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DESIGN OF A COMPOSITE GOLF DRIVER CLUB HEAD

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Abstract

The game of golf is enjoyed by a large number of people, from all over the world. According to the rules of golf, each player has to choose from a maximum of 14 clubs, before playing a shot. This makes the number of pieces of equipment required much higher than in any other ball related sport. This research project focuses on the design of a composite golf driver club head, the club head being the part of the golf club that strikes the ball. The driver club head is selected when a golfer wants to achieve a long distance shot. Modern driver heads are manufactured from metal, either steel or titanium and their performance can be defined as the accuracy and length of a shot. An investigation is made to compare the performance of composite and metal club heads.

The project included a study of an existing composite golf driver and the design of a new driver. The new shape was analyzed using non linear finite element software (Ls Dyna), and some overall design in composites and metals were done. It was found that the front face structural properties and geometry were critical to club's performances. So initially the front face only was considered (smaller model) using Ls Dyna and Nastran, before focusing again on the complete club head. Once the best design was done an attempt to manufacture a prototype was made in order to try to validate the computer model.

Experiments revealed that the new driver shape had a higher moment of inertia, which improves the accuracy of a shot, than the existing Callaway C4 club, for the same mass. The ball speed after impact for the new driver was 0.2 m/s less, when using a high strength carbon epoxy composite material compared to a titanium one. For this reason, it is concluded that it is possible to achieve similar overall performances with composite and titanium heads. It is anticipated that with more research into stronger fibres, 3 D fabrics and nano-reinforcements, a carbon composite club head will offer a greater overall performance than metallic golf club heads.

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Notation

- Back: Rear of the golf club head
- C4 Callaway: C4 Callaway Big Bertha
- CAD: Computer aided design
- Cm: Centimetre
- Cm^3 : Centimetre cube
- CNC: Computer numerically controlled
- COR: Coefficient of restitution
- CWE: Carbon woven epoxy
- Dm^3 : Decimetre cube
- E_1 : Young modulus in the main direction of the fibres
- E_2 : Young modulus perpendicular to the main direction of the fibres
- FEA: Finite elements analyses
- G_{12} : Shear modulus 12
- GPa: Giga Pascal
- m: Mass
- M / s: Meter per second
- Mm: Millimetre
- MPa: Mega Pascal
- Hz: Hertz
- UD: Unidirectional
- °: Degrees
- S_c : Shear strength
- V_f : Volume fibres fraction
- X_t : Tensile strength
- X_c : Compressive strength
- Y_t : Tensile Transverse strength
- Y_c : Compressive transverse strength
- ρ : Density
- [0/45/90]: That means the laminate has the plies oriented at 0, 45 and 90°.
- USGA: United States Golf Association

Introduction

The game of golf seems to appear in the 17th century. Since those old days the equipment and rules have evolved considerably and continuously. Today the rules of golf enable a player to carry 14 clubs during a game. Each club being different as some will be designed for hitting long shots from the tee (woods), others will be used to loft the golf ball over obstacles (wedges), and some others will be made for smoother accurate shots (irons). The biggest wood is known as the driver and is used to hit the longest shot from the tee. The driver's club head is usually made in titanium or steel, meanwhile some manufacturers have tried to sell some in composites with apparently little commercial success.

This project was done in collaboration with Cranfield University (School of Engineering) and the Audi design Foundation which was represented by the designer Mr. Gorse. For history, Mr. Gorse designed a new unconventional golf driver shape (supposed to have a better aerodynamic) and won a grant for this project. He then decided to develop the idea with the University of Cranfield where Prof. Vignjevic supervised the structural design work. The aim of the research was to design a composite golf driver club head from this new unconventional shape. Furthermore if the design was successful early in the project it could be tested via the manufacture of a prototype.

Numerous questions did spring to mind when starting this project, such as: What is a good performance driver? What are the structures of the best drivers (metal and composites) and how are they behaving during the swing? How do composites perform and how can they be modelled? Will the unconventional shape bring any advantages? Trying to answer those questions amongst other has been the focus of this research.

The first chapter reviews the latest information on driver design. Objectives of the project were set up and the methodology used was described.

In chapter 2, a high performance driver in composites from 2002 manufactured by Callaway was studied in an attempt to estimate its properties and design.

Some information on composite structures and FEA was then presented in chapter 3 in order to understand the structural design that was done. Numerous analyses were performed with two complete club head models and two front faces models. In order to understand the results, they are presented in a chronological order, as each model was

based on the results obtained from the previous one. The first model described in chapter 4 is a composite club head impacting a golf ball. Further tests were run on the front face only in order to better understand its behaviour and are presented in chapter 5. Finally a second complete club head model having a greater accuracy was run, leading to the final design that was then used to try to build few prototypes (one in high density foam and one in composite material). Following the presentation of the main results, a discussion links all those results together before proposing some directions for further work in the future.

Chapter I General

1.1 The aim

This project was aimed at designing a composite golf driver club head that would resist the impacts of the ball while giving an appropriate ball speed and shot accuracy. The new design was assessed by numerical simulation.

1.2 The need for the research

This research comes at a point where some big golf manufacturers like Callaway are trying and have developed some composite drivers as they have some advantages over metals. However this research is kept secret and the only way to make a performing driver in composites is by doing some independent research and starting from scratch. It is understood that the unconventional shape of Mr. Gorse's design which has an airfoil could increase the club head velocity and send the ball a longer distance. Composite materials have the advantages which allow for easy manufacture of a prototype and may lead to increase the structural performance of the club head. The aerodynamic considerations were not the scope of this study.

1.3 Background

1.3.1 Physics of golf

The golf driver club is number 14 in the golf club set and is designed to drive the ball as far as possible on a golf course. In order to achieve a long distance shot the driver club head has to be relatively big with a long shaft (about 1.1 meter) enabling a high club head speed (up to 42 m/s), the impact of the ball is equivalent to a force of 10000 Newton's on the front face, Penner [1]. During this very short impact (0.0001 seconds) the 4 cm radius ball can be deformed up to one centimetre. The club head front face deforms up to 0.2 mm (figure 1). Because of the high speed of the club head the driving golf shot is known as a very difficult one, hence the driver head is large in order to increase the chance of hitting the ball and increase its inertia and therefore its accuracy.

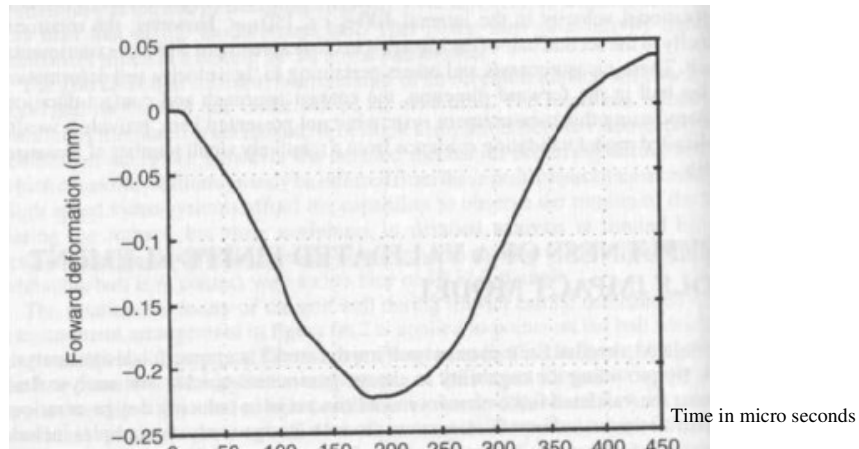


Figure 1: deformation of a titanium front face calculated from a finite element model, Hocknell [3]

1.3.1.1 Spring effect

Figure 2 shows the front face of the club head can be designed to flex at a natural frequency approaching the golf ball compression which is around 1000 Hz, Penner [1]. Figure 3 shows that the natural frequency of club heads can be lowered by increasing their size.

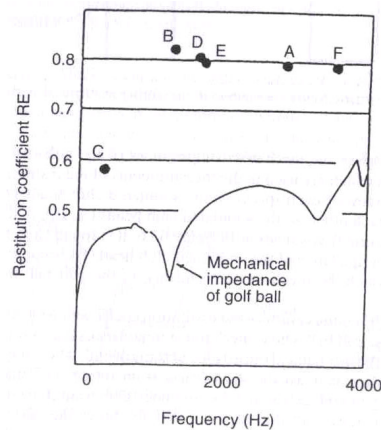


Figure 2: restitution coefficient of simulated golf club head, Yamagushi and al [2]

Matching those two frequencies can provide further energy to the golf ball after the impact enabling it to travel extra distance. This is known as “spring effect” and is forbidden in excessive proportion. Hence the rules of golf described in paragraph 1.3.2 specify that the coefficient of restitution should not be higher than 0.83.

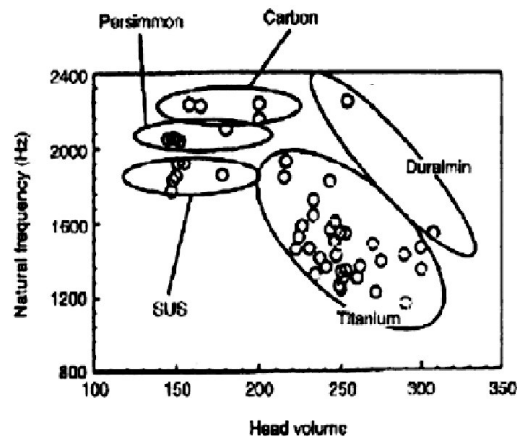


Figure 3: schematic figure outlining the relationship between the club head volume and natural frequency, Yamagushi and al [2]

The recent golf drivers made in titanium are designed with a large and thin front face (between 2 and 3mm) which possess a 1000 Hz natural frequency that other drivers struggle to reach (figure 1). It is thought that composite drivers have more difficulties in achieving those properties because the front face needs to be thicker (5mm) to withstand the impact and so if made in carbon epoxy it is too stiff to have any spring effect.

1.3.1.2 Moment of inertia

High moment of inertia will reduce the rotation of the club head during the impact especially for an off centre impact which should lead to a straighter and more accurate shot (see chapter 1.4 for more information on the subject).

1.3.2 Rules of golf

Below are quoted relevant extracts from the rules concerning the design of golf clubs set up by The Royal and Ancient Golf Club of Saint Andrews [4] are quoted (06/2003):

- 1-C The overall shaft shall be at least 18 inches (457.2 mm)
- 2-C The shaft shall be attached to the club head at the heel
- 4-A The club head shall be generally plain in shape

Features not permitted:

- i) Holes through the head
- ii) Transparent material

iii) Appendage to the main body of the head such as knobs, plates, rods or fins, for the purpose of meeting dimensional specifications, for aiming or for any purpose, (exception may be made for putters).

4-B The distance from the heel to the toe of the club head shall be greater than the distance from the face to the back

5-A Materials and construction: any treatment to the face or to the club head shall not have a spring's effect at impact

5-B The whole of the impact area must be of the same material. Exceptions may be made for wooden clubs

Some new regulations are coming into force in January 2004, Peter Gorse [5], especially regarding dimensions:

- Toe to heel (width) maximum 5 inches, 127 mm
- Hence, the distance front to back (length) must be less than 127 mm
- Sole to crown (height of front face) maximum 2.8 inches, 71 mm
- Volume of club head must not exceed 470 cm³

1.3.3 Comments on the impact

Different approaches can be used to describe and to analyze impact behaviour. The impact of a golf club on the ball can be analyzed using rigid body impact theory and is characterized by a very small impact area and a variable impulse. Stronge [6] acknowledges that in this case stresses decrease rapidly with increasing radial distance from the impact area. Because the region of high stresses is small it can act like a very stiff spring. The contact force is large enough to rapidly change the normal component of the relative velocity across the small deforming region that surrounds the contact patch. Based on this it is thought that the golf club will require a very strong and thick front face and could be relatively light elsewhere. But because the golfer constrains the shaft in rotation at impact, a bending moment develops between the shaft insert constraint and the impact force.

1.3.4 Fibres reinforced composites and impacts

One of the main problems in the use of fibres reinforced plastic is that they have a relatively bad resistance to impact in the direction normal to the laminate; this is especially true for carbon fibres reinforced composites, Maravilla and Vitoria [7]. Reid and Zhou [8] acknowledge more specifically that those fibres have no or little plastic

deformation during impact and possess low transverse and inter-laminar shear strength. They believe that in general fibres are strain rate insensitive in comparison to the polymeric matrix and that unidirectional composites are less strain rate sensitive than woven composites. It has also been shown that composites made of woven fabric have a better resistance to impact than unidirectional fabric, Abrate [9], and a lower resistance to fatigue compared to unidirectional ones, Matthews and Rawlings [10].

1.3.5 Shape optimization

Some very important considerations need to be taken into account when designing the shape of the club head. This shape needs to be appropriately designed in order to appeal to consumers, but also approved by the USGA (United States Golf Association), hence a plain and relatively traditional shape. The new golf driver designed by Mr. Gorse might encounter some problems regarding the traditional aspect of the design due to the presence of an airfoil and some “ears” features (figure 4). This was developed in order to reduce its drag coefficient, hence increasing the ball speed after impact.

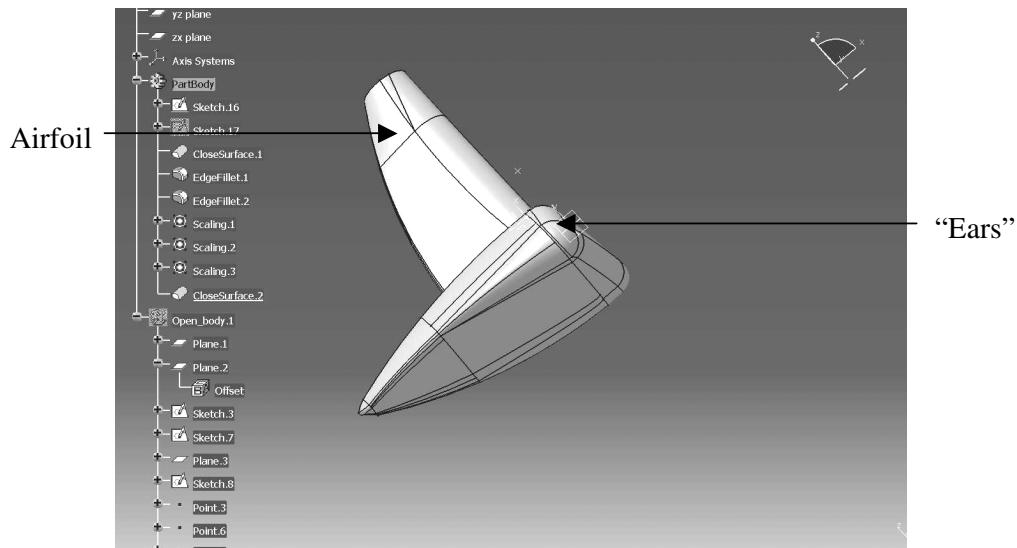


Figure 4: early new golf club head model

Another limitation is the maximum volume of the club head which must not exceed 470 cm^3 according to rules of The Royal and Ancient Golf Club of Saint Andrews [4]. Further considerations need to be taken into account in order to improve the ball speed. Those are mainly linked to the front face shape. Hocknell [17]

acknowledges that high performance drivers should have a larger face so that the larger volume will contribute to producing a greater moment of inertia.

The most appropriate way to increase impact efficiency will be met by increasing the area and the ratio of the front face, meaning that ideally the width should be similar to the height leading to a front face which will have a more circular appearance.

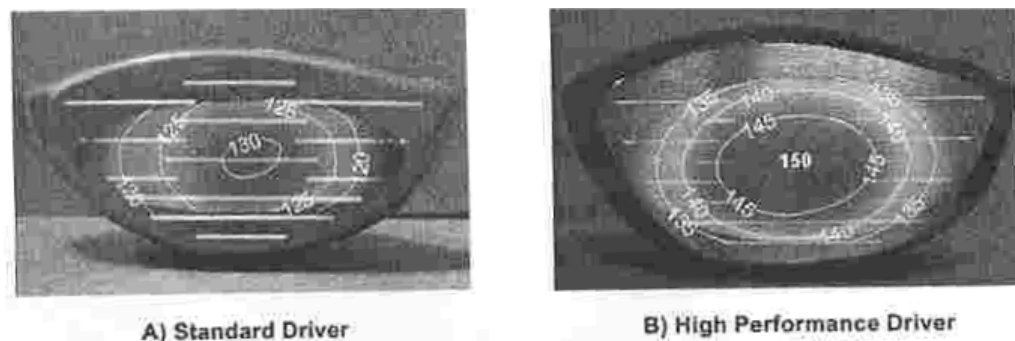


Figure 5: two types of drivers, Hocknell [17]

Figure 5 gives the ball speed at launch in miles per hours depending on location of impact on 2 different drivers. The large driver give a better ball speed as well as higher efficiency in the of centre impacts. This is of benefit to average golfer rather than to the accomplished ones [17]. Finally the ball speed can be increased by varying the front face thickness, which has to have a life of at least several thousands of hits.

1.3.6 Understanding the design problem

An important part of this project was to gain a correct understanding of the design problems of the golf club head (figure 6). Hence a careful analysis was essential to keep an open mind in order to move forward, concentrating on details enabling to get a successful new product [Mingo 2001].

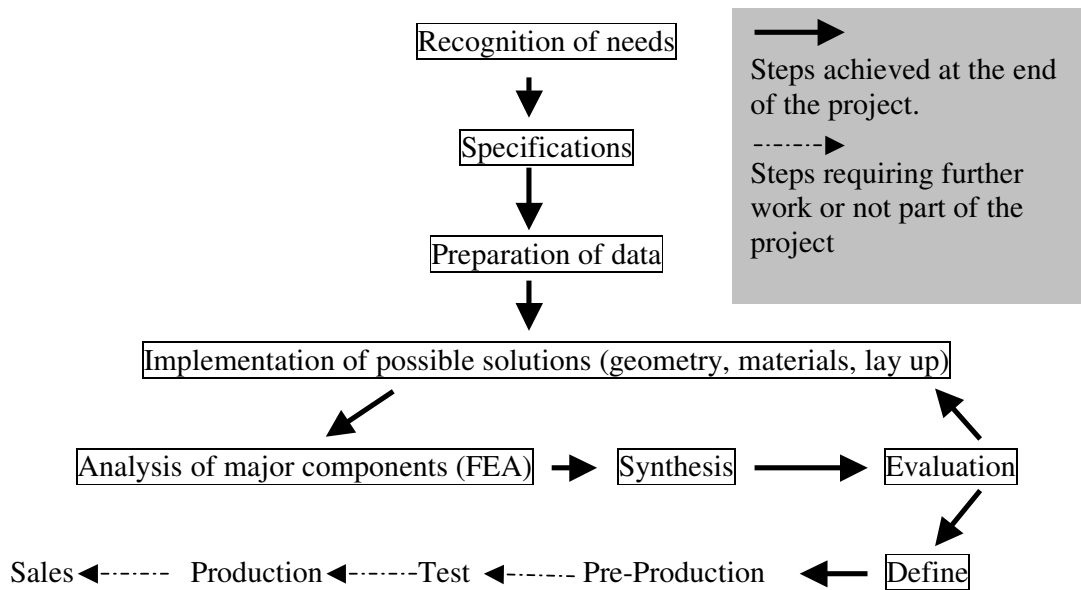


Figure 6: steps followed for the design procedure

Figure 6 is a detailed diagram describing the overall view on how the design procedure was approached. However this is quite a general view therefore an Ishikawa diagram (figure 7) for a composite golf club head will be done in order to provide a better understanding of the requirements on the design at the start.

