are laid up over the chassis. Then the loads and boundary conditions are applied and the results are found. Failure analysis is post processing to get a better understanding of failures per ply.

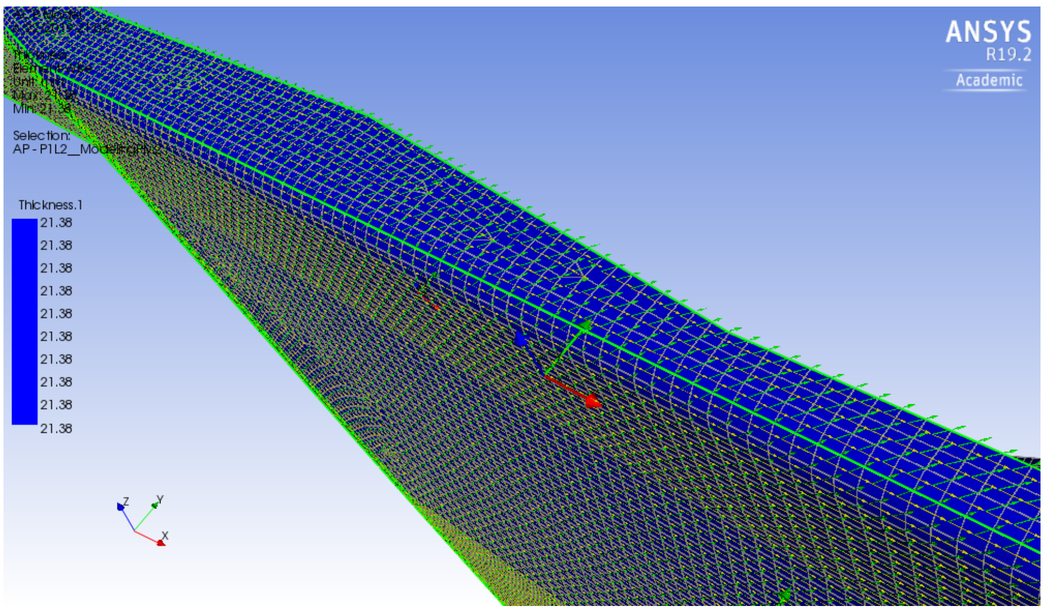


Fig. 6.7. Fiber direction in 45 degree direction

7. FAILURE ANALYSIS OF COMPOSITE MONOCOQUE

Various parameters like constituent property, lamination geometry, state of stress etc affect the failure mechanisms in fibre composites. At a microscopic level fibre-matrix interaction can be viewed while at macroscopic level the laminate can be viewed. In a laminate of angled ply cracks parallel to fibres are formed when the strain limit which is usually perpendicular to the load is exceeded. Failure patterns are hugely influenced by free edges. Around the notches a variety of stresses are noted that are not always predicated by any established theory [3]. The failure mechanisms for the composite materials vary widely with respect to the kind of loading it is subjected to. They are also related to the properties of its constituent phases which are the matrix, reinforcement i.e. fibres and interface-inter phase. Over a period of time numerous methods are proposed and are available to help a composite designer. The three groups are interactive theories (Tsai- Wu), non-interactive theories (maximum stress) and partially interactive (Hashin - Rotem, Puck) [19]. The composites behave as an orthotropic material; different types of failure modes are a possibility. This research takes into consideration two such failure criterion including Tsai-Wu and Maximum Stress failure. It is possible that a certain section of the lamina performs well under one criterion but fails under the other. Thus, A combination of two criterion helps to get more comprehensive and precise results. All stresses are independent and the occurring stresses in one direction does not affect the strength of the material in the other direction. In the Maximum Stress Theory failure will occur when any one of the stress components exceeds the corresponding strength in that direction. Tsai-Wu takes into account interactions between different failure mode. These are useful in calculating the margins of safety plots. These plots are used later to determine the failure under the different loading condition. Using the decided stack up of [(0,90) (+45,-45) (90,0)] the tests were performed and failure was observed.

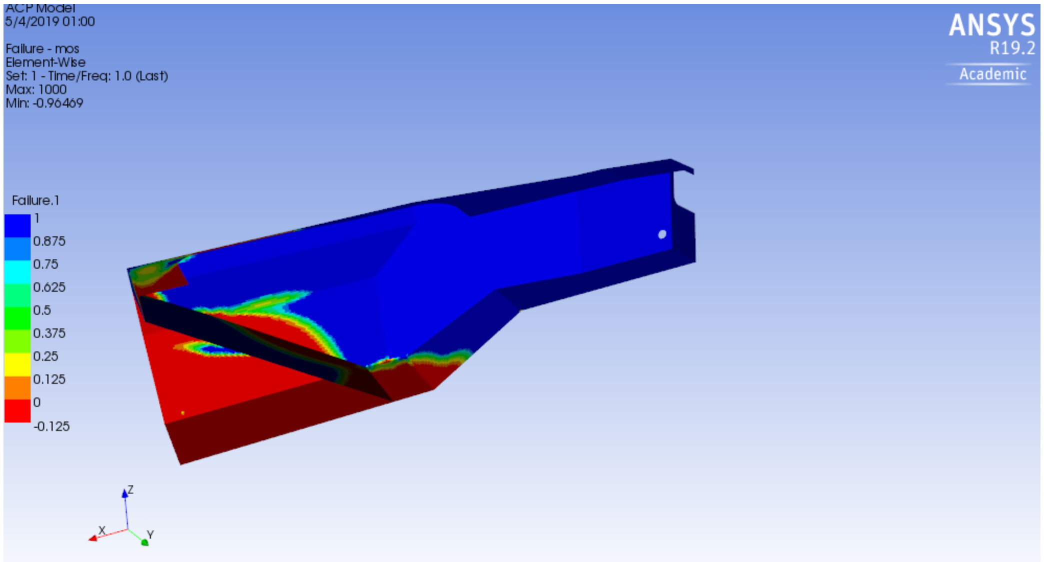


Fig. 7.1. Margin of Safety - Fuel Tank Test (6 plies)

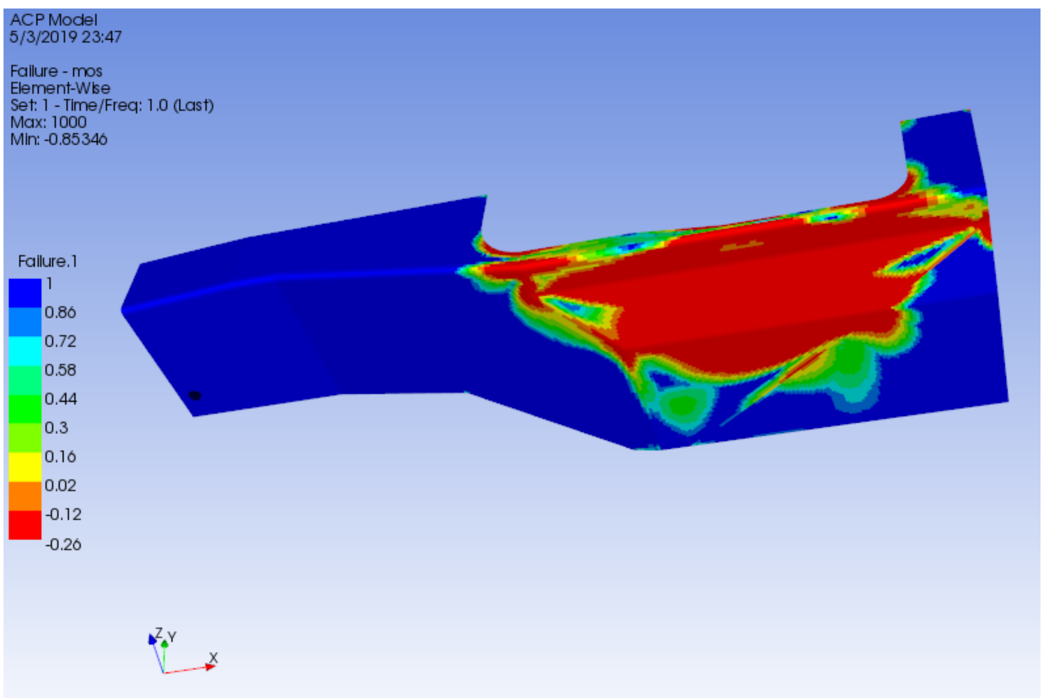


Fig. 7.2. Margin of Safety - Survival Cell Side Test (6 plies)

At 6 plies it was noted that the survival cell failed severely. This is evident from Figures 7.1 and 7.2. Both the margin of safety plots shows regions with negative margins of safety which are highlighted in red. This indicates that the tests have failed for either of the failure analysis theory. Since it was clear that the monocoque is not safe for 6 layers a study was setup to repeat the current stack-up a number of times until a decision can be made as to how may plies the monocoque will need to produce a positive margin of safety (MoS) plot or rather a safe design case. It was

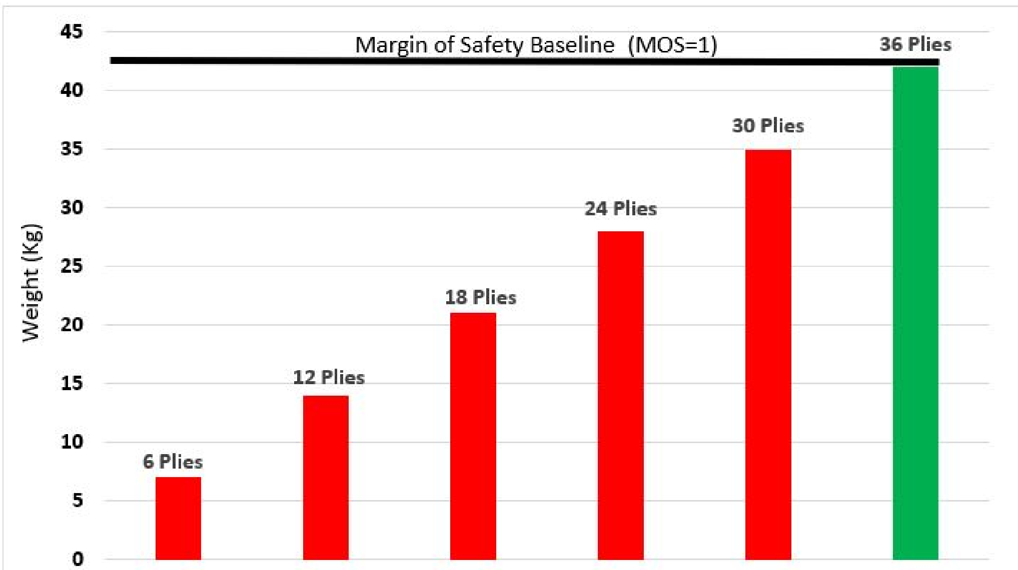


Fig. 7.3. Schematic of Effect of Increment in Ply Count on Weight and MoS of the Monocoque

noted that in order to produce a safe design 30 plies are required. It is concluded that the monocoque is safe under the loading condition for the Fuel tank Test if a total of 24 plies are applied (Positive MoS). Similarly, for the monocoque to be safe for the Survival Cell Side Test, it is noted that 36 plies are a minimum requirement (to produce a positive MoS). Thus, if a monocoque is to be constructed that passes both the static load tests it needs to have a maximum of 36 layers of the chosen fabric. In reality manufacturing a monocoque with repeating the stack-up even once i.e. with 12 plies is a time-consuming task. Every single ply is laid up manually over a monocoque mould. Furthermore, these plies undergo an extensive manufacturing process to produce desirable material and mechanical properties. Therefore, having a monocoque with 36 plies is neither time or cost effective. Addition of 36 plies is also going to make the monocoque bulky. A schematic of increase in weight with addition of plies is shown in Fig. 7.3. A final weight of 42.08 kgs of the monocoque with 36 plies is reported by ANSYS. Even if the chassis was divided in two sections and 24 plies were applied to the floor and the 36 plies were applied to the side wall, we achieved some reduction in weight. However, the deformation is still high. Furthermore, the weight of the roll hoops and the metal inserts necessary to mount the front and rear suspension systems, engine etc will add another few kgs to the structure. With an intention of reducing the number of plies and hoping to reduce the current weight a honeycomb structure was introduced in the stack-up.

8. ALUMINIUM HONEYCOMB CORE

A relatively weak honeycomb core structure is sandwiched between two thin stiff faces. The concept of such a sandwich construction is that the core transmits the shear load and the skin takes the bending load [20].

Sheet metal honeycomb core offers good properties at reasonable cost. Sandwiching a honeycomb structure helps to gain huge structural efficiency without a huge weight penalty [21]. The concept behind a sandwich construction is that the core transfers the shear load and the stiff skins take the bending load [21].

Table 8.1.
PCGA-XR2 AL Honeycomb Properties

Material Property	Units	Values
Density	PCF	5.2
Cell Size	in	0.25

This helps the chassis to reduce the deformations observed and keep the weight to a minimum. PCGA-XR2 commercial Al honeycomb of cell size quarter inch is chosen for this research (Table 3). The new stack up with the core sandwiched in between was thus resulting into a symmetric laminate. Failure analysis was now performed on the monocoque for Survival Cell Side test and Fuel Tank Test but with the new stack up.

9. FAILURE ANALYSIS WITH ALUMINIUM HONEYCOMB CORE

9.1 Failure Analysis with Aluminium Honeycomb Core (Survival Cell Side Test)

The monocoque was tested initially at 5mm core to observe the deflection achieved. It was noted that the deflection had greatly reduced but was still over 20mm. It was noted the deflection is 49.53 mm. Hence the core thickness was then gradually increased from 5 mm to a thickness where the deflection was below 20 mmas shown in the table below. The deflection at core of 14 mm is 19.8 mm. To reduce the

Table 9.1.
Effect of Core Thickness on Deformation - Fuel Tank Test

Core Thickness (mm)	Maximum Deflection (mm)
5	49.53
6	41.9
7	36.5
8	32.9
9	30.1
10	27.5
11	25.2
12	23.2
13	21.3
14	19.86
15	18.18