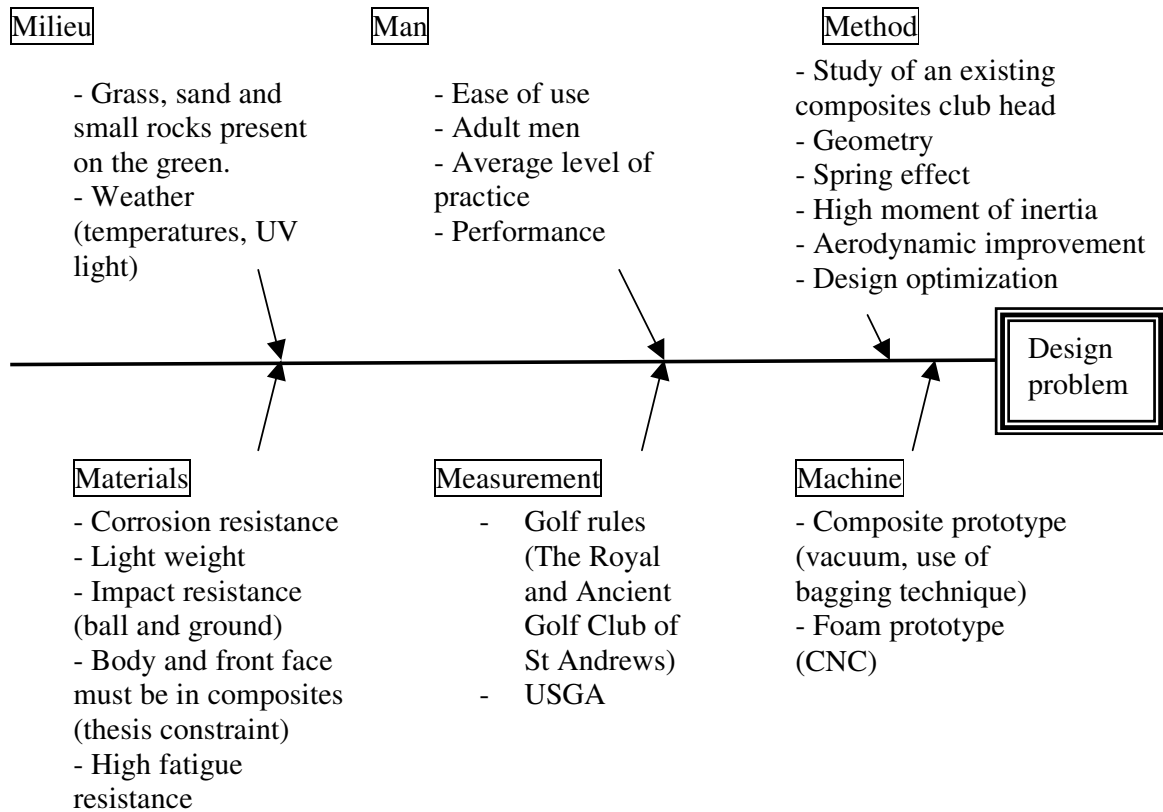


Figure 7: problem analysis/ design of a composite golf driver club head (Ishikawa diagram)

1.4 Objectives of the project

The purpose of this project was:

- To understand the project history, the physics of golf and the parameters important to the design.
- To create a CAD model of the club head in accordance with Mr. Gorse's ideas. This CAD model should be computer cut via a CNC machine in order to physically see the shape due to its high importance to appeal to consumer's eyes.
- To study an existing composite golf driver from Callaway (C4 Big Bertha) and determine its centre of gravity, moment of inertia, weight, front face radiuses of curvature and the front face lay up.
- To understand the mechanics of composites under impact loading and the use of FEA software.
- To model the impact of the ball on a composites club head and try to improve its moment of inertia of the club head and the ball initial velocity.

- To compare the outputs from the FEA software to the C4 Callaway (driver bought and studied in the project).
- To manufacture and test a prototype based on the optimum design.

1.5 Methodology used

The methodology used was complex to explain therefore a good way to understand this work is to look at the flow diagram given in figure 8.

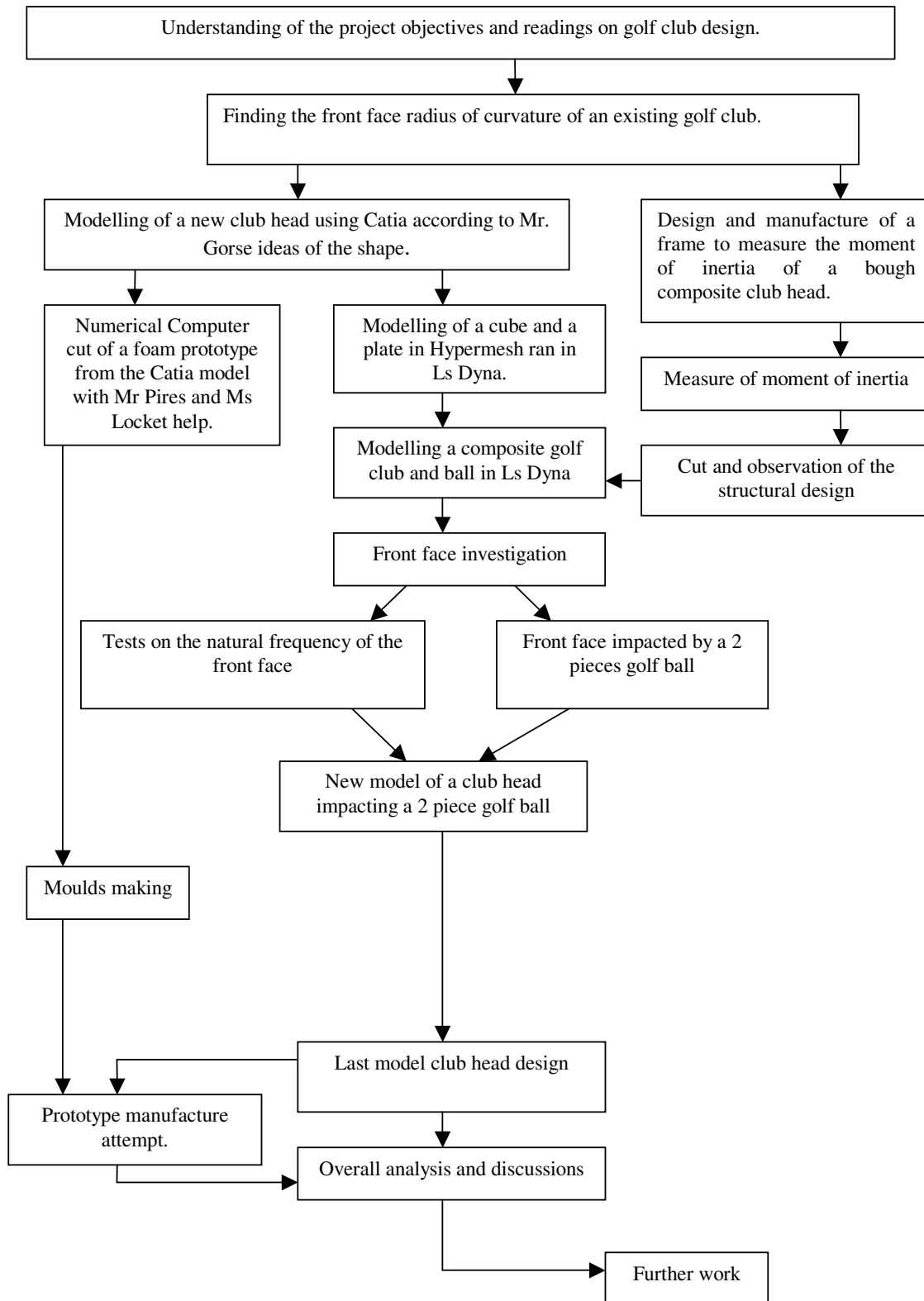


Figure 8: flow diagram of the research

Chapter II Study of the C4 Callaway club head

This section deals with the moment of inertia measurement and the structural study of the C4 Callaway driver made from composites.

2.1 Finding the centre of gravity and the moment of inertia of the C4 Callaway

By placing the club head on a rotating disc, its moment of inertia can be computed, via the frequency of the oscillations measured. For this measurement the club head centre of gravity had to be collinear with the axis of rotation of the rotating disc. Furthermore to get accurate results it was necessary to measure the period of several oscillations on 3 different orthogonal axes (X, Y, Z) and then 2 other measurements at plus and minus 45° for X, Y and Z axis.

2.1.1 Determining X, Y and Z orthogonal axes passing through the centre of gravity of the Callaway club head.

The centre of gravity of the club head had to be determined prior to finding the golf club head moment of inertia. The club's head was suspended from 3 different points and the intersection of those virtual lines was the centre of gravity. The practical procedure was to first find some visual orthogonal planes on the golf club's head. This was particularly difficult due to the curvature and non-symmetry of the shape.

2.1.1.1 Determining the Z axes position and orientation

Cotton was fixed to the club head, in a position where once the club head suspended by this cotton it had the grooves horizontal or the front face at 10.5° from vertical. A laser beam source collinear with the cotton was then lighted from underneath and a cotton was glued at this point (Figure 9). The virtual line between those two points was forming the z axes.

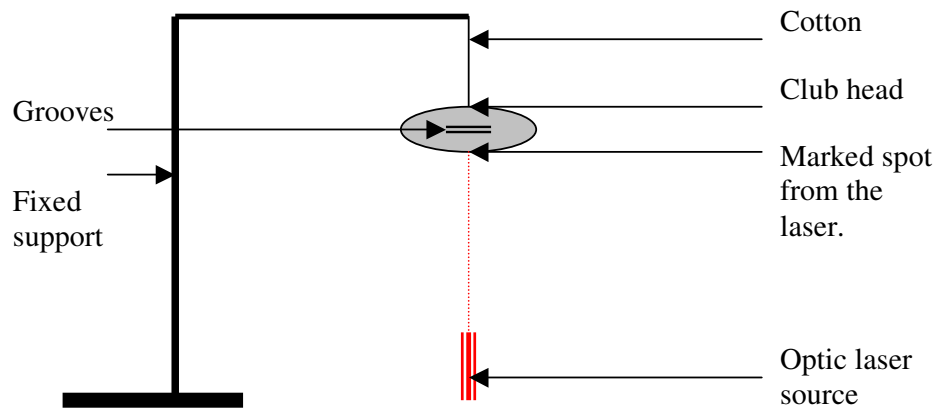


Figure 9: general view of the determination of the z axes passing trough the centre of gravity

2.1.1.2 Determining the Y axes position and orientation

Then the golf club is turned from 90° and suspended from its side, the grooves are this time vertical. The point underneath the club head indicated by the laser is marked again and cotton is glued, this was the second axis orthogonal to the first one (figure 10).

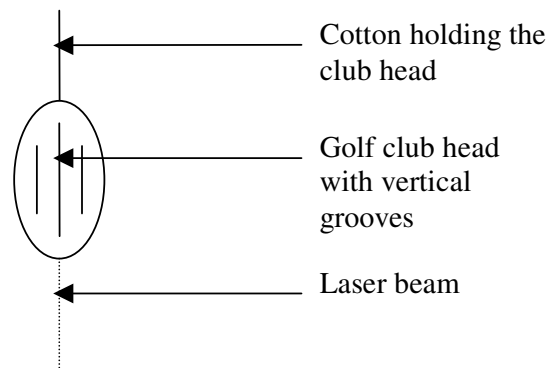


Figure 10: club head suspended trough the centre of gravity on the y axes

2.1.1.3 Determining the X axes position and orientation

Then the third plane was defined by suspending the golf club from its front face with the grooves being horizontal, the front face was oriented at 10.5° backwards (figure 11).

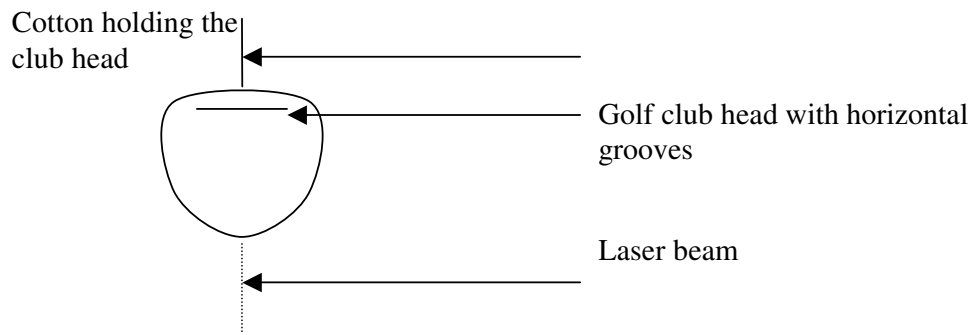


Figure 11: determination of the X axes orthogonal to Y and Z

2.1.2 Making of a frame to measure the moment of inertia

Because the inertia of the golf club head would be measured on those different axes, a frame was required and designed to allow such measurements. The frame had to be as light and small as possible and should allow for the measurement of the club head moments of inertia around the 3 orthogonal axes. For those reasons it was decided to manufacture a rectangular box (20×20×9.6 cm) out of light balsa wood (5.5 mm thick) incorporating an open side. In the middle of each face, a hole with small plastic inserts was made in which cotton threads were then passed and tensioned. The golf club was able to stand in the box and could be easily turned from 90° by simply rotating the box (figure 12).



Figure 12: Callaway Big Bertha Club head in balsa frames (the cottons represent the two orthogonal axes)

The golf club head was completely constrained by injecting some polyurethane blown foam (diphenylmethane 4, 4 diisocyanates, isomers and homologues) known for its easy use and light weight.

Figure 13 illustrate the club head constrained in the foam.

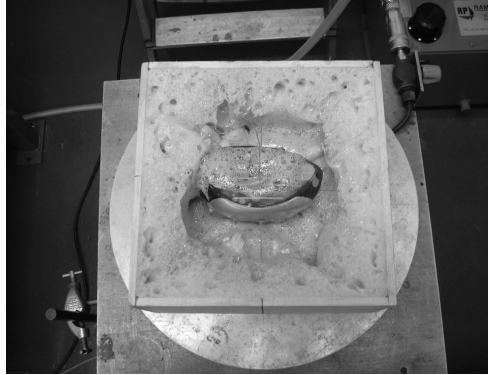


Figure 13: club head constrained with foam

2.1.3 The experiments

Calibration of the experiments was done by putting bodies with known moment of inertia on the inertia measurement apparatus. Based on measured data the stiffness of the springs was obtained, which was used later on for the club measurements (see below).

The moment of inertia was calculated along z axis using:

$I_{zz} = (1/12) * m * (a^2 + b^2)$ for a rectangular prism (with side dimension a and b, thickness c and mass m)

Or

$I_{zz} = 1/2 * m * (R^2)$ for a circular cylinder (radius R and mass m)

The moment of inertia on that axis was then measured by registering the period of an oscillation (several periods were actually measured).

Then the calculation of the experimental stiffness K of the two springs was done by using the formula adapted to this experiment:

$$I_{zz} = (k_1 + k_2) * (L^2) * ((T/2(\pi))^2)$$

With

$$K = (k_1 + k_2) * (L^2)$$

k_1 : stiffness of spring 1

k_2 : stiffness of spring 2

$L = 0.7$

T : Period of one oscillation

This calculation was done for each calibrating mass and a mean value of K was calculated (table 1). This value of K will be used when determining the inertia of the Callaway club head.

Experiment with	Shape	x	Y	Z	radius	mass	Izz theory	20 t for table plus calibrating masses	$(T/40\pi)^2$	K practical N/M
							calculated			
calibrating mass 1	rectangular	0.1	0.0761	0.0063		0.367	0.000482	8.765	0.00486	0.908
calibrating mass 2	rectangular	0.102	0.051	0.0126		0.506	0.000548	8.821	0.00493	0.923
calibrating mass 3	cylinder			0.046	0.02	0.453	0.000090	8.371	0.00444	0.876
table only								8.273	0.00433	
Mean stiffness of spring										0.902

Table 1: calibrating (finding the stiffness of the springs)

The theoretical value of K can also be calculated from the known theoretical value k_1 and k_2 with: $K=(k_1+k_2)*(L^2)=86.0636$ Newton meter.

Since the springs were old, their positions not perfect and there was some wear between the rotating disc and the support it was decided to use K's experimental value as it was more accurate than the theoretical value.

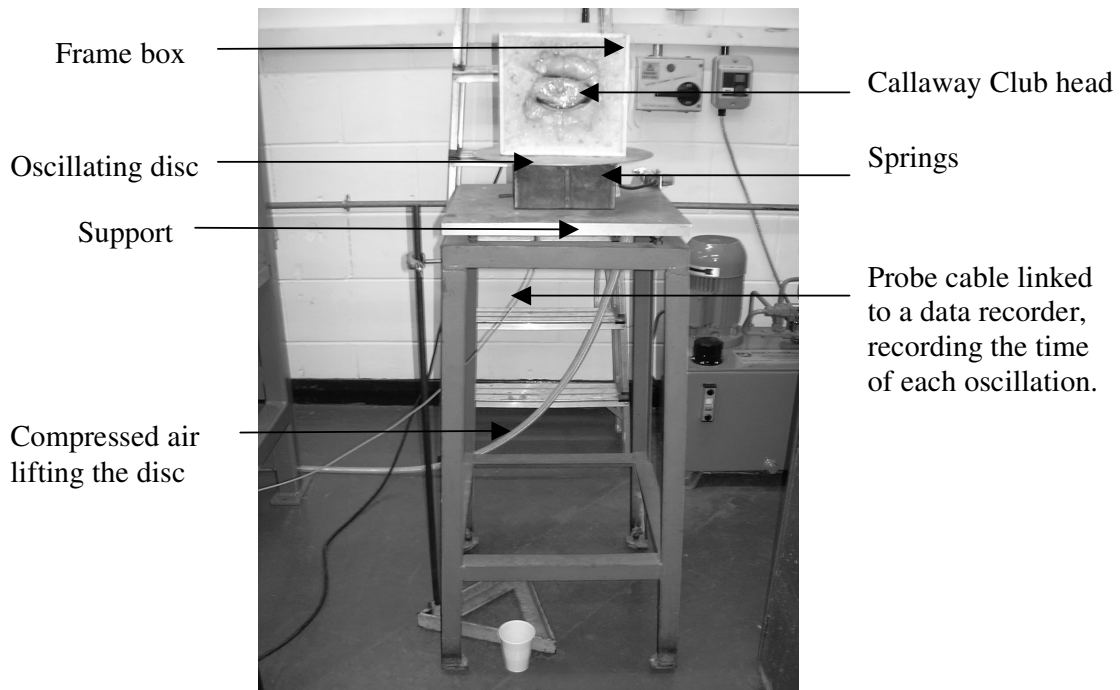


Figure 14: experimental setup

The frame box containing the golf club was placed on an oscillating disc (figure 14 and 15) making small rotation angles ($>5^\circ$). The disc had minimized friction because it was lifted by compressed air. The oscillations were initialized by just pushing softly the disc and could be assimilated to an impulse. The probe below the disc was then sending the timing of each oscillation to a computer recording 20 times 20 oscillations. Finally the computer gave the mean value of the period and the standard deviation. This experiment had to be repeated for the 3 axis (x, y and z) by simply rotating the box around those 3 axes and making sure that each time the centre of gravity of the club head would coincide with the disc axes of rotation.

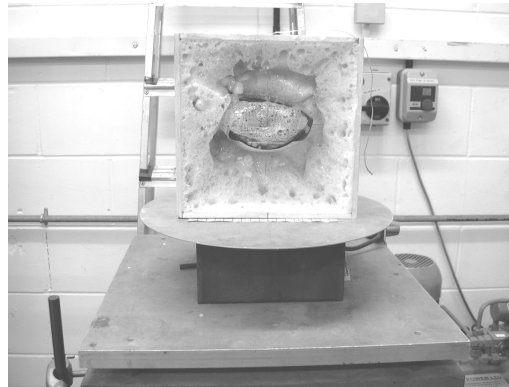


Figure 15: measuring the moment of inertia on z axis

In order to construct the inertia matrix, finding out the products of inertia was required and so the club head had to be rotated at plus and minus 45° in each plane xy, xz and yz (figure 16).