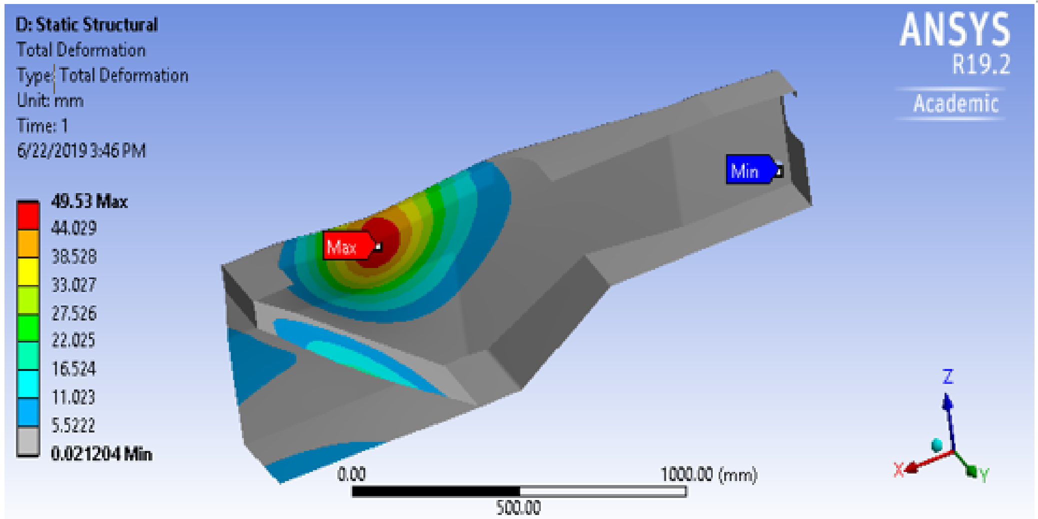


Fig. 9.1. Survival Cell Side Test - Deformation Plot - 5mm core

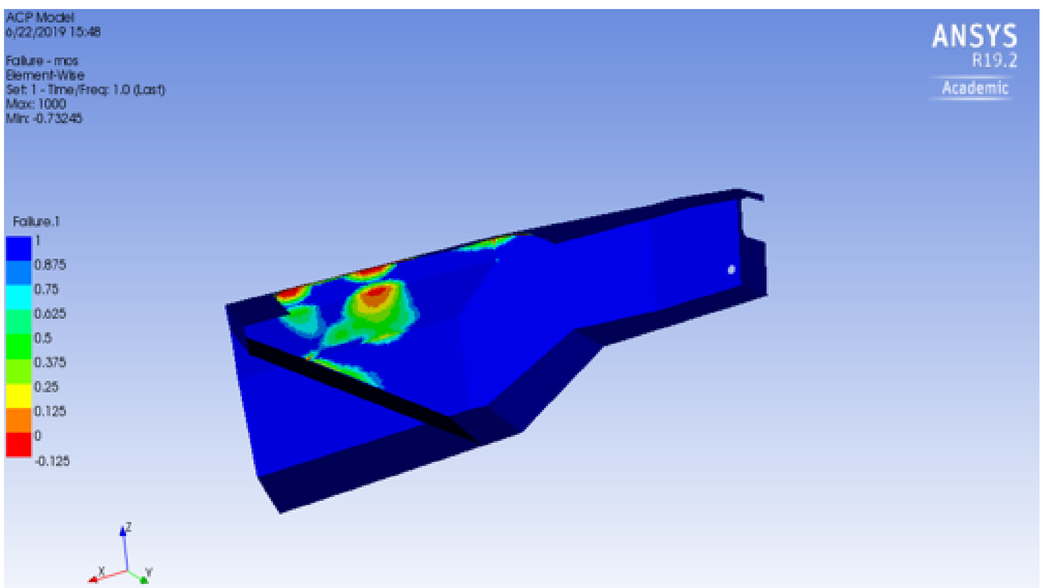


Fig. 9.2. Survival Cell Side Test - Margin of Safety Plot - 5mm core

deflection a bit more a core of 15 mm is finally selected. At a core of 15mm the failure analysis was performed. It was noted that the side walls performed well (Figure 9.2). However, the rim of the monocoque had elements that were still failing. The thickness was further increased gradually until the rim passed the failure criteria. It was noted

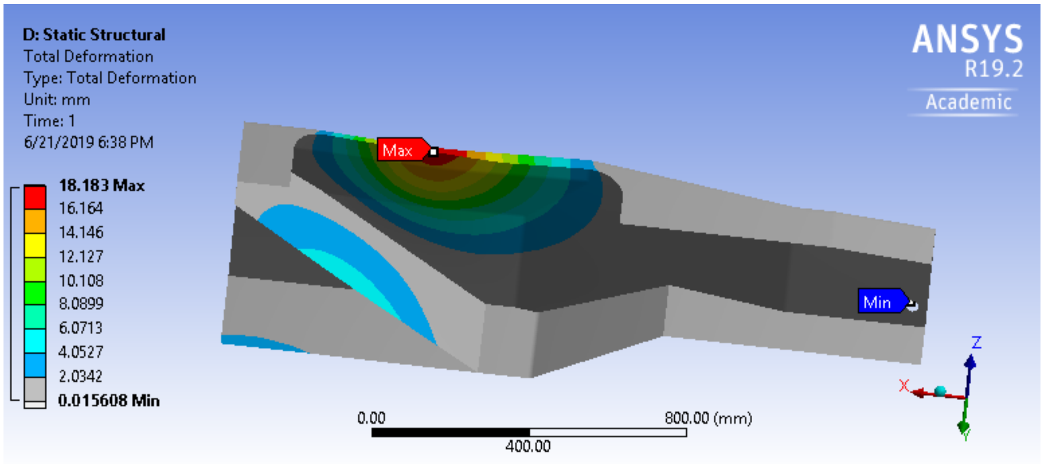


Fig. 9.3. Survival Cell Side Test - Deformation Plot - 15mm core

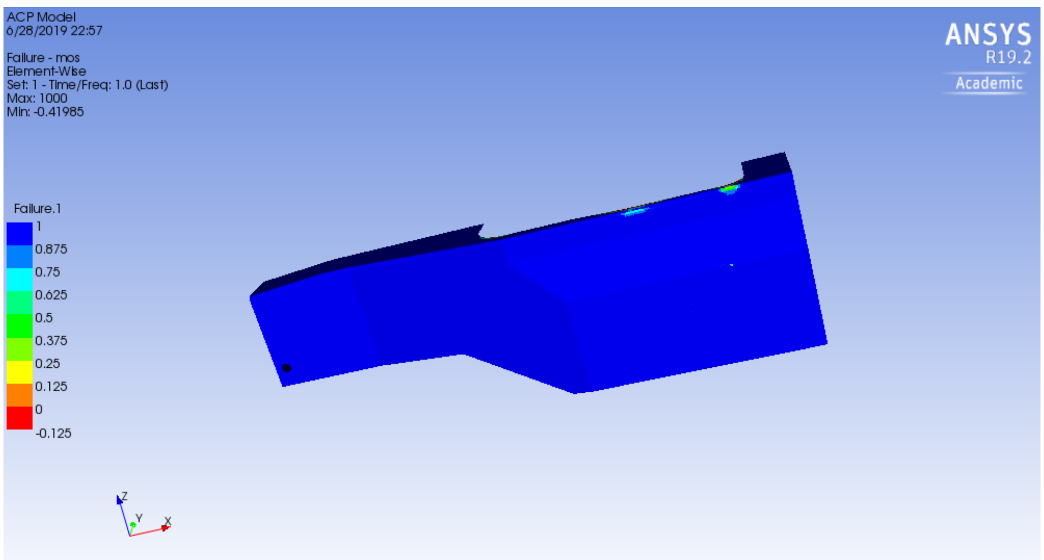


Fig. 9.4. Survival Cell Side Test - Margin of Safety Plot - 15mm core

that the rim had to be increased to a thickness of 23 mm to get satisfactory results. This was evident by the margin of safety plot. All the elements have a margin of safety of 1 and above. No red ones were seen. The test helped to come up with two zones.The rim of the monocoque and the side walls of the monocoque. The next region to be tackled was the fuel tank region.

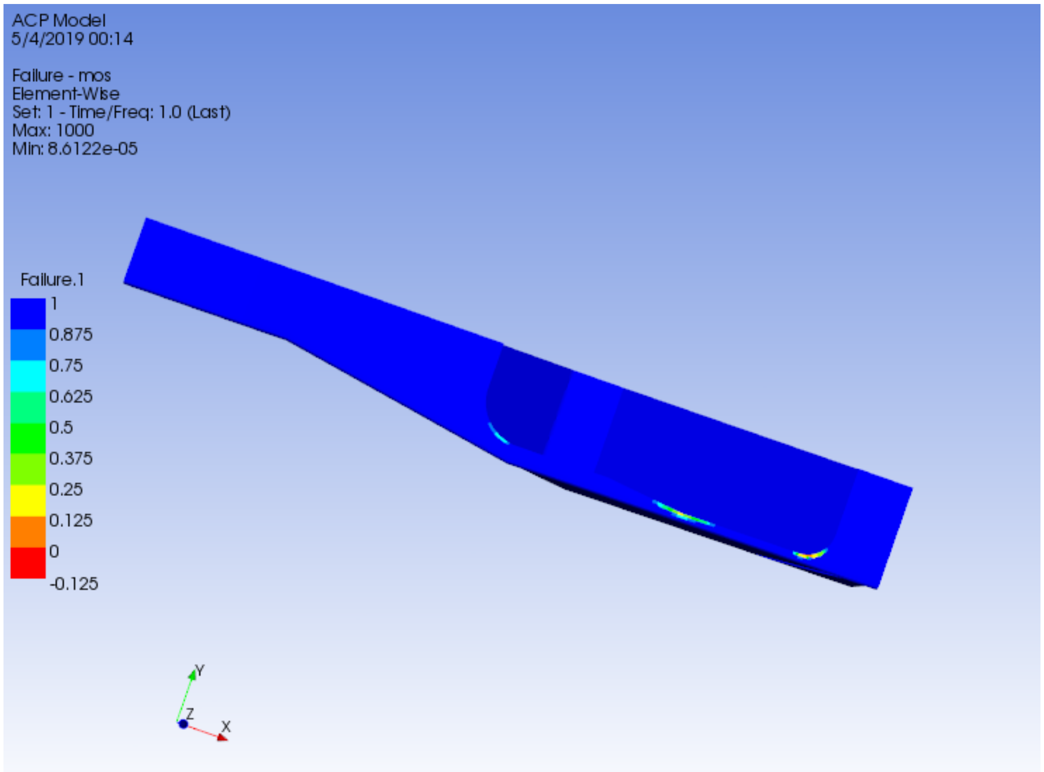


Fig. 9.5. Survival Cell Side Test - Margin of Safety Plot - 23mm core

9.2 Failure Analysis with Aluminium Honeycomb Core (Fuel Tank Test)

For the fuel tank test a pilot test with 5 mm thickness was performed. It was note that the deflection was 87.2 mm (Figure 9.4). Just like the survival cell side test parameterization was performed at the thickness was gradually increased. At each thickness the deflection was measured. It was noted that the fuel tank test performed well at the thickness of 13 mm. The deflection reported was 18.24 mm (Figure 9.5). Finally, it was decided that the floor was safe at a core of 13 mm. Failure analysis at this point was done. A positive margin of safety plot was produced. Since all the elements still passed. A core of 13 mm was finalized.As it is noted from above table that 12 mm core thickness gives a deflection of less than 20 mm. However, the deflection is very close to 20 mm. Hence the core is reduced even more to 13mm, At 13mm of core thickness the deformation is 18.24 and hence it is chosen. At this point it was clear that a core of 13 mm will help the monocoque to pass the fuel tank test. However, in order to pass the survival cell side test a core of 15 mm is required. Even at this point the rim around the cockpit was failing and hence the rim core thickness has to be 23 mm thick.

Table 9.2.
Effect of Core Thickness on Deformation - Side Test

Core Thickness (mm)	Maximum Deflection (mm)
5	87.3
6	64.3
7	49.6
8	39.5
9	32.4
10	27.04
11	22.9
12	19.9
13	18.24