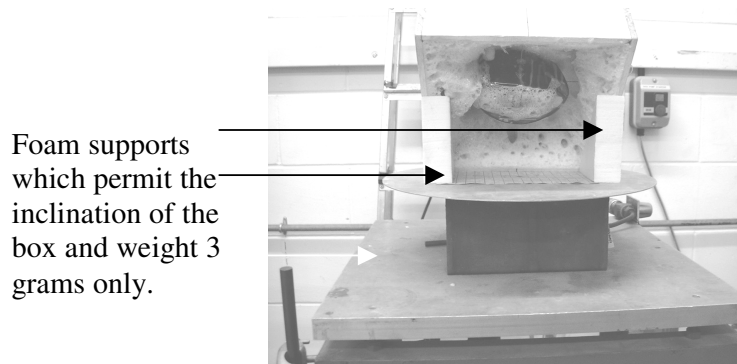


Figure 16: more measurements of inertia

2.1.4 Results and calculations for the moment of inertia

The results of the different moment of inertia measured are in table 2.

Type	Position/orientation	Time of 20 oscillations box + table + golf in seconde (mesured)	std deviation	$I = K \cdot (T/40\pi)^2$ box + table + golf	Time of 20 oscillations box+table in seconde (mesured)	std deviation	$(T/40\pi)^2 \cdot K$	$I = K \cdot (T/40\pi)^2$ for the golf club only (calculated)
Axes	Zz	9.678	0	0.00534	9.324	0.01	0.00497	0.000372
Axes	Yy	9.462	0.01	0.00510	9.261	0	0.00490	0.000203
Axes	Xx	10.195	0.01	0.00592	9.944	0.01	0.00565	0.000275
Plane	zy -45	9.623	0.01	0.00528	9.361	0.01	0.00501	0.000272
Plane	zy +45	9.651	0.01	0.00531	9.345	0.01	0.00499	0.000320
Plane	yx -45	9.949	0.01	0.00564	9.684	0.01	0.00536	0.000284
plane	yx +45	9.926	0.01	0.00562	9.707	0	0.00538	0.000233
plane	xz -45	10.032	0	0.00574	9.752	0	0.00543	0.000303
Plane	xz +45	10.021	0	0.00572	9.717	0	0.00539	0.000330

Table 2: measured moment of inertia ($m^2 \cdot kg$) of the Callaway club head

A program from the impact centre [34] using Mat lab then calculated the matrices of inertia with moments and products of inertia and found the principal moment of inertia and the orientations of the principal axes (see below).

27/05/03 14:34

MATLAB Command Window

Page 1

Callaway Golf Club Head

deviations from perfect fitting

1.0e-004 *

0.0356 ~~xy~~
0.1386 ~~yy~~
-0.0376 ~~zz~~
-0.0327 ~~yz~~ -
-0.0327 ~~yz~~ +
-0.1059 ~~xy~~ +
-0.1059 ~~xy~~ -
0.0703 ~~xz~~ +
0.0703 ~~xz~~ -

Unit:

Inertia in $kg \cdot m^2$

Angles in degrees

Moments and products of inertia

	x	y	z
x	0.00028 I_{xx}	-0.00003	-0.00001
y	-0.00003	0.00022 I_{yy}	0.00002
z	-0.00001	0.00002 I_{zz}	0.00037 I_{zz}

Principal moments of inertia

I1	I2	I3
0.00021	0.00028	0.00038

Direction cosines (column vectors)

x_direction
y_direction
z_direction

Theta1	Corresponding angles in degrees	Theta2	Corresponding angles in degrees	Theta3	Corresponding angles in degrees
0.31213	72°	-0.93292	-21°	-0.17953	-79°
0.94323	20°	0.28173	74°	0.17591	79°
-0.11353	-83°	-0.22425	-77°	0.96790	15°

>>

2.1.5 Discussion

The weight of the club head (194 grams) is comparable to some found in literature ([1] Penner) and will be the weight target for the new golf club design.

The centre of gravity was determined in great detail, but the experimental setup was difficult to realize and the margin of error on its determination was less than 2 mm. The moment of inertia ZZ calculated from the measurements is higher compared to I_{xx} and I_{yy} . This is due to the shape being larger in this plane and having ballast on the outside of the club which acts well to improve I_{zz} . Those values will be compared with the ones obtained for the new composite driver.

2.2 C4 Callaway structural analysis

2.2.1 General

In order to get a better understanding of the Callaway club head structure, the club head was cut approximately 3 cm from the front face using a metal saw. Surprisingly the inside of the Callaway club head was hollow and not fully solid as previously thought. The club head was made from a tapered carbon pre-impregnated epoxy shell including a tungsten ring at the rear. A note with the following initials, HST, was found inside the Callaway club head. Later Mr. Gorse [9] found out that this was referring to a company based in San Diego (USA) and specialized in the manufacture of advanced composites (www.hst-inc.com). The note also mentioned that the club head had been manufactured on 24th September 2001.



Figure 17: rear section of C4 Callaway Big Bertha club head

Figures 17 and 18 show that the laminate is tapered and thicker on the side where the shaft is fixed. Figure 17 shows the position of the tungsten ring (high density 19.3 dm³/kg) that increases the moment of inertia and some extra weight placed at the bottom of the club head to lower the centre of gravity.

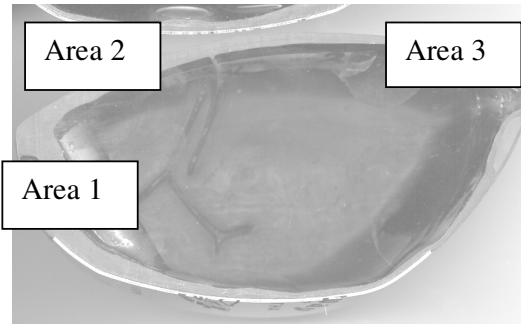


Figure 18: front face of the C4 Callaway from the inside

2.2.2 An attempt to microscopy

The front face section of the club head was looked at through a binocular microscope (magnification $\times 40$) in order to estimate the front face ply sequence (Cranfield University, Manufacturing Department). Prior to the observation, the front face was sanded and polished.

2.2.2.1 Observations

This brief description was useful and was an easy way to determine which plies were oriented differently from the horizontal and to what angles. The inner layer was a carbon UD epoxy layer oriented at 0° and this layer's appearance through the microscope resulted in plies 1, 3, 5, 7, 9, 11, 13 and 15 (table 3). No fibres were seen individually in those plies. Initially it was thought that those plies were carbon UD epoxy at 0° , the other layers had different orientation and the individual fibres could be seen.

However a concern arose quickly since through the binocular magnification 40, all fibres sections which were oriented above 0° (ply number 2, 5, 7, 9, 11, 13 and 15) were white and with identical size. This was not expected since carbon fibres are black when cut. At a later stage in the project, a prototype in carbon epoxy was made and the front face had also some plies which had a clearer colour. This shows that depending on a

carbon ply's orientation, it can reflect differently the colour, hence some looking whiter than others. Those whiter plies looked also unidirectional as no waviness were noticed.

The whole front face can be composed of unidirectional carbon epoxy fibre plies except for ply number 16 (table 3) which is a fabric one. Some had different thickness resulting in a different weight per area. In summary the front face can be composed of 16 layers of carbon fibres epoxy (15 unidirectional and one fabric).

layer number	orientation estimated	Materials	thickness (arbitrary ratio)
1 (inner)	0	UD carbon epoxy	4
2	45	UD carbon epoxy	30
3	0	UD carbon epoxy	30
4	15	UD carbon epoxy	4
5	0	UD carbon epoxy	30
6	45	UD carbon epoxy	4
7	0	UD carbon epoxy	60
8	60	UD carbon epoxy	10
9	0	UD carbon epoxy	60
10	45	UD carbon epoxy	4
11	0	UD carbon epoxy	30
12	30	UD carbon epoxy	4
13	0	UD carbon epoxy	30
14	60	UD carbon epoxy	4
15	0	UD carbon epoxy	10
16 (outer)	0/90	Twill carbon epoxy	2

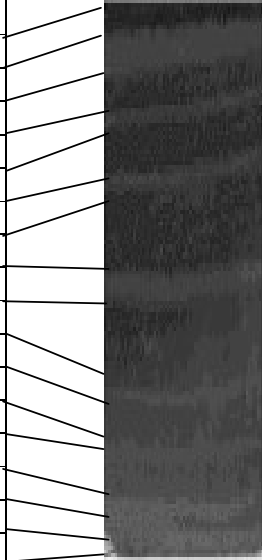


Table 3: details lay up of C4 Callaway Big Bertha front face

2.2.3 Brief discussion

The lay up of the Callaway club head that was found above should be considered with care as it was the result of a single attempt made during a very limited time. In order to learn more about the lay up, the opinion of someone who is used to look at carbon fibres through binoculars would help greatly. Another solution would be to dissolve the epoxy matrix with nitric acid at 70°C, and then to wash the remaining fibres with water, enabling hopefully to still be able to distinguish each layer from one another.

2.3 Manufacturing Process

Advice was given by J.Spooner and J. Hearley (two composite technicians) that the part was made via bladder moulding process. This is possible as this process is used to mould allow shapes. “Bladder moulding utilises a single mould cavity that produces a single controlled surface. The pressure is applied via compressed air onto a flexible membrane in contact with the composite. This manufacturing method has cheaper

tooling costs and can produce parts with undercuts or re-entrant surfaces. The heat is provided through an integrated tool heating system”, [27]. Figure 19 shows a mould used in bladder moulding process.

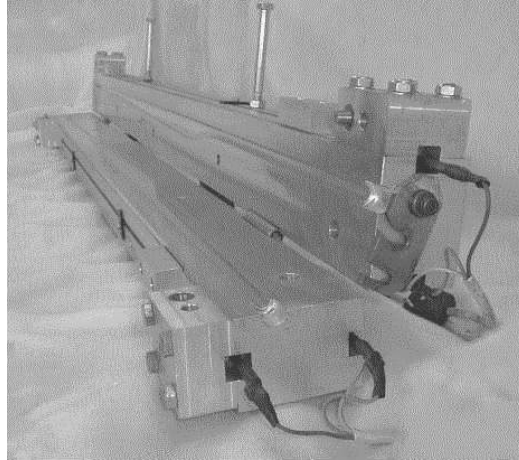


Figure 19: a picture of a mould used in bladder moulding process [27]

Chapter III Preparing the structural design

This chapter deals with the various tasks that were undertaken in order to prepare the structural design.

3.1 Creating the geometry

3.1.1 Front face bulge and roll

The front face of a driver has 2 radii of curvature, one horizontal and one vertical, the bugle and roll, respectively (figure 20). They are difficult to obtain and are critical to the ball flight. In order to find the appropriate numbers for those 2 radiuses, the front face surface of the C4 Callaway was 3D scanned by Dr. de Vuyst. The file was imported in Pro Engineer where the surface was reconstructed by linking all the dots that the 3D scanner had registered with lines. Then the surface in between the lines was filled prior to exporting the file to Catia VR 5.8 using an IGS format.

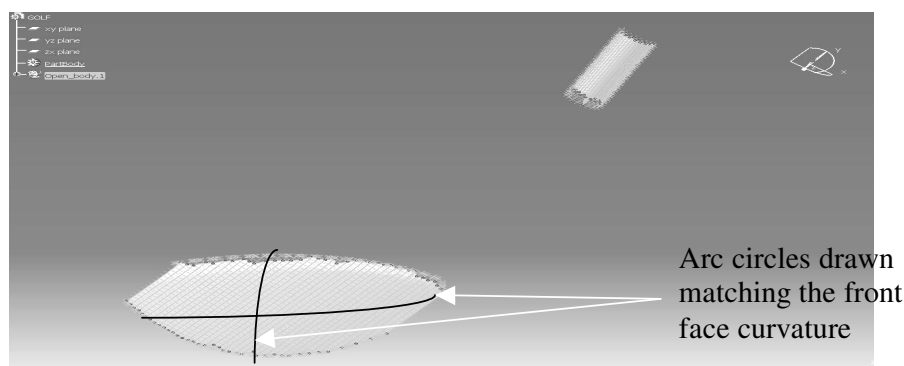


Figure 20: front face measured

The bugle and roll were found by drawing two arc circles of known radii matching the scanned rebuilt surface in the horizontal and vertical direction (Figure 21).

The values measured were as follow:

- Bugle: 260 mm → 10.24 inch
- Roll: 305 mm → 12 inch

3.1.2 Body modelling

The body modelling was realized using the “wire-frame” and “surface” modules from Catia VR 5.8 and included the front face design with bugle and roll radii, loft angle and other critical dimensions at first. Then 2 other sections were designed at the rear of

the club head according to the initial drawing and Mr. Gorse's [5] suggestions. Based on the front face and those two sections, the main body was built using the tool loft with guides in between the section in order to have a better control of the operation. Secondly an airfoil (built in sections as well) and a tube with the correct angles representing the shaft's position were added. The part made in surfaces was converted to solid allowing features like fillets to be added. Figures 21 and 22 shows different airfoil design tested on cad.

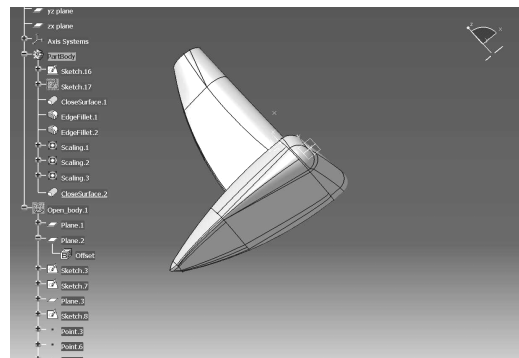


Figure 21: airfoil from the plan given initially

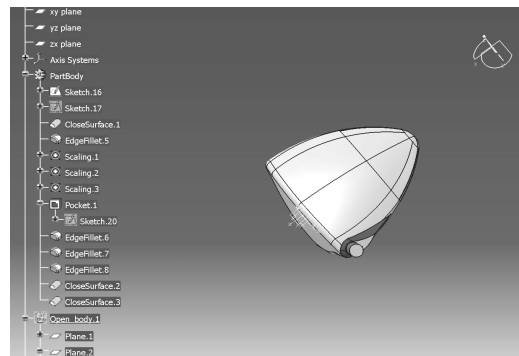


Figure 22: asymmetric airfoil

Figure 23 shows a circular shaft constrained in the club head, it can be noticed that the attachment position is not ideal for a strong mechanical joint. Therefore the club head body was modified slightly to contain a bigger part of the shaft. But the overall shape was kept because it was thought that the airfoil could help constrain the shaft in the club head.

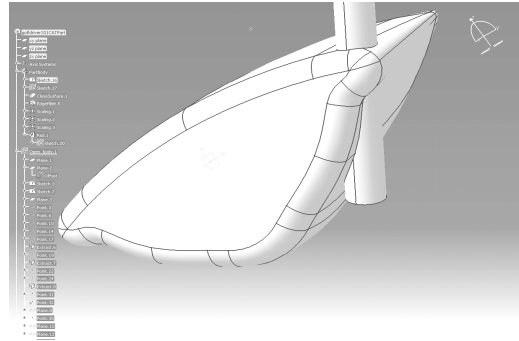


Figure 23: the shaft position at the early stage

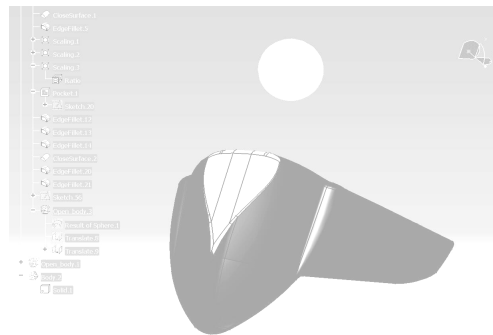


Figure 24: model from the latest golf club (short airfoil)

Figure 24 shows that the bottom of the golf club head has been cut. This should make the club head more stable before the shot as golfers usually gives a few swings to try to position the golf club adequately, but this tends to damage the fluidity of the initial shape.

3.1.3 Some dimensions on the latest golf driver shape

This paragraph outlines briefly some of the parameters measured on the golf driver. The volume was approximately 400 cm^3 . The front face has a height of 52.7 mm, a width of 173 mm and a length of 125.86 mm. The shaft's angle is 54° sideway and 2° forward from vertical.

3.2 Brief review of composite materials

This part gives review of properties and the types of fibres available when choosing composites for the club head. By definition composites are a physical, rather than chemical combination of two or more separate components, which act together to give unique properties not found in either of the materials in isolation, Acmc [33].

3.2.1 Fibres

There a wide range of fibres to choose from organic, non organic and even metallic. Figure 25 lists and gives some information on the strength and weight of the most interesting fibres (more information can be seen appendices 2 and 11).

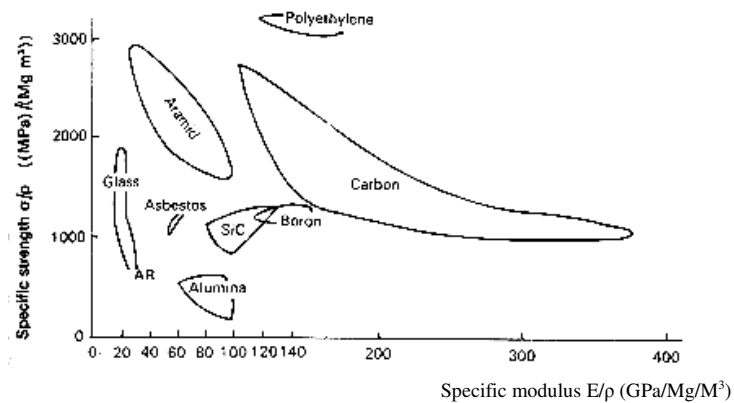


Figure 25: specific strength against specific modulus for different types of fibres, Rawlings [10]

There are numerous fibres and weaves types to choose from. Weave types will influence the mechanical properties because they influence the fibre orientations but also because of the high waviness of some of them (crimp) which can produce large resin rich area resulting in worse performance (especially plain weave). Some fibre characteristics can be seen in appendix 2 and different weave types in figure 26. According to Yurgartis [28] the primary purpose of the fabric is to make a structure that has good in-plane properties but a very low bending stiffness. He added that often composite reinforcement fabrics are chosen for their ability to drape.

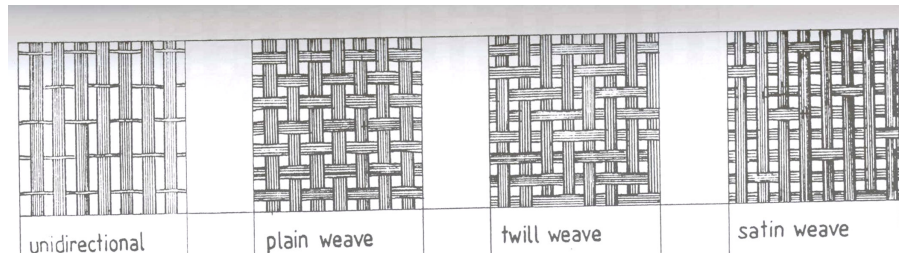


Figure 26: different fiber's weave

3.2.2 Matrix

The resin choices are also complex and the focus on this project will be on plastic resin. Metal matrix will not be considered because of the limited time available (but some information can be seen in appendix 7). Figure 27 shows the different categories of polymers that exist.