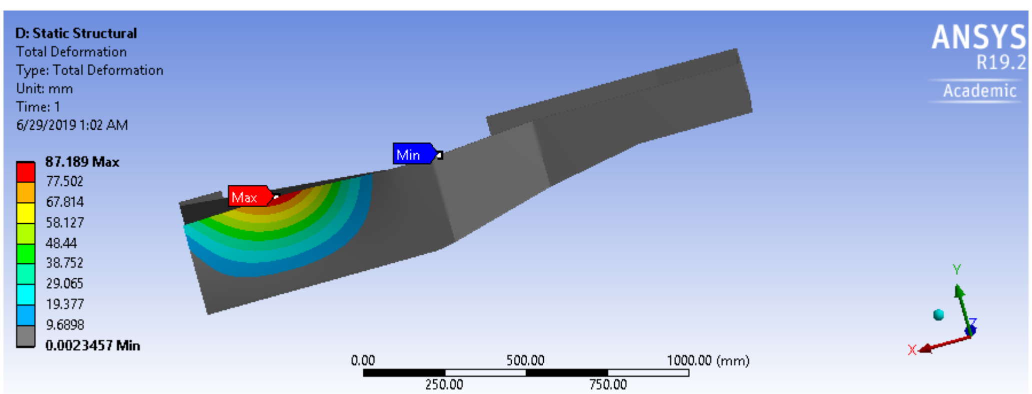


Fig. 9.6. Fuel Tank Test - Deformation Plot - 15mm core

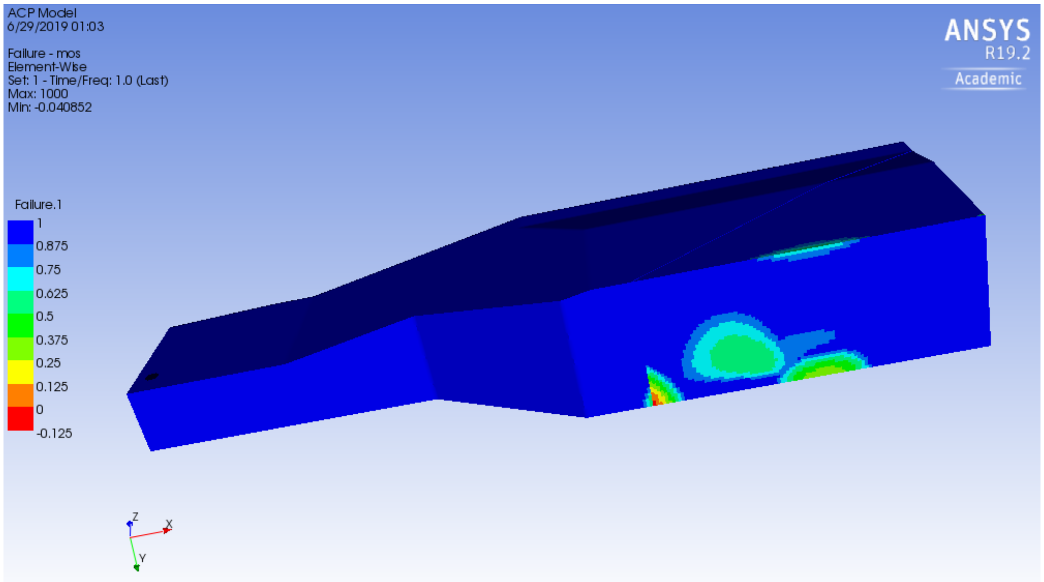


Fig. 9.7. Fuel Tank Test - Deformation Plot - 15mm core

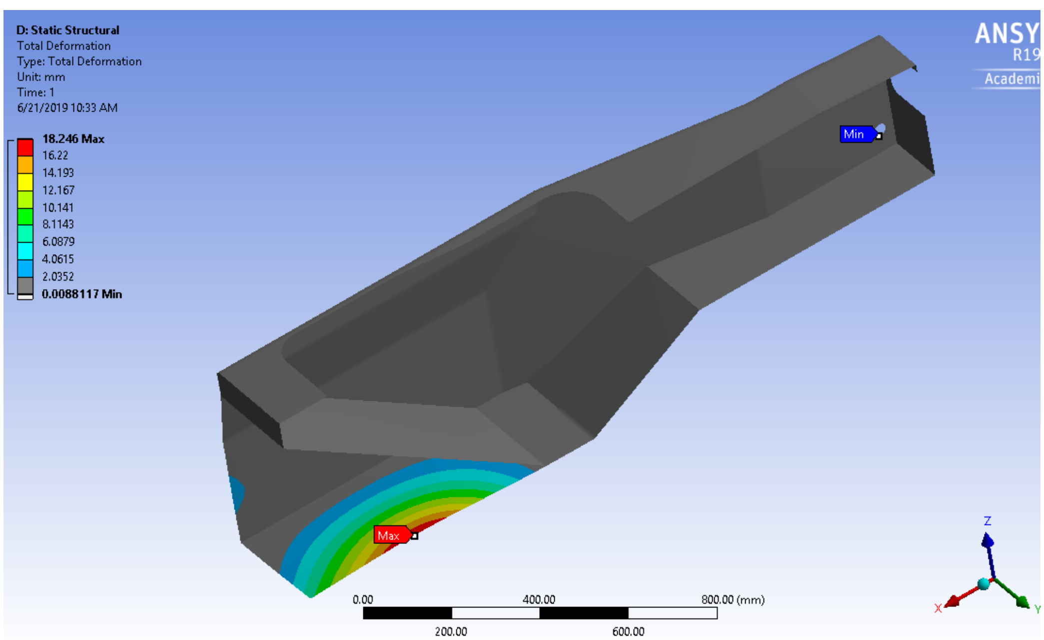


Fig. 9.8. Fuel Tank Test - Deformation Plot - 15mm core

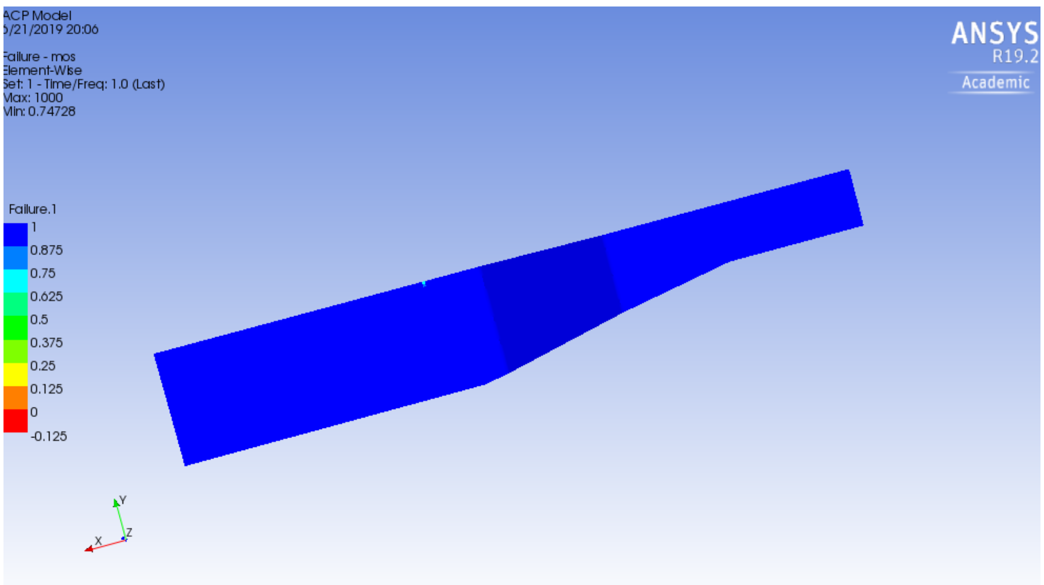
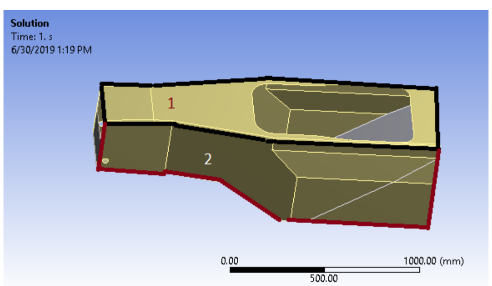


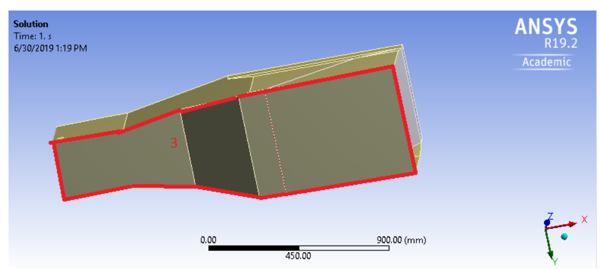
Fig. 9.9. Fuel Tank Test - Deformation Plot - 15mm core

10. MONOCOQUE DESIGN WITH VARYING CORE THICKNESSES

From previous failure analysis results it was proved if the monocoque had a core of 23mm throughout its body it will pass the both the tests. However a 23 mm core is not required all over the monocoque body as this will add unnecessary weight. Finally, to optimize the monocoque for weight it was divided into three parts and the core thickness varied in these three regions from 13 mm to 23mm.The rim area was given a thickness of 23 mm. The entire floor of the chassis would have 13 mm core thickness and the side walls along with the area in from of the bulkhead would have 15 mm core thickness. The weight at this point was 11.42 kgs. The monocoques weight



(a) View 1



(b) View 2

Fig. 10.1. Monocoque with Three Zones

change through a series of steps before coming to a final core thickness variation is shown below. It is fair to estimate that the chassis with metal inserts,roll hoops and rear section tubings would be another 13.13 kg heavier. In that case we can assume this by adding 13.13 kgs to the current composite weight