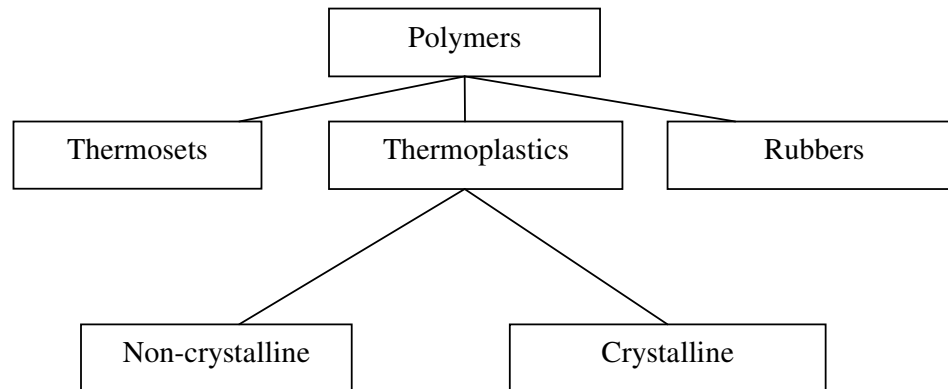


Figure 27: simple classification of resin for composites, [10] Rawling

Tables 4 and 5 will show some of the mechanical properties of thermoset and thermoplastic. Epoxy is seen to be very interesting because of its high mechanical properties and ease of processing in the form of pre-impregnated resin.

		Epoxy	Polyester	Phenolics	Polyimides
Density	(Mg/m3)	1.1-1.4	1.1-1.5	1.3	1.2-1.9
Young modulus	(Gpa)	2.1-6	1.3-4.5	4.4	3-3.1
Tensile strenght	(MPa)	35-90	45-85	50-60	80-190

Table 4: mechanical properties for some thermoset matrices, [10] Rawling

		Acrylic	Nylon	Polycarbonate	Polypropylene
Density	(Mg/m3)	1.2	1.1	1.1-1.2	0.9
Young modulus	(Gpa)	3	1.4-2.8	2.2-2.4	1.9-14
Tensile strenght	(MPa)		60-70	45-70	25-38

Table 5: mechanical properties for some thermoplastic matrices,[10] Rawling

3.3 Mechanics of materials relevant to the project

This section gives a small background on composite mechanics.

3.3.1 Stress - Strain relationship for an isotropic material

Stress (σ) and strain (ϵ) are linked by Young's modulus E .

Hooke's law gives:

$$\sigma = E\epsilon \quad (1) \quad \text{Only true in the elastic region (figure 28)}$$

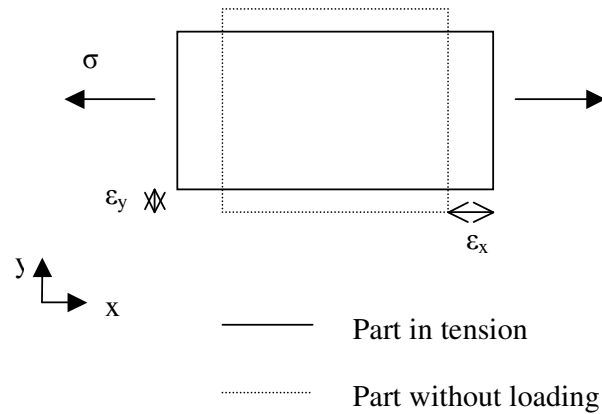


Figure 28: part of material under tension

E characterizes the stiffness of the part and can be seen as the director coefficient of the curve on the figure below.

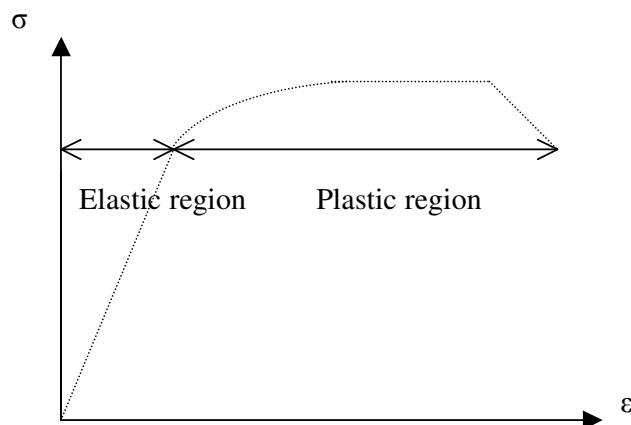


Figure 29: stress versus strain

The material will only recover to its initial state if the stress and strain are limited to the elastic region (figure 29), if not the material will be deformed permanently and damage will initiate. In our study we will be focusing on the linear elastic region, because of the needs of the golf club front face to recover to its initial state after each impact.

Hookes law states that in an isotropic material a single stress (σ_1) will result in 2 strains given by:

$$\begin{aligned}\varepsilon_1 &= \frac{\sigma_1}{E} \\ \varepsilon_2 &= \frac{-\nu^* \sigma_1}{E} = \varepsilon_3\end{aligned}\quad (1)$$

Shear stress (τ) and strain (γ) are linked by the shear modulus G.

$$\tau = G * \gamma$$

The Poisson's ratio (ν) linked together the strain in two orthogonal directions (drawing 1)

$$\nu = -\varepsilon_y / \varepsilon_x$$

If we consider only plane stress which can apply to thin structures with no stress through the thickness then $\sigma_z = \tau_{xz} = \tau_{yz} = 0$

The strain response under plane stress is thus

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{E} & \frac{-\nu}{E} & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \quad (2)$$

The notation of this matrix can be simplified using a different notation S_{ij} .

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \quad (3)$$

Then equation 1, 2 and 3 can then be used to find the stress in term of strain when the samples, when the part in figure 31 is subjected to various stresses. This is much better in practice as it easier to apply a load than a strain.

$$\sigma_x = \frac{E}{1-\nu^2} (\varepsilon_x + \nu \varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\nu^2} (\epsilon_y + \nu \epsilon_x)$$

Or in matrix term:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{pmatrix} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{pmatrix} \text{ With } Q_{11} = Q_{22} = E / (1-\nu^2), Q_{12} = \nu E / (1-\nu^2), Q_{66} = G$$

Principal axes

When looking at strength, it is common to look at “principal stress” and “strain” with failure criteria which will provide some information on the state of the component (basically if it has failed or not).

The principal values can be found from the stress and strain values and they are the maxima at a point in a component expressed in a convenient set of orthogonal axes [10] Rowling.

After using some transformation equations and differentiating them with regard to Θ which is the angle between the principal axes and the basic axes.

The followings equation can be found, giving the maximum principal stress:

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm 0.5 * \left[(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 \right]^{\frac{1}{2}}$$

And the maximum shear stress:

$$\tau_{xy \max} = \frac{1}{2} \left[(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 \right]^{\frac{1}{2}}$$

Similar equations can be found for strain but will not be developed here.

When looking at failure there is in particular two common failure criteria which are used which is the maximal principal stress theory, and the Von Mises criterion. The Von Mises criterion will be used later on to look at the stresses on metal front faces.

3.3.2 Laminate analysis

A laminate is composed of a sequence of plies (figure 30), which are often characterized by a thin woven or unidirectional fabric reinforced by a polymeric matrices in most cases, those plies are bonded together to form the laminate.

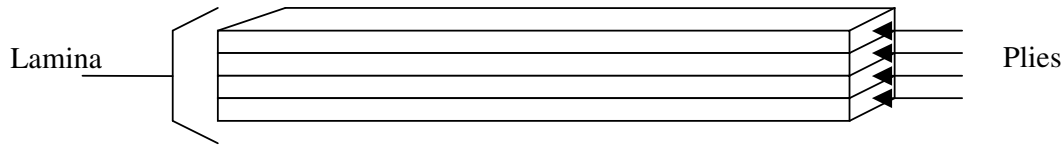


Figure 30: laminate

The laminate is often thin compared to the composite structure itself and so it can be modelled as a 2 D shell with a 2 D stress system, it will be assumed that the plies are bonded together perfectly (the bond will be very thin). The mechanical properties of the different plies will dictate the behaviour of the whole laminates.

To understand the behaviour of composite structures and because of the laminate definition, there is a need for two considerations. The first one is based on micro-mechanics and permits the calculation and estimation of the mechanical properties of the plies. The second one is called macro mechanics and allows the calculation of strain and stresses on each ply considering the whole lamina and is called macro-mechanics.

If micro-mechanics is applicable at the early design stage, it requires tested and measured properties for the final design based on experiments or manufacturers inputs. Macro-mechanics requires quickly the use of finite element analysis because of the complexity of the calculation involved on curved surface, or complex loading on lamina.

3.2.2.1 Micromechanics for stiffness

Micro mechanics was used in this project to double check stiffness and strength properties when given or found on the internet. In some case where no information was found on a particular layer it permitted an estimation of the mechanical properties. This was very useful for the general purposes of comparatives and initial design. But for the final design complete accurate data will have to be used from test or manufacturers.

Micromechanics for stiffness from the rules of mixtures:

$$E_{11} = \beta_1 * \beta_2 * E_f * V_f + E_m * (1 - V_f) \text{ (Rules of mixtures)}$$

(Source: Matthews [10])

Where:

- V_f : is the fibers percentage in volume of the composites, which depends on the manufacturing process.

$V_f = 60\%$: autoclave vacuum bagging.

55%: for vacuum bagging.

40%: for hand laminating.

Note: $1 - V_f = V_m$ matrix percentage in the composites.

- E_f : the young modulus of the fibres.
- E_m : the young modulus of the resin.
- β_1 : Depends of the fabrics type:

$\beta_1 = 1$ unidirectional layer

$\beta_1 = 0.5$ woven fabric 0/90

$\beta_1 = 3/8$ random in plane

- β_2 : Lengths correction factor for short discontinuous fibres, (if continuous $\beta_2 = 1$)

- Longitudinal stiffness (E_{11}) which is the elastic modulus in the longitudinal direction.

- Transverse stiffness E_{22}

E_{22} is the elastic modulus in the 2 direction

$$\frac{E_m}{E_{22}} = \frac{V_f}{\frac{E_f}{E_m}} + V_m \quad \text{or} \quad E_{22} = \frac{E_m}{\frac{V_f}{\frac{E_f}{E_m}} + V_m} \quad \text{source: Matthews [10]}$$

For the transverse stiffness a corrected model can be used

- Shear Modulus G_{12} (in plane shear modulus in 1-2 axes)

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \quad \text{or} \quad G_{12} = \frac{1}{\frac{V_f}{G_f} + \frac{V_m}{G_m}} \quad (\text{source: Matthews [10]})$$

- Poisson's ratio ν_{12} (major poisons ratio)

$$\nu_{12} = \nu_f * V_f + \nu_m * (1 - V_f) \quad (\text{Source: Matthews [10]})$$

Material 54 in LS DYNA is appropriate to model composites damage, but the software often ask for G_{23} and G_{13} . For those two values if not found for a specific layer, a best guess has to be made because no micromechanic model was found to exist.

Another equation that is useful to characterize a single ply is the way to calculate the ply thickness from the area / weight, the volume fibres fraction and the density

$$t = \frac{weight / area}{Vf * \rho_f}$$

Some data computed at the early design stage with some of those micromechanics formula are in appendix 8.

3.3.2.2 Micromechanics for strength

If micromechanics for stiffness are relatively accurate it is much more difficult to obtain proper complete model for strength because of the diversity of the failure mode. Though for unidirectional layer some model exist. In this review not every model will be studied only the one of those that is relevant for the study will be considered.

The followings models will be only applicable for unidirectional fibres with a high fibre fraction volume.

Longitudinal tensile strength: σ_{1t}^* dominated by the fibres strength.

$$\sigma_{1t}^* = \sigma_f^* * Vf$$

Longitudinal compressive strength: σ_{1c}^* dependant on resin properties, and bond strength and void content.

$$\sigma_{1c}^* = \frac{Gm}{(1-Vf)}$$

Also Matthews [10] acknowledges that this formula over estimates the compressive strength compared to experimental tests. And so the value calculated will need to be lowered.

Transverse tensile strength σ_{2t}^* , has the particularity to be very low compare to σ_{1t}^* and it is often less than the strength of the matrix polymer.

$$\sigma_{2t}^* = \sigma_m^* * \left[1 - \left(\frac{Vf}{\pi} \right)^{1/2} \right]$$

For transverse compressive strength and in plane shear failure, no proper model exists and so no approximation can be calculated which make the estimations of data sheet and approximations compulsory.

Some properties computed with that formula can be seen in appendix 8.

3.3.2.3 Macro mechanics

Macro-mechanics deals with the mechanics of several plies under load; they are often assimilated to a shell which simplifies the stress strain relationship.

For composites the matrix can be:

$$\begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & 0 \\ \frac{-\nu_{12}}{E_2} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [S] \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \text{ and } \nu_{12} / E_1 = \nu_{21} / E_2$$

Source Groove [25]

So that orthotropic materials are defined with four constants.

To define the stresses in term of strains it is needed to take the inverse of [S] which is

$$[S]^{-1} = \begin{pmatrix} \frac{E_1}{J} & \frac{\nu_{12}^* E_2}{J} & 0 \\ \frac{\nu_{12}^* E_2}{J} & \frac{E_2}{J} & 0 \\ 0 & 0 & G_{12} \end{pmatrix}$$

Where $J = (1 - \nu_{12}\nu_{21})$

$$\text{So that } \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [S]^{-1} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{pmatrix}$$

To determine the stresses when the stresses are not aligned with the materials axes it is needed to transform the above matrices.

T will be the transformation matrix and is defined as follow.

$$[T] = \begin{vmatrix} \cos^2 \theta & \sin^2 \theta & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & -2 \sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{vmatrix}$$

$$\text{then } \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [T] \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} \text{ and } \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \frac{\gamma_{12}}{2} \end{pmatrix} = [T] \begin{pmatrix} \epsilon_x \\ \epsilon_y \\ \frac{\gamma_{xy}}{2} \end{pmatrix}$$

Combining those equations with the Hookes law for orthotropic materials gives:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [T]^{-1}[Q][T] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \frac{\gamma_{xy}}{2} \end{bmatrix}$$

The formula above will explain the behaviour of one ply but it is all more complicated when a sequence of plies are stuck together with different orientation, thickness and nature. Then the equation is known as the constitutive equation and can be written as:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix}$$

Where N are the loads, M the moments, k the mid plane curvature of the laminate, ε^0 mid planes strains of the laminate, [A] is a matrix defining the in plane stiffness, [B] is a coupling matrix which relate curvature to in plane force and [D] is the bending stiffness matrix, (source Groove [25]). The calculation of the above equations when the loading and the ply sequence are complex requires the use of finite elements analysis. A laminate design guide can be seen in appendix (6) it shows that the plies needed to be checked individually for failure or stress and strain with adequate failure criteria. The failure criteria that will be used later in the finite element analysis are Chang-Chang criteria and are as follows [26]:

for the tensile fiber mode,

$$\sigma_{aa} > 0 \quad \text{then} \quad e_f^2 = \left(\frac{\sigma_{aa}}{X_t} \right)^2 + \beta \left(\frac{\sigma_{ab}}{S_c} \right) - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0,$$

for the compressive fiber mode,

$$\sigma_{aa} < 0 \quad \text{then} \quad e_c^2 = \left(\frac{\sigma_{aa}}{X_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$E_a = \nu_{ba} = \nu_{ab} = 0.$$

for the tensile matrix mode,

$$\sigma_{bb} > 0 \quad \text{then} \quad e_m^2 = \left(\frac{\sigma_{bb}}{Y_t} \right)^2 + \left(\frac{\sigma_{ab}}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$E_b = \nu_{ba} = 0. \rightarrow G_{ab} = 0,$$

and for the compressive matrix mode,

$$\sigma_{bb} < 0 \quad \text{then} \quad e_d^2 = \left(\frac{\sigma_{bb}}{2S_c} \right)^2 + \left[\left(\frac{Y_c}{2S_c} \right)^2 - 1 \right] \frac{\sigma_{bb}}{Y_c} + \left(\frac{\sigma_{ab}}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}$$

$$\nu_{ba} = \nu_{ab} = 0. \rightarrow G_{ab} = 0$$

$$X_c = 2Y_c \quad \text{for 50\% fiber volume}$$

In a laminate if a ply failed it is recommended that its stiffness be lowered in order to have the load carried by others plies. If after this procedure the overall stiffness of the laminate is too low or some plies still fail then the laminate thickness has to be increased source Matthew [10] (more information can be seen in Appendix 6).

Note: to reduce the stiffness of a ply it is common to change its orientation or material nature.

3.4 Non linear finite elements analysis

The non linear finite element program used in this project is based on updated Lagrangian formulation.

The governing equations for updated Lagrange Formulation are:

- Conservation of mass

- Conservation of linear momentum
- Conservation of angular momentum
- Conservation of energy
- Constitutive equations
- Rate of deformation
- Boundary condition
- Initial conditions
- Interior continuity conditions

source (Ted Belytschko [18])

Finite element analysis software has been the tool chosen to improve, compare, and design several composite drivers. If the inertia properties were easy to improve by adding more ballast to the club, the composite front face behaviour in order to improve the launching speed of the ball after impact wasn't. Consequently the route followed to achieve a good composite design is not straight forward at all. It is unfortunately impossible to report all the results and then discuss them because 4 FEA models had been created with lots of analyses. Each time a model was being built from the results of the previous one. Explaining this chronology proved to be very difficult as the models are complex, a summary being in figure 31.

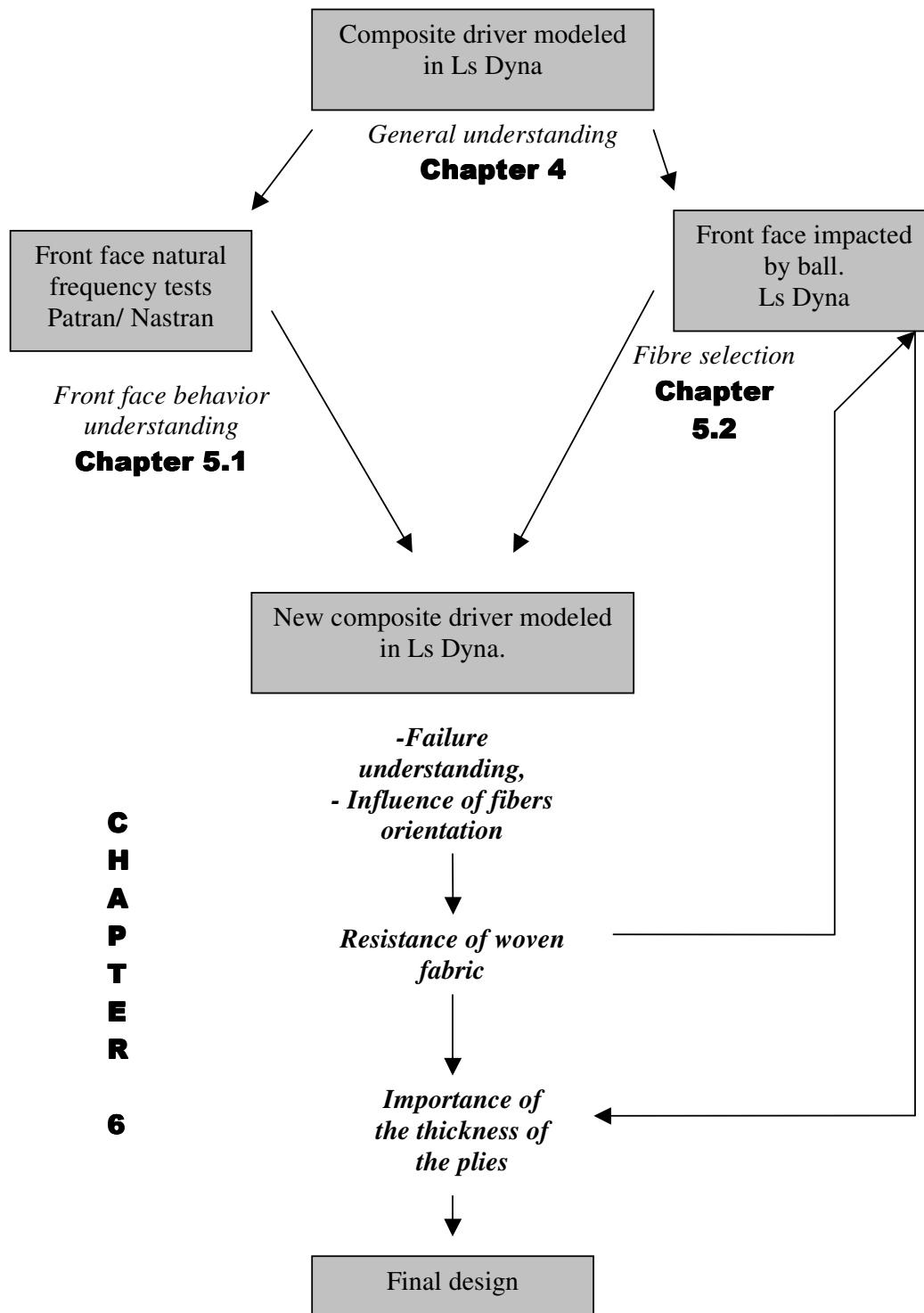


Figure 31: chronology of the design work with finite element analysis software in order to obtain a performing composite driver

Chapter IV Club head impacting a ball (first model)

4.1 The swing: simplification

The club head is in a circular motion during the swing (figure 32).

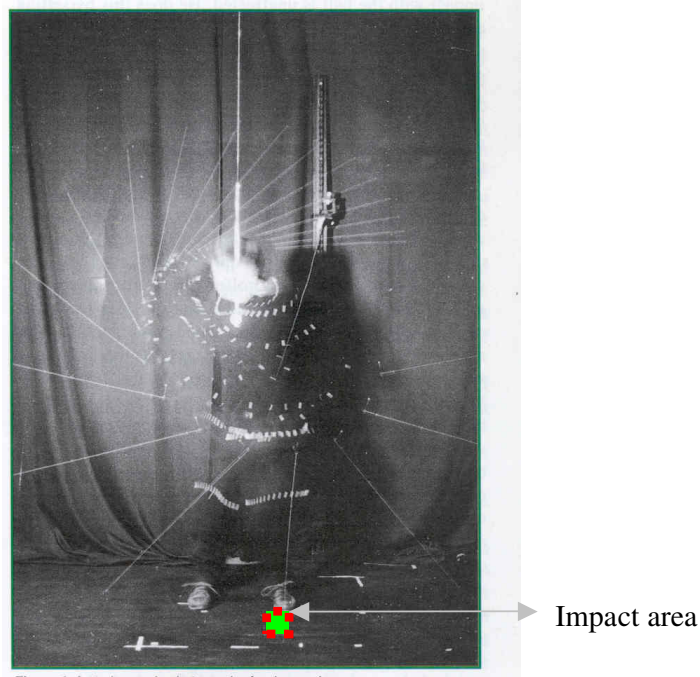


Figure 32: driving swing, Mather [31]

The time during which the ball stays in contact with the club head at impact is small (around 0.0001 second) when the club head is moving at (160 km/h). Considering this the club motion could be assimilated as a translation over this very small time (δt). This was thought to be a good approximation of the real motion and will simplify the FEA models.

4.2 First model

This model was the first one giving sensible outputs. It is explained in the following part and gives a first assessment of the final design. This model has some limits that will be shown.

4.2.1 Methodology used to build the model

Methodology for building the model was complex and can be seen below in figure 33.

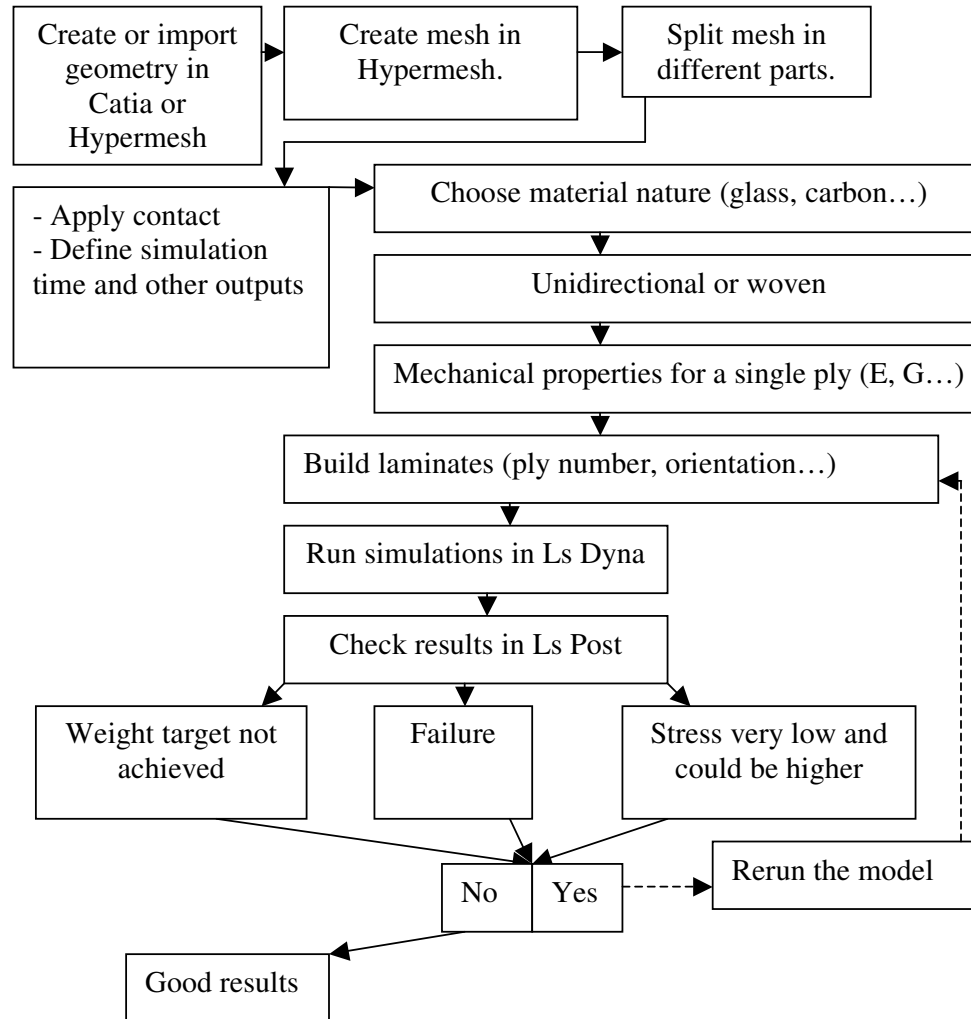


Figure 33: flow diagram of the first FEA model

This methodology will be briefly explained in the following sections.

4.2.2 The model

In this model the club head impact the ball at a speed of 160 kilometers per hour. The Catia model used for the making of the foam prototype (Chapter 3) was converted to IGES format and imported in Hyper-mesh.

4.2.2.1 Club head model

The club head geometry was meshed using shell elements (quad and tria). It was seen in the rules of golf (chapter 1) that the shaft had to be secured at the heel of the

club. A tubular metallic insert which block the shaft in position was created, meshed and attached to the club head heel by constraining nodes to the surface, see figure 34.

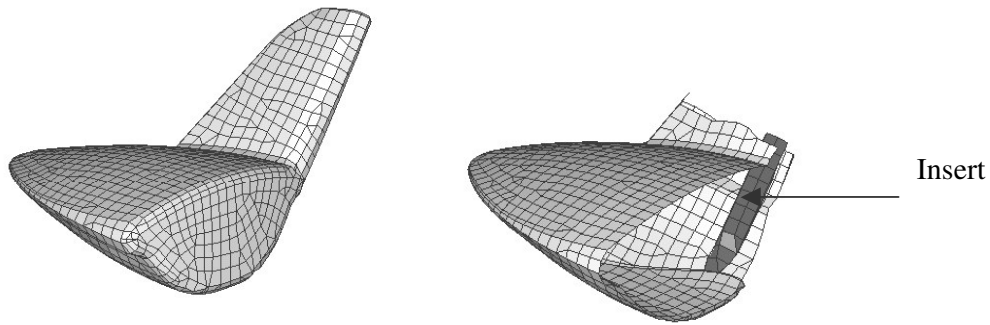


Figure 34: golf club head meshed

The mesh was split into different parts to permit the assignment of different materials on the club head. The club head model was made of laminates with different number of layers, with a ballast ring and a sole plate (figure 35 and 36).

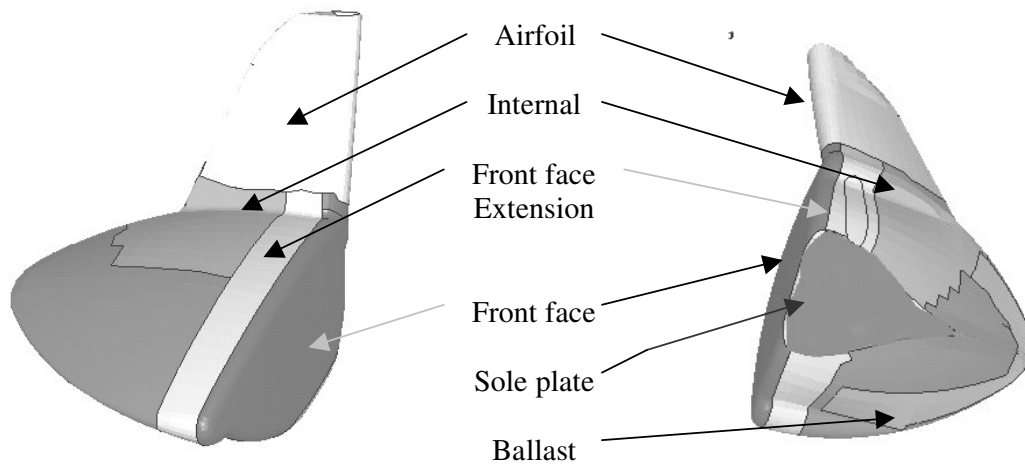


Figure 36: top view of the club head

Figure 35: bottom view of the club

The parts made from a composite laminate were the front face, the front face extension, the airfoil and the internal reinforcement the other parts being made of aluminium and steel at this stage.

4.2.2.2 Golf ball model

A 1/8 piece of ball was meshed and the solid quad elements were duplicated and rotated several times to give the golf ball mesh (figure 37). This mesh is known as butterfly mesh.

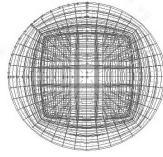


Figure 37: solid golf ball meshed

4.2.2.3 General modelling

- All the nodes of the insert part were constrained in rotation, and translation except on x axis to slide and impact the ball.
- Initial velocity was applied to the insert on X axis (42 m/s)
- The contact was automatic general
- End time termination 0.002 second

4.2.2.4 Materials modelling

Different composite lay-ups were applied and material number 54 (MAT_ENHANCED COMPOSITES_DAMAGE) was chosen to model them. Material number 54 from Ls Dyna is appropriate to model orthotropic materials with shell elements and various type of failure. The failure criterion proposed by Chang, takes into account several failure modes: matrix traction, matrix compression, and fibre traction and compression Avalle [12]. For each failure mode a failure criteria can be applied using the different stresses and the initial mechanical properties of the composites. Material properties are defined in a local coordinate system. Also a section card and integration shell card had to be added to the materials in order to define the number of layers, their coordinates and the overall thickness of the laminate.

- Rubber

The FEA model initially assumed the ball was constituted of one material, then in the more advanced simulation 2 materials. The core ball material was model using material number 7 (MAT_BLATZ-KO_RUBBER) which is ideal for modelling rubber. Only

the density and the shear modulus needed to be entered, this material is not compressible.

- Metals

The metals were model with material number 3 “MAT_PLASTIC_KINEMATICS” which is ideal to model isotropic materials and can include different types of hardening plasticity.

- Sandwich composite materials

Modelling sandwich laminates is easy when the materials used can be modelled using the same constitutive model, for example both 54. Then it is simple, two parts and two materials have to be created. One of the materials will need a section card and an integration card and the other will not because the integration card created will be able to call both materials at the required place in the laminate. Modelling the “sole plate” and the “ballast” proved to be much more difficult because in that area carbon epoxy and metal are in the same laminate. In LS Dyna there is a “problem” when modelling sandwich structures made from different materials. A special “trick” had to be done to solve this problem. Two shell elements, had to be created and the nodes equivalenced. Then Ls Dyna help page [31] stated the rules that should be followed to achieve correct stiffness of the overall composite element are:

- The sum of individual element thicknesses should equal the total composite thickness.
 - The thickness coordinates for each integration point should be multiplied by the total composite thickness and divided by the corresponding element thickness.
- This proved to be difficult to compute especially because the thickness of the “ballast” had changing thickness.

4.2.3 Material selections

Before and after running a few analyses it was understood that choosing the appropriate composite materials will be extremely difficult because of the huge number of possibilities. Effectively it was thought that to test only 2 matrix system, 3 types of fibres, 2 fibres orientation, unidirectional and may be two likely thicknesses would require at least 50 simulations. To simplify this material choice problem at the start it

was decided to choose the materials that are known to be used in golf engineering such as carbon woven epoxy and carbon unidirectional epoxy.

- **Material properties**

The properties of basic unidirectional layers were computed by using the formula derived from the rules of mixture, Matthews and Rawlings [10]. Also it was difficult to compute data for strength for woven fabric so that finally the properties input in the model were from (Eurocopter) but shear modulus (G23 and G31) were guessed.

Material	Density kg/m3	E1	E2	Nu 21	G12	G23	G31	Xc	Xt	Yc	Yt	Shear Modulus
Cwe	1600	6.2E+10	6.2E+10	0.06	3.45E+9	2.E+9	2.00E+9	5.00E+08	8.8E+8	5.E+8	8.8E+8	6.90E+07

Table 6: mechanical properties of woven carbon epoxy (all units in Pascal except density), source Eurocopter

The FEA model assumed the ball was constituted of one material only at this stage and only required density and shear modulus data to be input.

Ball material	
Density K/m3	G Pa
1100	8000000

Table 7: characteristics of the ball model

The shear modulus data input was an average number for rubber from Gere & Timoshenko [11].

4.2.4 Results

After numerous iteration using figure 41 methodology the final first driver design was defined and was inspired by the C4 Callaway design.

- **The design**

	Model	Insert	Front face (ff)	ff extension	airfoil	internal	External	MOI ring	sol plate
	First design carbon	Aluminium	Cwe Ud Mixed materials	Carbon woven epoxy	Carbon woven epoxy	Carbon woven epoxy	Carbon woven epoxy	Steel	Aluminium
Ply number		1	10	4	14	5	10	5	1
Thickness in m		0.001	0.0042	0.0042	0.0015	0.003	0.0015	0.001	0.001

Table 8: the first driver design

- **The simulation**

The simulation can be seen in figure 38

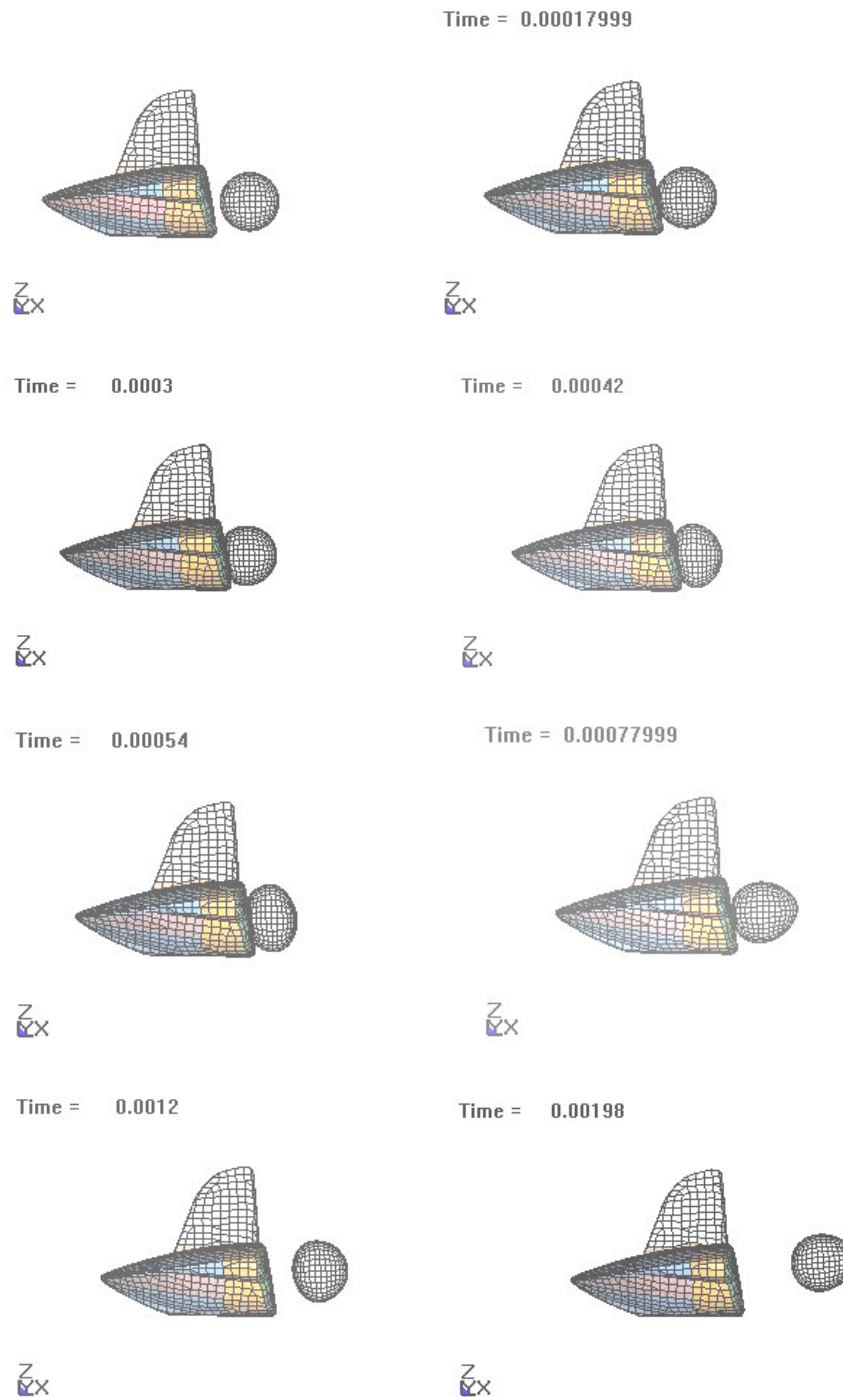


Figure 38: simulation of the first driver design in carbon woven epoxy

This showed that the ball was compressed significantly during impact as according to Penner [1] the ball should compress by one centimetre. But still this high deformation (2cm) could be due to the shear modulus of the ball material that is too low, and the

front face deflection was very limited (+/- 1 mm). Finally the stresses in the ‘front face’, ‘front face extension’ and near the insert were high but no elements in the golf club was deleted so that no failure were understood to have happened at this stage, this will prove to be partially untrue in chapter 6.

- **Moment of inertia**

With the LS post (post processor) the inertia properties of this driver were compared to the one measured in chapter 2, (table 7).

	s	lxx	lyy	lzz	lxy	lyz	lxz	I1	I2	I3
New design	0.1948	0.000293	0.000285	0.00047	7.37E-06	1.66E-05	-6.47E-06	0.00029	0.00028	0.00047
C4 callaway	0.194	0.00028	0.00022	0.00037	-0.00003	0.00002	-0.00001	0.00021	0.00028	0.00038

Table 9: moment of inertia (m²*kg) of the first new driver design compared to the C4 Callaway one's

From this table it was seen that the moment of inertia of the new design was higher and especially Izz (vertical axes) which is important for better shot accuracy in off centre impact of the ball.