Table 10.1.
Monocoque with Three Zones with Varying Thicknesses

Area Number	Core Thickness (mm)
1	23
2	15
3	13

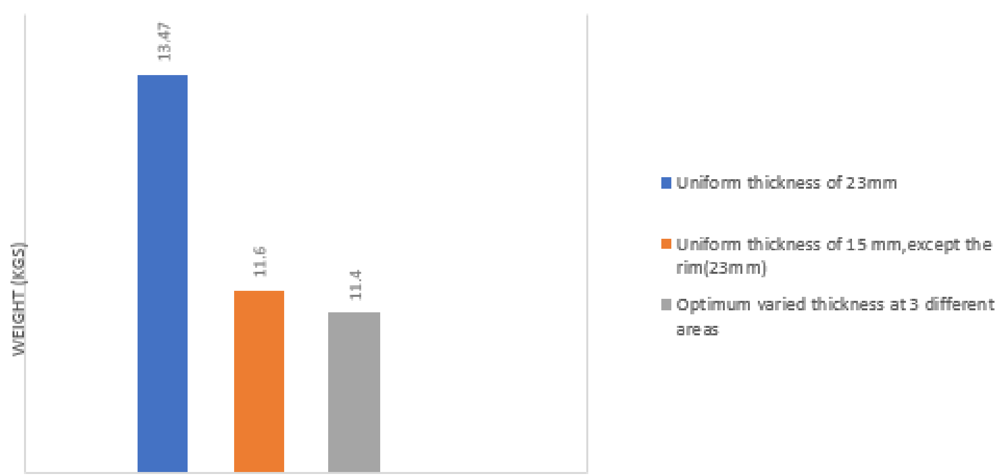


Fig. 10.2. Effect of Varying Core Thickness on the Monocoque Weight

11. TORSIONAL RIGIDITY OF THE MONOCOQUE

A very important characteristic of a chassis is its torsional rigidity. A newly manufactured chassis is is often judged by its handling performance, stiffness, lightness and the weight distribution [22]. If a race car handles correctly it will be easy to tune the handling balance. This essentially means that the driver can adjust the extent of the grip available from the front or rear of the car. A chassis believed to be balanced if both the front and rear axles produce similar force to produce similar acceleration [23]. A low stiffness is undesirable as it allows displacement of suspension attachment points. This can lead to changes in the suspension kinematics and lead to increase in vibrations. The suspension and vehicle dynamics team usually comes

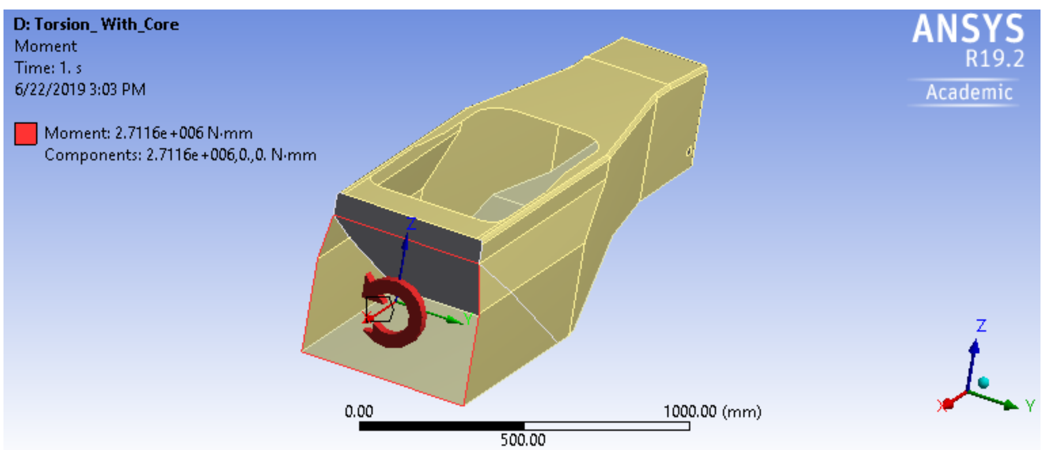


Fig. 11.1. Monocoque Subjected to Suspension Torque

up with a desirable value of torsional rigidity for a monocoque. For a formula student type racing sport a torsional rigidity of 500 Nm/deg- 800 Nm/deg is considered to be desirable [24]. These values usually come from experience and driver feed-backs about how well the monocoque performs during cornering in an actual test. These specifications vary for every team according to their monocoque design layup and to

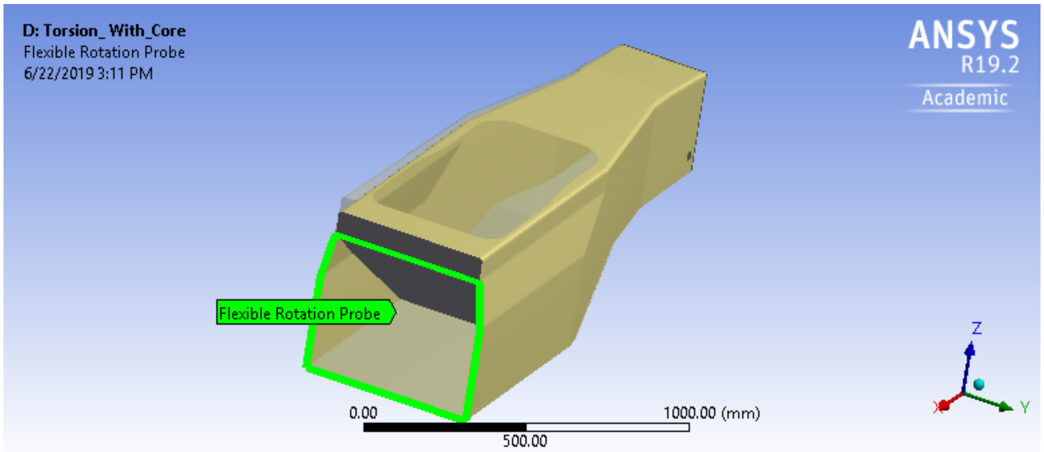
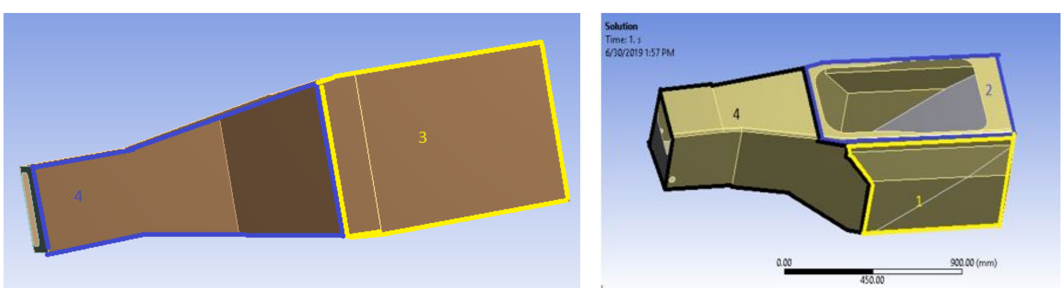


Fig. 11.2. Monocoque with Flexible Probe Activated

name but a few. A test for torsional rigidity is set in ANSYS as shown in the figure below. The monocoque is subsequently subjected to a suspension load(2711.6 Nm) and the behaviour of the monocoque is monitored.