- **Ball speed**

To measure the ball speed an element in the ball is chosen at the end of the simulation its velocity was recorded. The ball speed in this model was 64.736 m/s. This value was found to be comparable to values recorded in the literature.

4.2.5 Conclusion (club head impacting a ball)

This design was said to be satisfactory and proved that the large driver shape, long, with airfoil and ballast is ideal for having a high moment of inertia (table7). Carbon fibre seemed ideally suited for the rear of the golf club because of its high stiffness and low mass which allowed large “ballast”. The shear modulus of the ball which influences the loading on the front faces and so the stresses were not based on measured data. The contact didn’t have any friction coefficient which doesn’t reproduce a realistic impact. Finally the understating of the failure mechanism of the front face is limited and only a few materials were tested (only carbon is reported here). But some questions arise about the front face. Could it be thinner? Will another material be more suitable? What about the fibres orientation? In order to better the understanding of the front face behaviour and choose the optimum material a number of simulations were run on the front face only to shorten the analysis time.

Chapter V Front face analyses

This chapter studies the front face behaviour in order to improve its understanding. The natural frequency effect was first investigated and in a second part a material selection was attempted.

5.1 Natural frequency (modal) of the driver front face

Natural frequency analysis (modal) determines a part's natural frequency and mode shapes. It can determine if a part resonates at the frequency of an attached, power-driven device, such as a motor. While resonance in structures must typically be avoided or damped, engineers may choose to exploit resonance in other applications, [23] Fagan. In golf it is said that the natural frequency of the front face has an effect on the coefficient of restitution (COR), effectively by decreasing the natural frequency of the front face the COR can increase. This is explained by the fact that the natural frequency of the front face can decrease to a value near the natural frequency of the golf ball which is of 1000 Hertz [1], and so both will release their internal energy at the same time, giving more kinetic energy to the ball after impact.

5.1.1 General theory

Fagan [23] stipulates that the equation for the dynamic behaviour of structures can be expressed for modal analysis as:

$$[M] \{U''\} + [k] \{U\} = 0$$

M: total mass matrix of the structures

C: is the structural damping matrix

k: stiffness matrix

U'' , U' , U are the nodal acceleration, velocity and displacement

And then transformed to:

$$([k] - w^2 [M]) \{U\} = 0$$

w^2 : eigen value

$\{U\}$ eigen vector (describe the shape of the structure as it vibrates).

If a model as n degrees of freedom then there will be n combination of U and w and the body will have n natural frequencies and mode shapes.

The finite element analysis method was used to apply this equation to the driver front face and find the lowest natural frequency mode. But some formulas exist in the literature that are the solution to the above formula for specific shapes. The next part will detail one of them.

5.1.2 Applied theory for elliptical plate

The natural frequencies of a plate can be understood assuming linear behaviour, small deflections, and isotropic materials. The golf club front face will be approximated to an ellipse for simplification. The natural frequencies (cycle per second) for an ellipse plate of major radius (a) and minor radius (b) with fixed edge will be:

$$f_{nm} = \frac{k_1}{2\pi} \sqrt{\frac{D * g}{w * a^4}}$$

Source: Young [22]

Where,

k_1 : is a tabulated for various value:

a/b	1	1.1	1.2	1.5	2	3
k_1	10.2	11.3	12.6	17	27.8	57

Table 10: correspondence between a/b and k_1

w : uniform load per unit area including own weight

g : is the acceleration of gravity

d : is the weight density of the steel in the plate

t : is the thickness of the plate

$$D = \frac{E * t^3}{12(1 - \nu^2)}$$

E is Young's modulus

ν is Poisson's ratio

This formulas shows that there are several way to decrease the natural frequency of the front face:

- An aspect ratio (k_1) for the radius of the ellipse closer to one
- A low young modulus (E)
- A low thickness (t)
- A large major radius (a)
- A high density (linked to w)

The equations above shows a large heavy front face of circular shape with a reduced thickness composed of flexible materials was lowering the natural frequency of the front face. The shape evolution was relatively limited due to the rules of golf and the limited time but an attempt to understand better the front face behaviour was done using Nastran and Patran.

5.1.3 Experimental setup

Natural frequency analysis deals with the prediction of the natural frequencies and mode shapes of undamped structures under free vibrations, and is the most frequently performed type of dynamic problem, Fagan [23]. The analysis was run on the front face only. The mesh was realized on surfaces and shell elements were chosen. A mesh seed which set the number of nodes was done prior to mesh the part using Iso mesh or Paver mesh depending on the surfaces with quad 4 elements (figure 39).

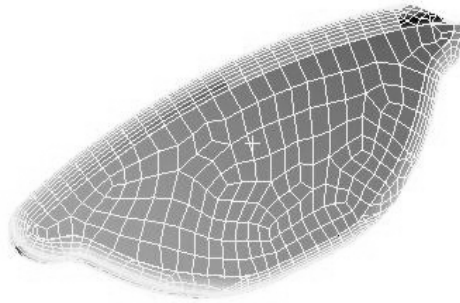


Figure 39: front face with different mesh density

Boundary conditions were created constraining all rotation and translation and were applied to the curves on the outside of the front face. Some simulations were also run with some different boundary condition (free rotation) and the results were similar.

The materials tested were different ranging from isotropic metals to orthotropic composites. The mechanical properties input were either found in the literature or estimated via micromechanics. Then a laminate was built up, with a sum of different layers with different orientations and thicknesses. The analysis ran was aimed to find the lowest normal mode of the front face.

5.1.4 Discussion and results from the linear natural frequency analyses

After sending the .dbf files to the Nastran server then eventually if the simulation ran without fatal error, the result could show the lowest natural frequency mode (figure 40).

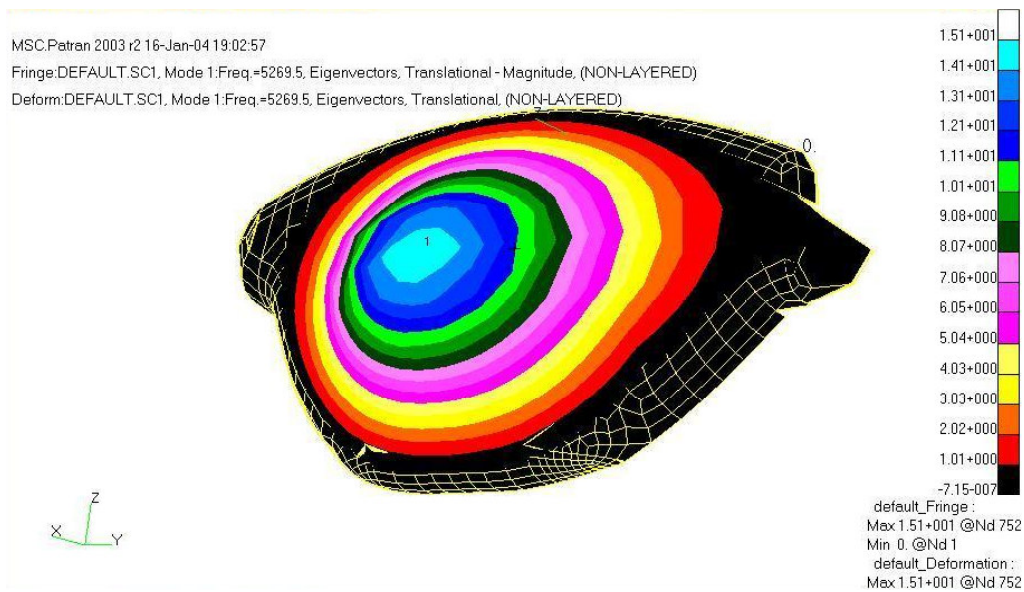


Figure 40: mode 1 for a 3.6 mm front face in glass fibers with plies at [30/-30]

Figure 41 shows the natural frequency of mode 1 for different materials and front face thicknesses.

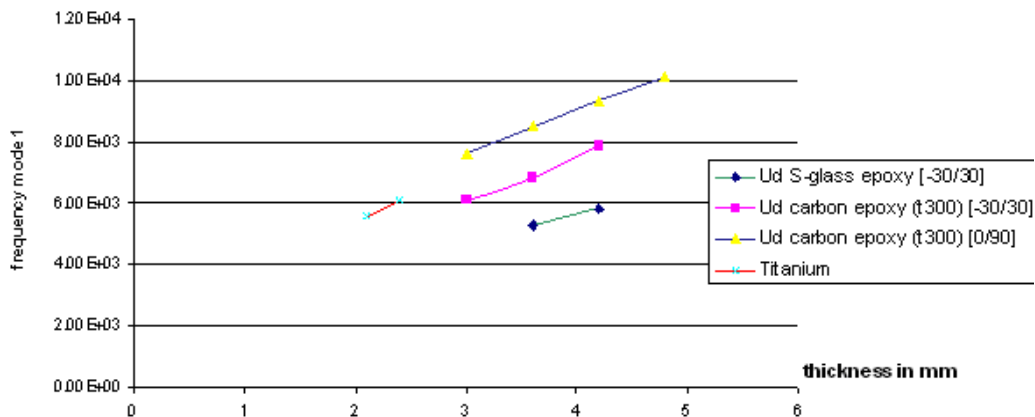


Figure 41: Patran / Nastran normal mode analysis of the front face

Those results showed that a smaller frequency in the model could be achieved with:

- A reduced front face thickness
- Fibres with low stiffness
- Ply orientation in the direction of the biggest width.

This in accordance with what was found with the theoretical formula for ellipse behaviour. It also showed that metal front face can be designed thinner (chapter 4) higher impact resistance and can have a low frequency even with a relatively stiff material like titanium. From this analysis it was concluded that heavy, low stiffness material with a special orientation could decrease the natural frequency and so increase ball speed after impact.

5. 2 Impact response of the front face while being hit by a golf ball

In order to have a better understanding of the front face response it was decided to simulate different materials and simplify the club head model for time analysis considerations to a simple front face impacted by a ball. This was chosen because it was difficult to impact the front face on the ball realistically considering there was no club head body. Figure 42 shows the work done on this front face.

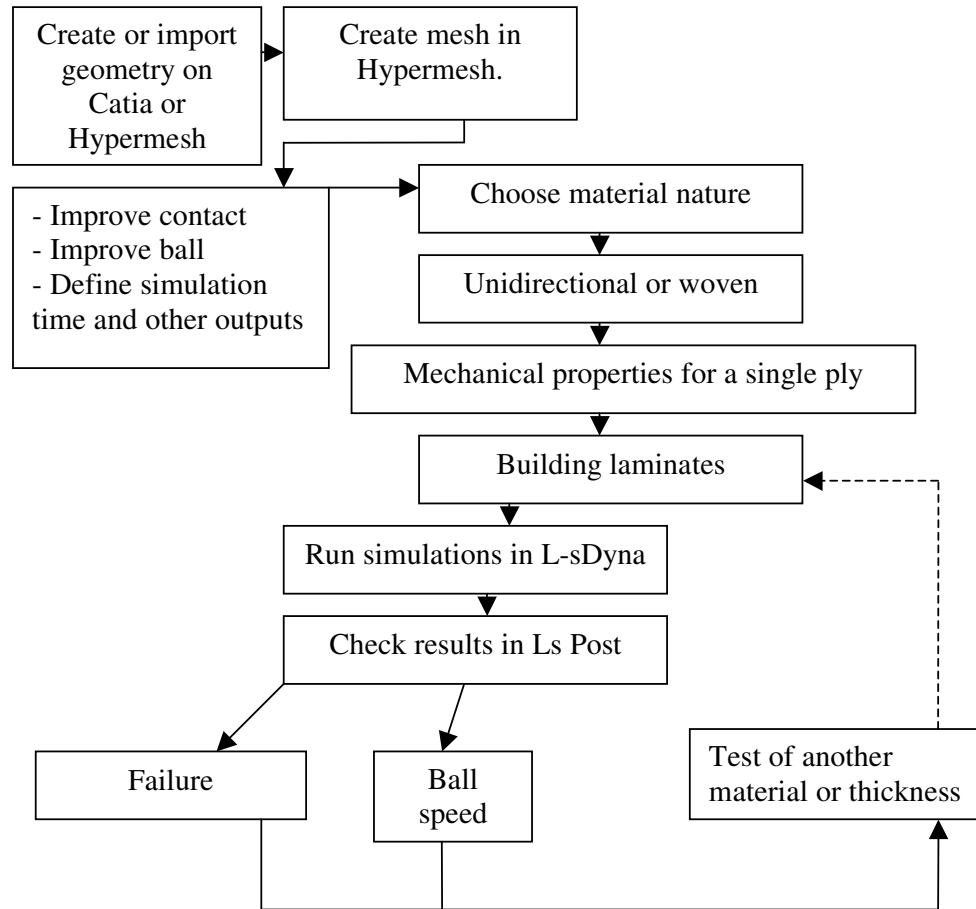


Figure 42: flow diagram for this front face model

The hypothesis on this model is that a laminate made of heavy and flexible fibres could lower the natural frequency and be similar in performance to metal front faces.

5.2.1 Front face

The front face has the same geometry than in the previous model but the mesh is using a 3 mm mesh size and has been customized on high radiuses of curvature to avoid large angles between elements (figure 43). It is thought that this mesh will give more accurate results compare to the previous model simulating impacts.

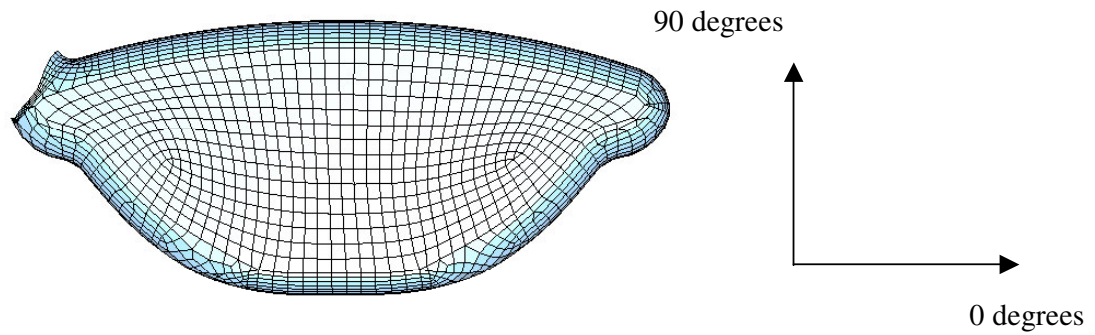


Figure 43: front face mesh and orientation for lamina

The materials tested in the front face were numerous, but few material properties were found on the internet or in books. Most composites ply properties were calculated using micromechanics (chapter 3). The materials tested were titanium (AU4G), steel, carbon woven [0/90], boron UD epoxy [0/90], glass high strength UD epoxy [0/45/90/135...], carbon woven epoxy [0/30/60/90/120/150...], tungsten UD epoxy [0/45/90/135...], steel fibres epoxy [0/45/90/135...], Kevlar 49 UD epoxy [0/45/90/135...], and boron UD epoxy [0/45/90/135]. Most of the mechanical properties used have been reported in appendix 8.

5.2.2 Ball made of 2 materials

To have a realistic impact the ball was composed of two materials because a real ball was constituted from an outside 1.5 mm thick polymeric layer (probably Duralyn) and the core from a rubber material (probably polybutadiene) like illustrate figure 44.

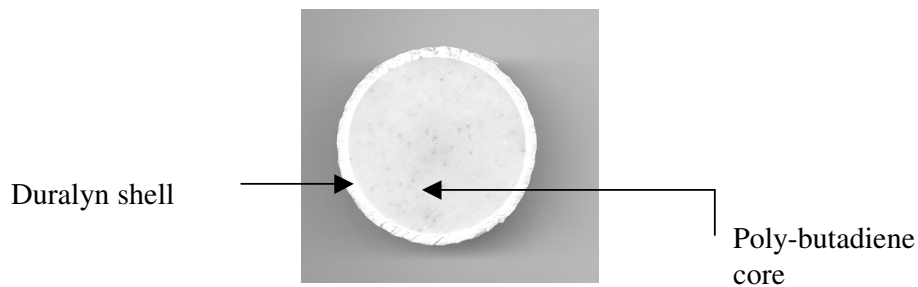


Figure 44: cut from a real golf ball

Figure 46 and 45 shows the inner core and the outer shell, both were modelled with quad solid elements and butterfly mesh. The materials properties for the ball were optimized with some data found in the literature and in Cochran [24], see (table 10).

		G Pa	E Pa	Nu	Density kg/m3
outer shell	Plastic (Surylin)	...	3.72E+08	0.3	936
inner core	Rubber (rubber)	22000000	..	...	1210

Table 11: material properties for the ball

The overall weight of the ball is of 45.137 grams which is a realistic golf ball weight.

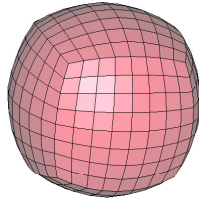


Figure 45: Inner core

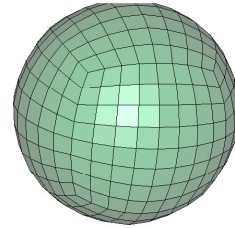


Figure 46: outer shell

In order to have a more realistic impact a coefficient of friction was added to the contact. A value of 0.27 was found to be realistic in the literature and used by Iwatsubo [16].

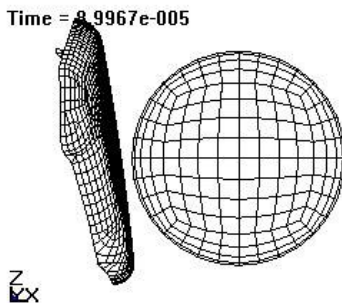
5.2.3 Constrains

The edge of the front face was constrained by blocking all rotations and translations. Further analysis had only the translation blocked and results can be seen in appendix 9. The difference in ball speed achieved was minor but influences the stresses in the front face.

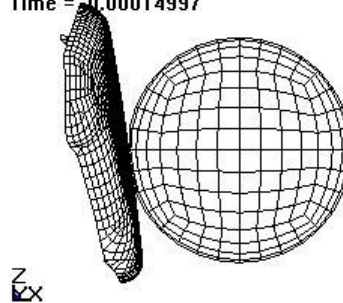
5.2.4 Simulation

The analyses ran quickly because of the small size of the model permitted numerous analyses. Figure 47 show the ball impacting a 2 mm titanium front face.