The procedure for this tests was to simply check the change in angle the edge where the suspension load is applied goes through. Once this angle is known the torsional stiffness at that laminate and core thickness can be found. For this research a target of 1000 Nm/ deg was set. This value comes from the vehicle design team. A probe is then activated in ANSYS to see its change in angular motion or to measure the distance in theta that it moved by, this angle was used to divide the applied torque and torsional rigidity was found. At a weight of 11. 4kgs and a monocoque



(a) View 1 (b) View 2

Fig. 11.3. Monocoque with Four Zones

Table 11.1.
Weight and Torsional Rigidity of Monocoque With Varying Thickness - 3 ZONES]

Floor	Side Walls	Entire top	Weight	Torsional Rigidity
mm	mm	mm	kgs	Nm/deg
23	23	23	13.5	1420
15	15	23	11.5	895.6
13	15	23	11.4	906.2

with three different core thicknesses, the torsional rigidity was tested. It was seen the torsional rigidity was lowered than the target, it was 906.2 Nm/ deg. If the monocoque has uniform core thickness of 23mm the torsional rigidity was found out to be 1485.5 Nm/deg. However as seen in Figure 10.2 the chassis weight increased to 13.5 kgs. It was noted that the area from the steering wheel of the driver and forward was unexplored. To study the effect of changing the core thickness in the above mentioned area on the weight and the rigidity it was decided to divide the monocoque in four different regions as below. Different scenarios are tested to check an optimum thickness for the the fourth region to get the target torsional rigidity as well as the previous case of three thicknesses is checked. Table11.1 shows that if the monocoque has a maximum torsional rigidity of 1420 Nm/deg if the monocoque had a uniform thickness of 23 mm as per case I(Thickness at which it passes all the tests). However the weight of the monocoque in that case is 13.5 kgs. Since the target torsional rigidity was 1000Nm/deg the thicknesses chosen for area 1,2 ,3,4 are 16 mm, 23 mm, 13mm, 17 mm respectively. The weight of the monocoque at case 5 is 11. 2 kg and the torsional rigidity is 1008.6 kg. Further failure analysis at this case is also done and no failure was noted. Finally, the torsional rigidity and the weight of the composite monocoque at case 5 have been compared against CMT 2013 chassis is a 4130 steel alloy chassis [5]. The steel space frame weighed 32 kg for the team . We have added another 13.31 kg to our current weight of 11. 1 kg considering the added weight of the roll hoopes and rear engine section tubing.

Table 11.2.
Weight and Torsional Rigidity of Monocoque With Varying Core Thickness - 4 ZONES]

Area 1	Area 2	Area 3	Area 4	Weight	Rigidity
mm	mm	mm	mm	kgs	Nm/deg
15	23	13	14	19.3	8393
15	23	13	13	18.9	850.5
15	23	13	15	9.9	876.1
15	23	13	16	10.6	889.1
15	23	13	17	11.2	1008.6
15	23	13	19	11.9	1126.4
15	23	13	23	12.5	1359.1
15	23	13	24	12.7	1418.8
15	23	13	25	12.9	1507.8

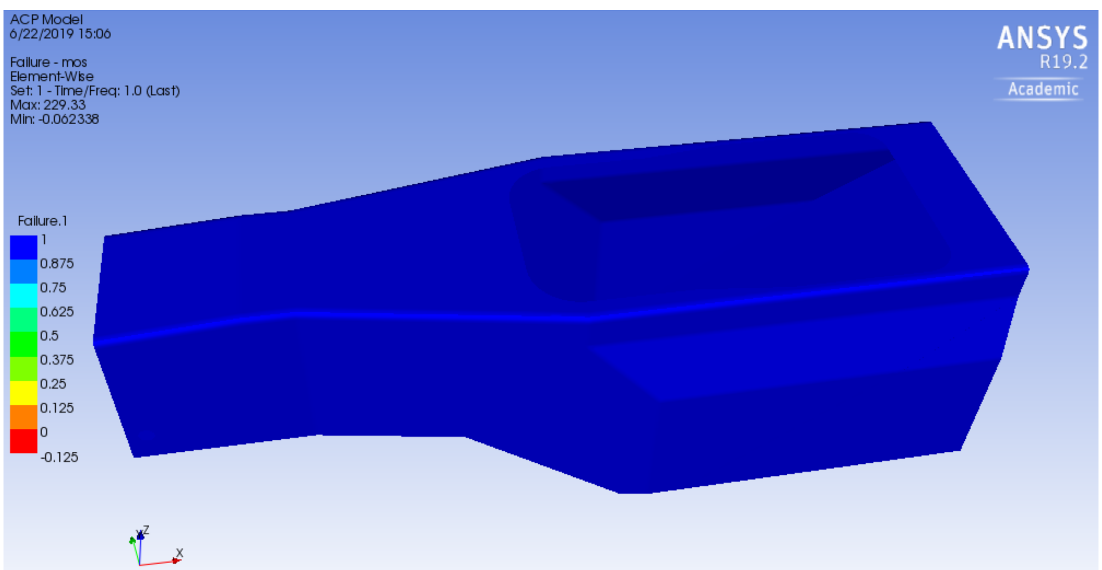


Fig. 11.4. Failure Analysis with Varying Core Thickness (4 Zones)

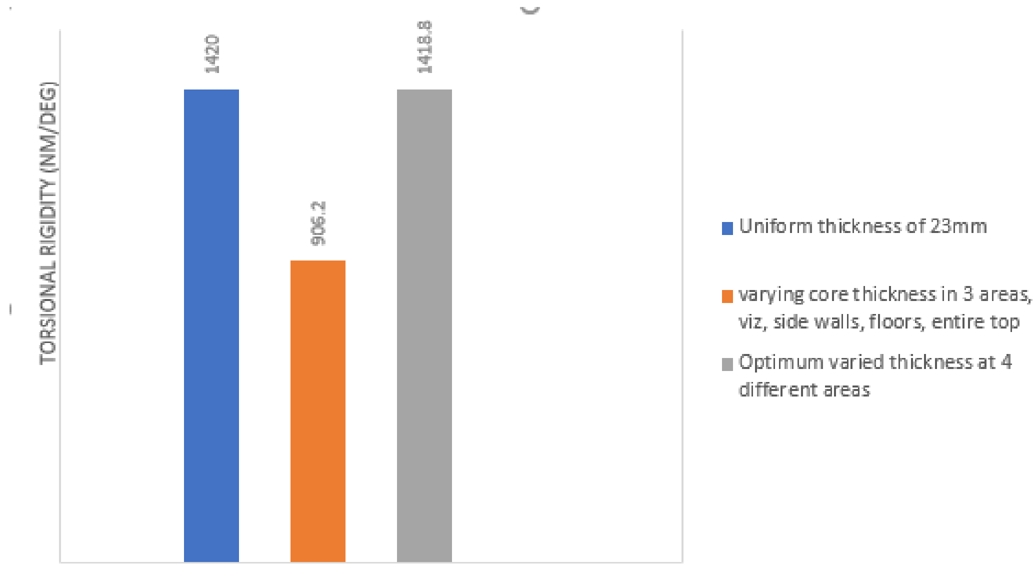


Fig. 11.5. Torsional Rigidity of the Monocoque at Varying Thickness

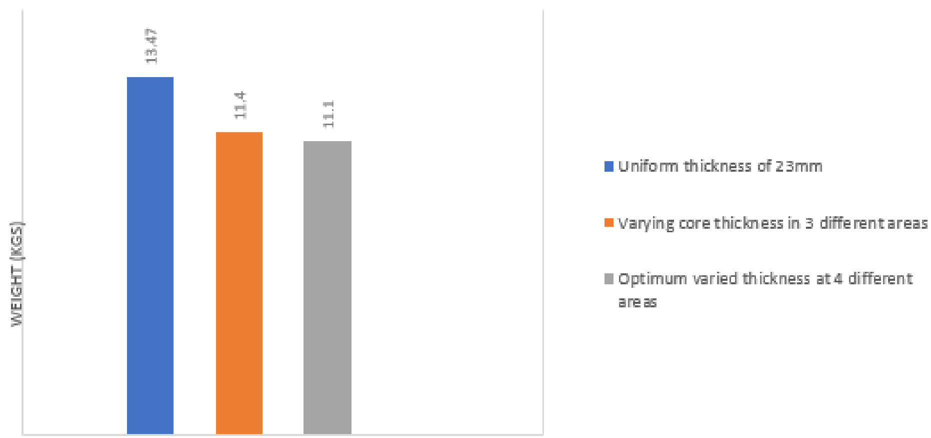
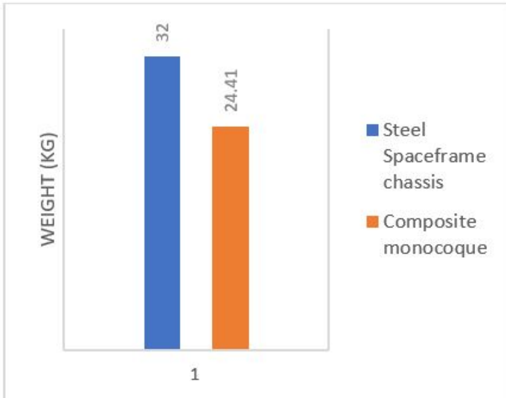
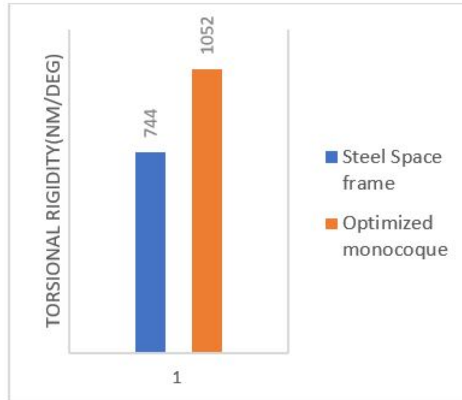


Fig. 11.6. Weight of the Monocoque at Varying Thickness

The weight of our chassis comes to 24.41 kg. The CMT steel space frame has a stiffness of 799Nm/ deg at a suspension load of 2000 Nm as opposed to our chassis of 1052 Nm/deg. (Fig. 11.7). The CMT chassis is a steel frame one, which assumes that the rear engine section take the load of the engine as well. Hence the rear section is a structural member as well. However for the composite monocoque designed it is assumed that the monocoque itself takes all the suspension load.



(a) Final Weight



(b) Torsional Rigidity

Fig. 11.7. Comparison of Carbon Fiber Monocoque and Steel Frame Chassis

It is not decided yet if a full monocoque should be constructed. If that decision is taken one has to consider one will have to consider heat transfer calculations and nodal calculations as well. An easier approach will be having a semi monocoque with steel sub-frame.

12. CONCLUSION

With the help of advanced simulation techniques a methodology is established to design and develop a composite chassis for SCCA races. Using Formula 3 regulations as a guideline the strength and the integrity of the chassis is evaluated. A stack-up which passes the mandatory static load test is designed. Designing our own fabric has helped to reduce the errors that industry usually faces by assuming some orthotropic properties. It is seen that introducing a core has had a significant impact on the stiffness of the chassis. Applying the failure theory criteria helped to identify the exact ply failing under a certain failure criterion. Instead of having a chassis with same laminate thickness over the body, critical zones are identified and reinforced. The chassis after being developed for weight saving and target stiffness was divided into four regions including of varying thicknesses of thicknesses of 13mm, 15mm and 23 mm and 17 mm. A comparison study with CMT Motor-sports team steel frame chassis showed that the current composite monocoque is 23 times lighter and 35 times stiffer.

REFERENCES

REFERENCES

[1] X. Chen and Y. Liu, *Finite element modeling and simulation with ANSYS Workbench.* CRC Press, 2014.

[2] F. Campbell, "Introduction to composite materials," *Structural composite materials*, vol. 1, pp. 1–29, 2010.

[3] R. Koide, G. von Zeska de Frana, and M. Luersen, "An ant colony algorithm applied to lay-up optimization of laminated composite plates," *Latin American Journal of Solids and Structures*, vol. 10, pp. 491–504, 05 2013.

[4] B. O'Rourke, "The uses of composite materials in the design and manufacture of formula 1 racing cars," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 204, no. 1, pp. 41–48, 1990.

[5] J. Christensen, "Carbon fibre monocoque chassis feasibility and manufacturability for fsae," SAE Technical Paper, Tech. Rep., 2015.

[6] J. Sloan, "Focus on design: Formula 1 team accelerates design-to-track speed," *High Performance Composites*, vol. 16, no. 3, p. 94, 2008.

[7] W. F. Milliken, D. L. Milliken *et al.*, *Race car vehicle dynamics.* Society of Automotive Engineers Warrendale, 1995, vol. 400.

[8] J. Dixon, "Tyres, suspension and handling," *Cambridge University Press*, 1991.

[9] G. Savage, "Formula 1 composites engineering," *Engineering Failure Analysis*, vol. 17, no. 1, pp. 92–115, 2010.

[10] C. Sulsters and R. Bekker, "Simulating formula one race strategies," *Vrije Universiteit Amsterdam*, 2018.

[11] L. L. Thompson, S. Raju, and E. H. Law, "Design of a winston cup chassis for torsional stiffness," *SAE transactions*, pp. 2571–2584, 1998.

[12] G.Savage, "Composite material technology in f1 motor racing," Honda Racing F1 Team, Report.

[13] P. Galpin, R. Broberg, and B. Hutchinson, "Three-dimensional navier stokes predictions of steady state rotor/stator interaction with pitch change," in *Proceedings of 3rd Annual Conference of the CFD Society of Canada, Banff, AB, Canada*, vol. 3, 1995.

[14] L. Hamilton, P. Joyce, C. Forero, and M. McDonald, "Production of a composite monocoque frame for a formula sae racecar," SAE Technical Paper, Tech. Rep., 2013.

[15] J. Wu, O. A. Badu, Y. Tai, and A. R. George, "Design, analysis, and simulation of an automotive carbon fiber monocoque chassis," *SAE International Journal of Passenger Cars-Mechanical Systems*, vol. 7, no. 2014-01-1052, pp. 838–861, 2014.

[16] L. R. Weidner, D. Radford, and P. Fitzhorn, "A multi-shell assembly approach applied to monocoque chassis design," SAE Technical Paper, Tech. Rep., 2002.

[17] Y. Liu and G. Glass, "Effects of mesh density on finite element analysis," SAE Technical Paper, Tech. Rep., 2013.

[18] M. G. Bader, "Selection of composite materials and manufacturing routes for cost-effective performance," *Composites Part A: Applied science and manufacturing*, vol. 33, no. 7, pp. 913–934, 2002.

[19] I. M. Daniel, "Failure of composite materials," *Journal of Strain*, vol. 43, no. 1, pp. 4–12, 2007.

[20] K. F. Karlsson and B. TomasÅström, "Manufacturing and applications of structural sandwich components," *Composites Part A: Applied Science and Manufacturing*, vol. 28, no. 2, pp. 97–111, 1997.

[21] F. E. Penado, "Effective elastic properties of honeycomb core with fiber-reinforced composite cells," *Open Journal of Composite Materials*, vol. 3, no. 04, p. 89, 2013.

[22] A. Deakin, D. Crolla, J. P. Ramirez, and R. Hanley, "The effect of chassis stiffness on race car handling balance," SAE Technical Paper, Tech. Rep., 2000.

[23] W. F. Milliken, D. L. Milliken *et al.*, *Race car vehicle dynamics*. Society of Automotive Engineers Warrendale, 1995, vol. 400.

[24] E. Sampo, A. Sorniotti, and A. Crocombe, "Chassis torsional stiffness: analysis of the influence on vehicle dynamics," *Tire and Wheel Technology and Vehicle Dynamics and Handling*, 2010.