Time = 8.9967e-005



Time = 0.00014997



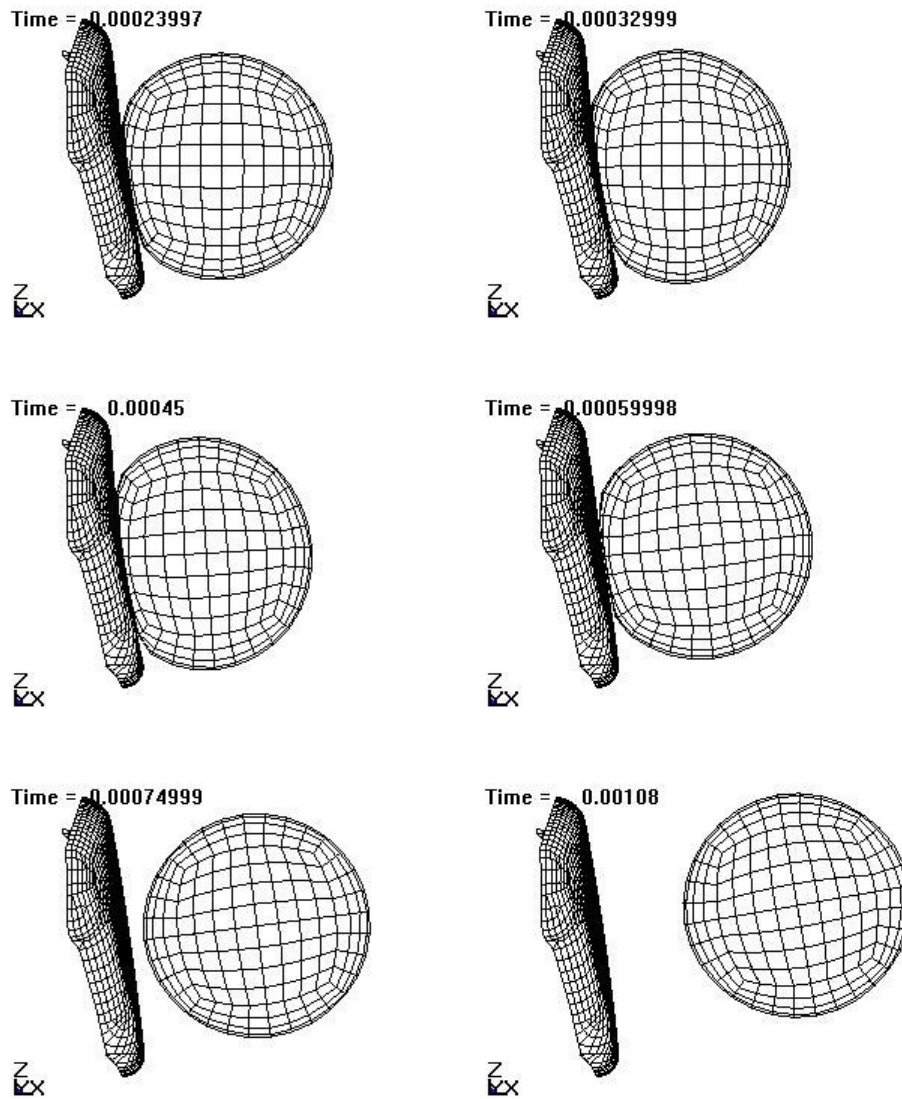


Figure 47: 2mm titanium front face impacted by 2 pieces ball

Figure 47 showed that the ball was deforming realistically and that the titanium front face flexes slightly.

5.2.5 Results and discussion

Figures 48 and 49 shows the stresses on a 2 mm titanium front face while being impacted by a golf ball (2 pieces).

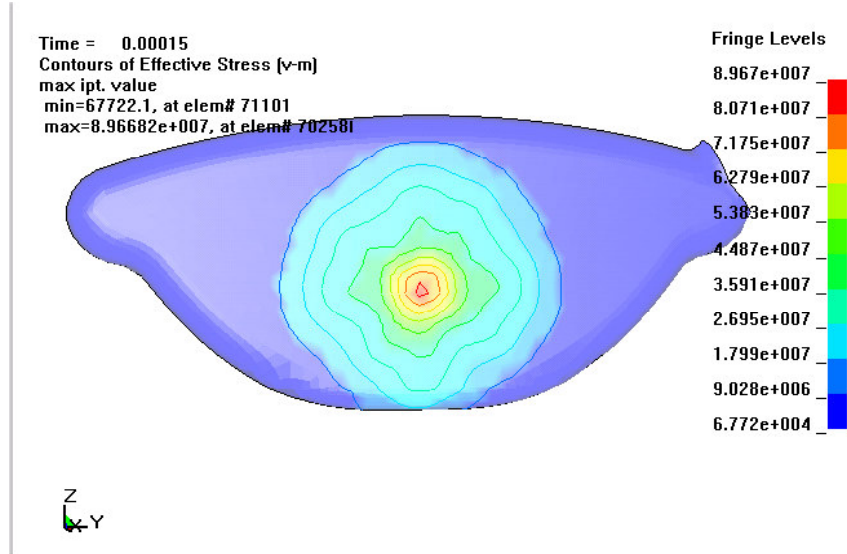


Figure 48: von misses stresses in Pa on a 2 mm titanium front face at 0.00015 seconds

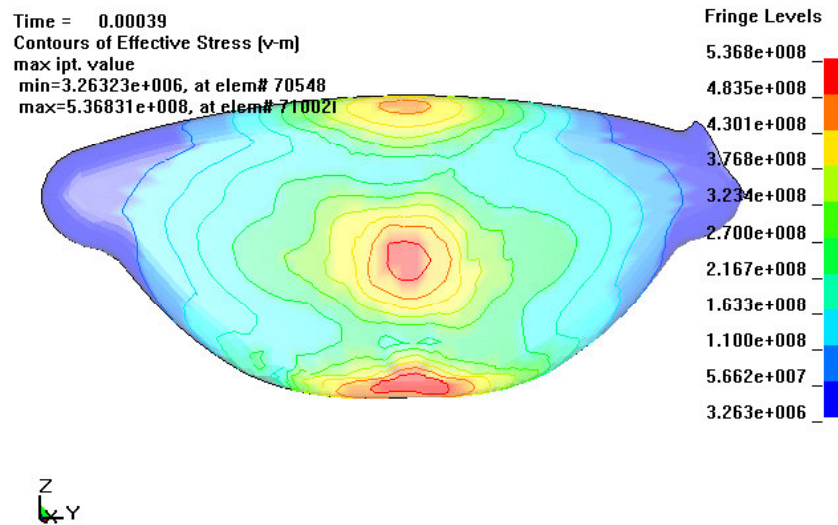


Figure 49: von misses stresses in Pa on a 2 mm titanium front face at 0.00039 seconds

The Von misses stresses were maximum at 0.00039 second in the simulation (figure 49) at the impact point. The stresses were decreasing radially from this point. The heel and the toe of the front face were highly stressed, the reason might be that the main body of the golf club was missing and so the stresses could not propagate and remain high in those areas. The ‘ears’ had very low deformations which must reduce the spring effect (figure 50).

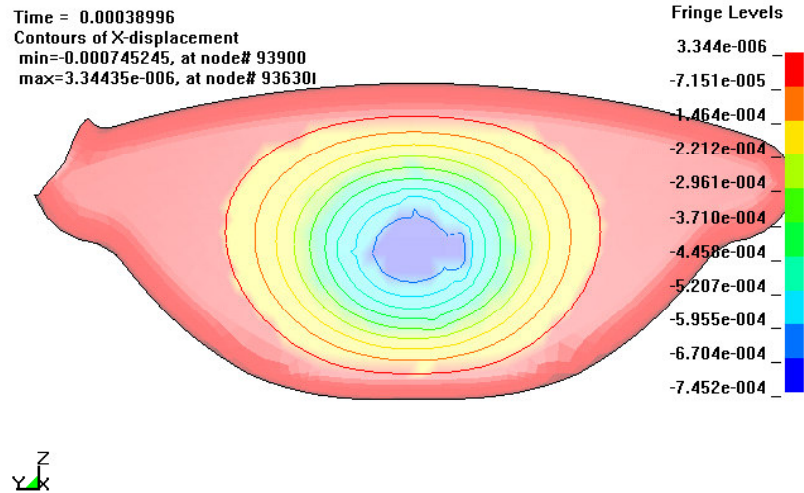


Figure 50: contour of displacement at 0.00039 second in the simulation

Figure 50 was a 2 mm titanium front face under impact and the maximum displacement was of 0.7mm. This figure shows that the height of the front face is the limiting factor to increase the deformation; a higher front face will deform more increasing its spring effect.

The speed of the ball was measured more accurately by measuring the kinetic energy of the inner core and outer core for each time step after the maximum kinetic energy was reached.

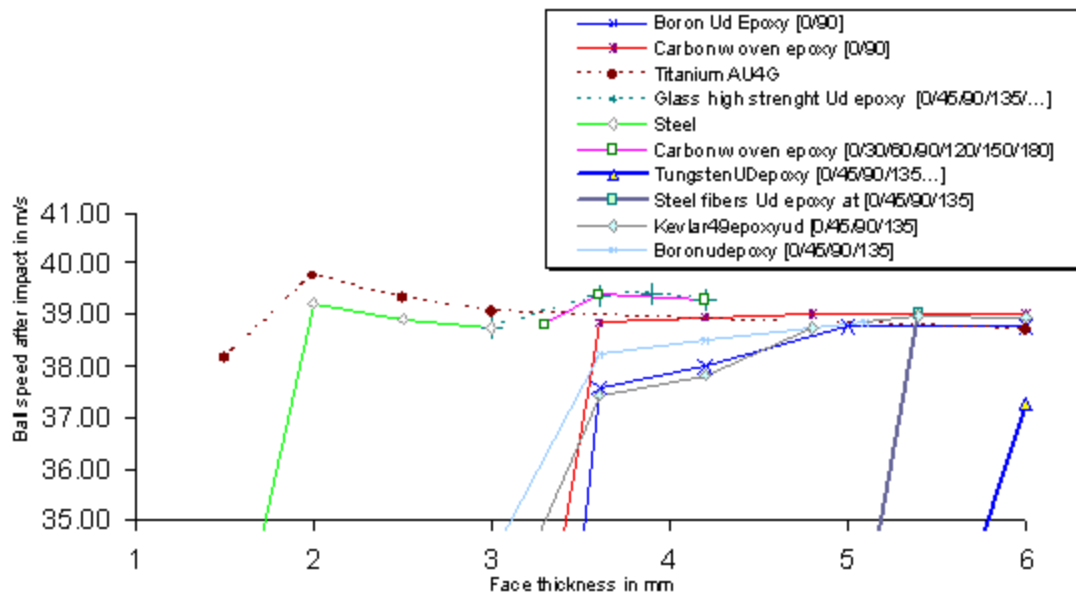


Figure 51: various front face thickness and materials subjected to a 2 pieces golf ball impact at 42 m/s. The figure plots the ball speed versus the front face thickness.

Then the energy of the 2 cores was summed and average and the basic formula was used: $E_c = \frac{1}{2} * m * v^2$

Where m is the mass of the ball, E_c the kinetic energy computed and v is the ball speed. Figure 51 shows that the ball speed increases until a certain front face thickness and then decreases. When it increases that meant the front face was still failing under plastic deformation for metal or that some plies failed for composites. The maximum speed reached gave the optimum front face thickness. When the front face thickness was increased the natural frequency and stiffness increased and the ball speed dropped.

This result showed several things:

- The metal front faces were designed thinner and were performing better especially titanium compared to the composite faces.
- Titanium is about twice less stiff and heavy than steel but was performing better, so that low stiffness seems more importance than high mass.
- The metal fibres are not strong enough and so behave badly compared to common engineering fibres like glass or carbon. The fact they could have performed because of their high weight (lowering the natural frequency of the striking faces) proves to be untrue in reality.
- Composites made from high strength and average stiffness fibres like carbon or glass behave better than stiff fibres like boron (high strength very high stiffness) or aramid (low stiffness, average strength).
- Woven fabric seemed to behave better than unidirectional
- Turning the plies in the front face improve the response.

This model can give the front face mass versus its thickness for different materials and the results are plotted in figure 52. It shows that front faces in carbon are the lightest and that front faces in titanium, glass epoxy and boron epoxy are heavier but of similar order. The front face weight and stiffness for titanium increase more rapidly. Finally some plies in steel epoxy are very heavy (about 3 times the weight of carbon one's).

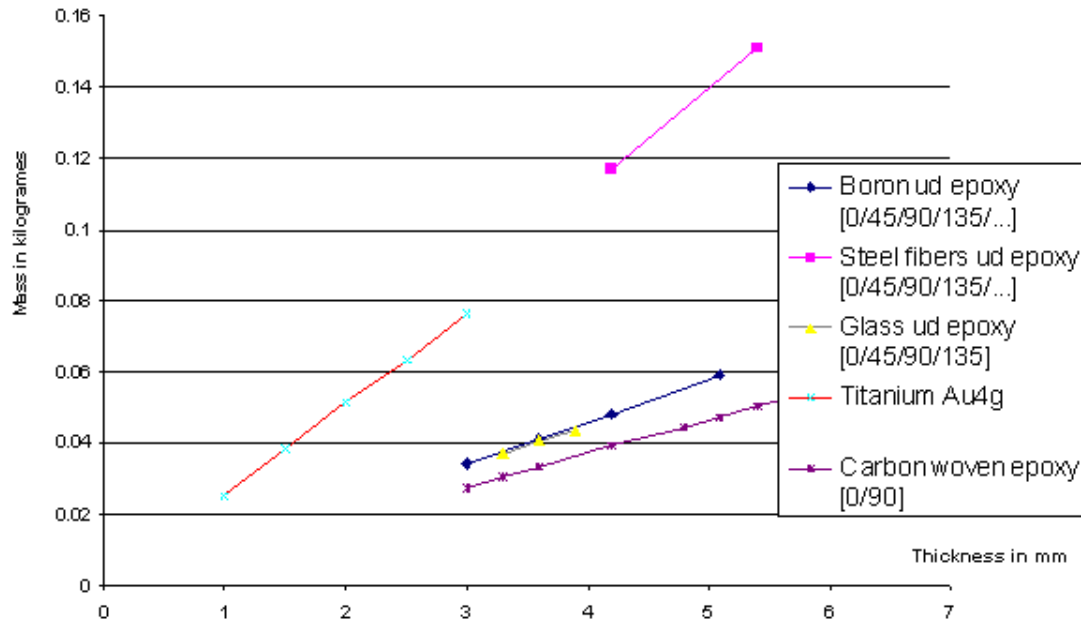


Figure 52: various front face material weight versus their thickness

5.2.6 Conclusion on this model

High strength fibres with low stiffness such as glass or carbon were performing very well, but were still not as good as titanium. Metallic fibres proved to be of low interest. A low thickness of the front face seemed to be a very efficient way to increase the ball speed. The front face shape could be designed higher and the ears could be more integrated in shape.

The limit of the model: some of the mechanical properties input for some composites materials in the model were not that accurate (appendix 8) and the understanding of the failure of the composites was not properly explored.

CHAPTER VI Club head impacting a ball

(second model)

In this chapter results from the front face experiments were incorporated in a complete accurate club head model in order to have a final design which could be manufactured. Also the behaviour of different carbon and glass fibres will be investigated. Finally special attention will be given to the failure of the composite laminate by checking stresses and failure ply by ply as Matthew [10] suggests (in the previous model, failure was said to occur when the elements were deleted).

6.1 The mesh

This new model is an improvement from the model shown in Chapter 5. It has a finer mesh on highly curved surfaces and on the front face (figure 53).

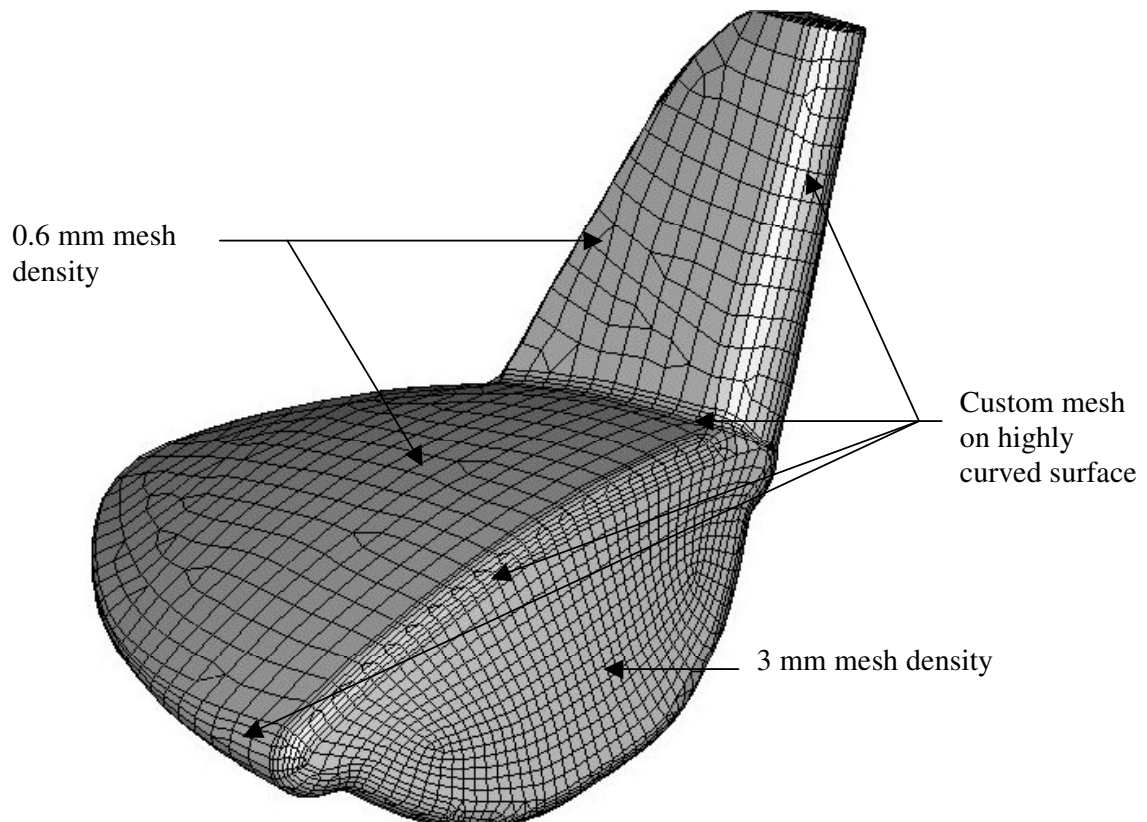


Figure 53: complete model with a finer mesh

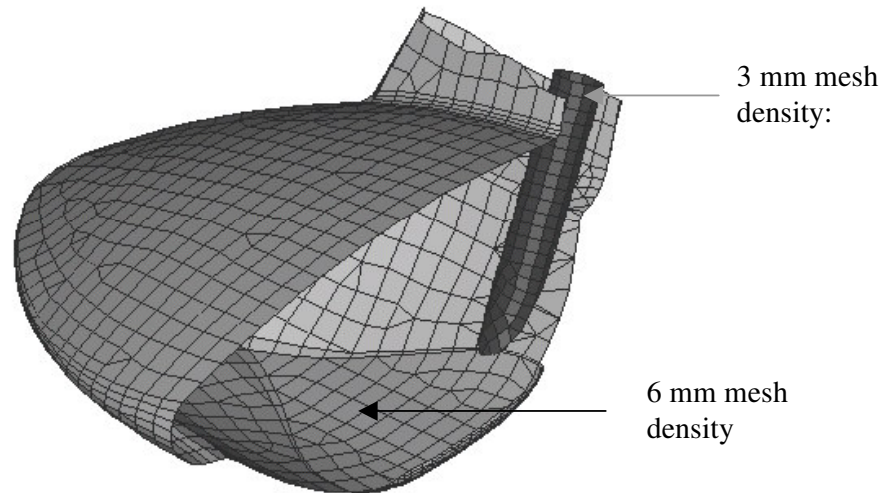


Figure 54: mesh inside and at the bottom of the golf club head (without front face)

The ball model was exactly the same as described in Chapter 5. Pictures of the mesh can be seen in figures 53 and 54.

6.2 The model

The constraints of the club head and the speed of the ball were the same ones as applied to the model described in Chapter 4. A tungsten ballast was preferred to one made out of steel because of the very high density of tungsten (19300 kg/m^3) compared to steel (7800 kg/m^3) allowing a thinner laminate more uniform in ply thickness.

6.2.1 The different grade of carbon fibres

The front face tests (chapter 5) showed that glass and carbon fibres were performing well. If choosing appropriate glass fibres wasn't too difficult as the choice was limited to E glass or S glass (appendix 11), choosing the appropriate carbon fibres proved to be extremely difficult (table 12) because of the existence of numerous manufacturers and the non-linear variation of stiffness and strength.

Grade	Tensile Modulus (GPa)	Tensile Strength (GPa)	Country of Manufacture
Standard Modulus			
T300	230	3.53	France/Japan
T700	235	5.3	Japan
HTA	238	3.95	Germany
UTS	240	4.8	Japan
34-700	234	4.5	Japan/USA
AS4	241	4	USA
T650-35	241	4.55	USA
Panex 33	228	3.6	USA/Hungary
F3C	228	3.8	USA
TR50S	235	4.83	Japan
TR30S	234	4.41	Japan
Intermediate Modulus			
T800	294	5.94	France/Japan
M30S	294	5.49	France
IMS	295	4.12/5.5	Japan
MR40/MR50	289	4.4/5.1	Japan
IM6/IM7	303	5.1/5.3	USA
IM9	310	5.3	USA
T650-42	290	4.82	USA
T40	290	5.65	USA
High Modulus (320-440GPa)			
M40	392	2.74	Japan
M40J	377	4.41	France/Japan
HMA	358	3	Japan
UMS2526	395	4.56	Japan
MS40	340	4.8	Japan
HR40	381	4.8	Japan
Ultra High Modulus (~440GPa)			
M46J	436	4.21	Japan
UMS3536	435	4.5	Japan
HS40	441	4.4	Japan
UHMS	441	3.45	USA

Table 12: strength and modulus figures for commercial PAN-based carbon fibres, [28]

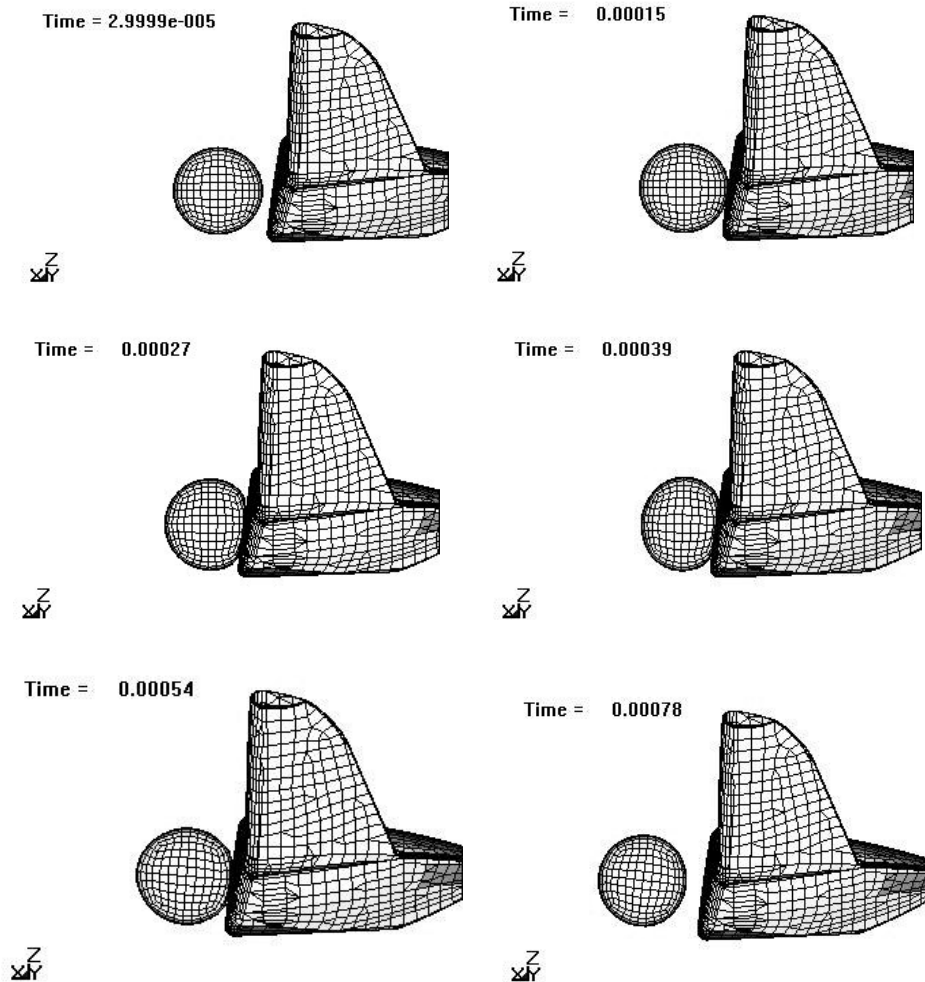
T300 fibres shown in Table 9 are understood to be similar to the carbon fibres that were tested in Chapter 5. It shows that it has a relatively low tensile modulus (130 GPa) and an average tensile strength of 3.35 GPa. In order to reduce the front face stiffness and thickness a carbon fibre with a low modulus but high strength will be of great interest. For those reasons T700 which has a low stiffness and high strength, T800 that is slightly stiffer and stronger were selected for testing. The resin chosen was once again epoxy resin because of its high mechanical performance and ease of use in the pre-impregnated form.

6.2.2 The fibres characteristics

In order to adjust the stiffness of the front face so that the width could be stiffer than the height, unidirectional fibres which allow precise fibre orientations were chosen. The ply thickness for all the plies was chosen arbitrary to 0.3 mm so that the model do not have to be completely changed each time a new lamina was tested.

6.3 The simulation

Figure 55 shows one of the simulations run with this model.



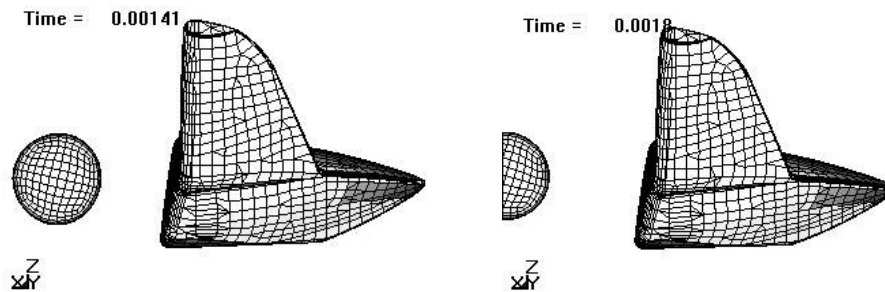


Figure 55: golf club head with a carbon epoxy T700 front face of 5.1mm having the plies at 30 degrees form one another and a body of woven carbon epoxy (T300) at [0/90] impacting a 2 piece golf ball

Different golf club designs were run in Ls-Dyna. The rear of the model was kept the same using carbon woven epoxy plies but the front face was changed testing different materials including titanium (the reference).

6.4 Results

In order to measure the ball speed after impact, once again the ball's kinetic energy was measured and averaged. The ball speed was then computed from its mass as previously done in Chapter 5. Those results are described in figure 56.

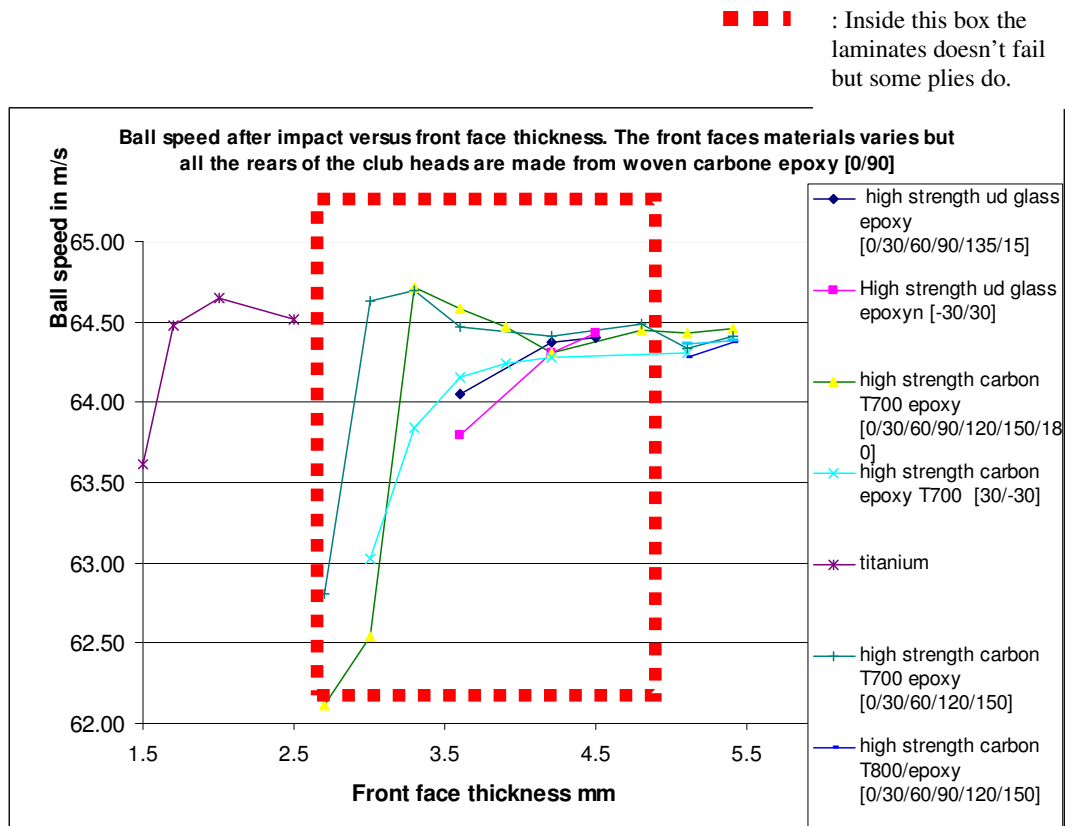


Figure 56: ball speed after impact versus front face thickness. The front faces materials varies but all the rears of the club heads are made from woven carbon epoxy [0/90]

6.4.1 Observations

Those results show as did the front face tests (Chapter 5), that the front face can be thinner when made out of metal. It was also noticed that performance of front face made from plies at plus and minus 30° perform badly compared to front faces where the plies were turned with regular angles through the laminate such as [0/30/60/90/120/150]. Plies with regular angles changed through the laminate but without the 90° ply were also tested [0/30/60/120/150] and showed overall a higher strength but slightly less performance compared to the ones which included the 90° ply.

A front face laminate made with T700 carbon fibres epoxy plies at [0/30/60/90/120/150] a spring effect was seen for a 3 mm front face. This spring effect was comparable to the one observed with a metal front face, but some plies in the front face were failing.

6.4.2 Strength investigation

In order to understand how this spring effect seen for a 3 mm front face was possible, more attention was given to the material model behaviour. It was understood that the element would only be deleted when all the plies would have failed meaning by definition that in Ls-Dyna the laminate would not fail until all the plies had failed. This meant that in most previous simulations runs, the laminate did not fail but some plies did. The way to check the failure is difficult due to the need to define further output options in the control card. A way to tell the software that it had to look at the failure mode in each ply was necessary in order to record the stresses in each ply, which made the out put files become very large. The failure process was then followed and it was noticed that failure of plies was happening until the front face thickness reached 5.1 mm in these experiments. This meant that the spring effect for a 3 mm front face could exist but only once, after the first hit the performances would degrade quickly to reach complete failure.

The failure mode found was by tensile matrix mode and is defined as follow:

$$\sigma_{bb} > 0 \quad \text{then} \quad e_m^2 = \left(\frac{\sigma_{bb}}{Y_t} \right)^2 + \left(\frac{\sigma_{ab}}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}$$

$$E_b = \nu_{ba} = 0. \rightarrow G_{ab} = 0,$$

Where Y_t is the tensile transverse strength and S_c the shear strength.

By looking more in details into the output results from Ls-Dyna it became obvious that the problem occurred with

$$\left(\frac{\sigma_{bb}}{Y_t} \right)^2$$

This term was becoming higher than 0 and so initiating failure.

Figure 57 shows a front face that was checked for failure in all its 17 plies. It is possible to notice (in blue) that damage occurred in the inner plies 1, 2 and 3 and that it almost occurred on the outer ply 17.

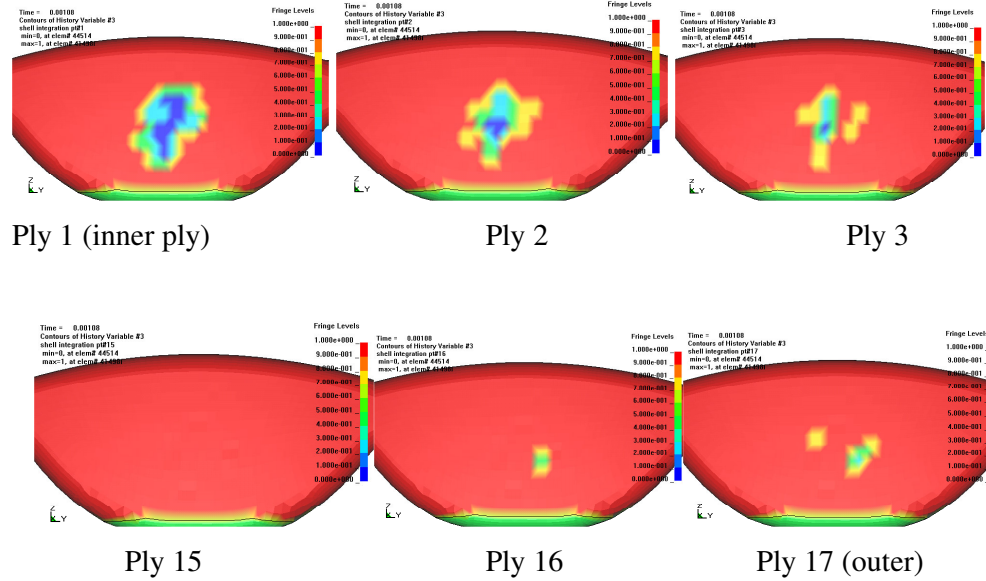


Figure 57: failure of a 4.7 mm front face made in T700 epoxy [0/30/60/90/120/150] impacted by a ball made from two materials

If this experiment showed that a front face in unidirectional (UD) T700 epoxy with plies [0/30/60/90/120/150] was behaving best, it also showed it failed in tensile matrix failure mode. A way to increase the strength of the laminate was to have a high transverse tensile strength. It was known that the tensile transverse strength for unidirectional plies is low and a way to increase it was to use a woven fabric. Appendices 12 provided by Gorse [5] showed that the material properties of M46j unidirectional and M46j as a fabric were different. In fact the transverse tensile strength for unidirectional plies was of 30 MPa whereas for the fabric it was of 600 MPa which was more than 12 times better. The model also showed that glass fibres were having twice as much ply failure than carbon fibres for a given front face thickness.

6.5 Corrections to the model

6.5.1 Corrections

Because of the availability of UD T700 epoxy from Sp system, a design for a prototype will be done using this material even though it didn't resist failure so well. Another design in T700 woven fabric, believed to behave best, was planned but this fabric was not available from manufacturers. Hence in order to build a prototype made out of woven fabric, another fibre had to be chosen because manufacturers contacted were out of stock. This was a carbon (T800) toughened epoxy in carbon woven in 5

harness satin way. This material is very strong but slightly stiffer than T700 and is known as Hexply 920 CX-926-42%. It is manufactured by Hecxel composites. The 5 harness satin weave gives high mechanical properties because of the low waviness of the fabric (crimp).

- Ply thickness for T700 UD epoxy: 0.281 mm
- Ply thickness for HexPly 920 CX-926-42%: .375mm (source Hearley [29])

Some of the mechanical properties used in this model are described in Table 12.

	Materials	Aluminum	Polybutadiene	Tungsten	Ball cover
	Density (kg/m3)	2800	1210	19300	936
Constant for isotropic	E (Pa)	7.50E+10		4.00E+11	3.72E+08
	poison ration (nu)	3.00E-01		0.28	0.31
Materials	Sigma y (Pa)	4.50E+08			3.00E+07
	G (Pa)		2.20E+07		

Table 12: the mechanical properties of the isotropic materials used in this model

The mechanical properties for the composites are in table 13.

Material	Density kg/m3	E1 Gpa	E2 GPa	Nu 21	G12 Gpa	G23 Gpa	G31 Gpa	Xc MPa	Xt MPa	Yc MPa	Yt MPa	Sc MPa
Hex ply 920	1600	87	78	0.06	4	4	4	912	1430	912	1400	82
T700 ud	1600	134	9.4	0.023	4	4	4	1400	2420	138	45	82
Epoxy	1600	66	66	0.06	3	4	4	516	1060	563	920	100
T700 woven epoxy	1600	66	66	0.06	3	4	4	516	1060	563	920	100

Table 13: mechanical properties for the composites materials

6.5.2 Results

The model was then re-run with this new lay-up and the speed of the ball once again was measured via the computing of its kinetic energy (Figure58).

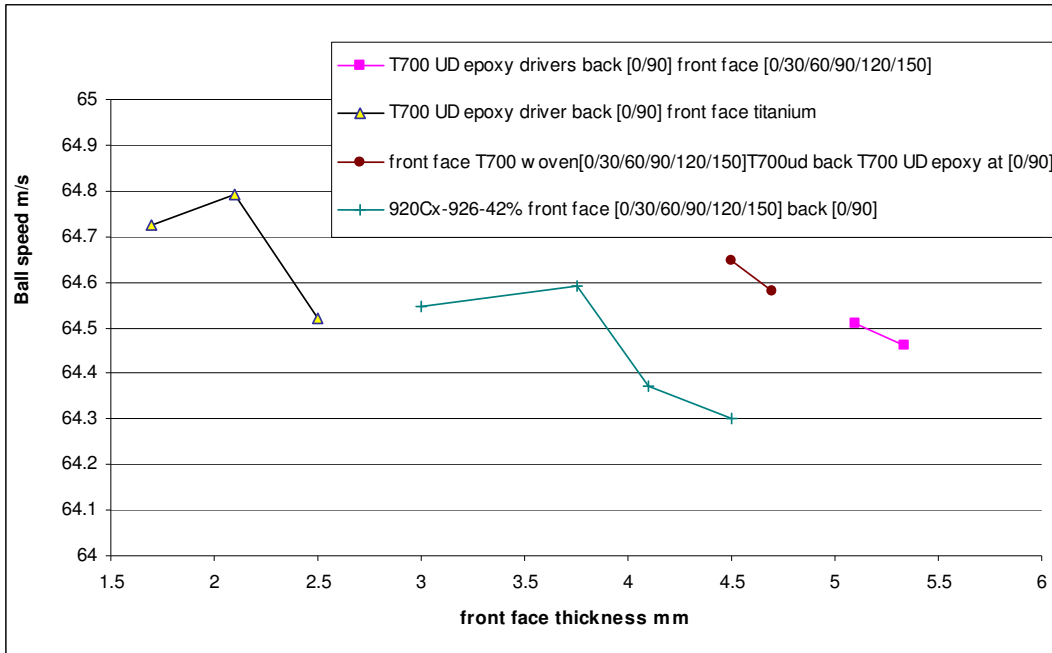


Figure 58: final new drivers, ball speed versus front face thickness

These results showed that once again a club head with a titanium front face will behave best (64.78 m/s ball speed) and could have a very thin design (± 2 mm). Also as expected the models with the front faces made of T700 woven fabric could perform well and achieve ball speed of up to 64.66 m/s and could be designed 2 plies thinner than the front face made of T 700 UD fabrics.

There was not much time remaining on this project but it was noted that the front face from Hexcell (HexPly) fabric could be designed 1 mm thinner compared to the other T700 woven fabric, however the performance in term of ball speed was not as good (64.59 m/s). This may be due do the stiffness of this fabric ($E=\pm 82$ Gpa) compared to the T700 fabric ($E=\pm 64$ Gpa) and its higher strength.

Also it was understood that the HexPly fabric was failing in a different way to the UD plies effectively it failed in compressive fibre mode as shown by the following equation:

$$\sigma_{aa} < 0 \quad \text{then} \quad e_c^2 = \left(\frac{\sigma_{aa}}{X_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}$$

$$E_a = \nu_{ba} = \nu_{ab} = 0.$$

Source: [26] Ls Dyna user manual

Effectively X_c is relatively low 0.912 GPa and the stress σ_{aa} (or x) at impact was relatively high.

However there was something unusual about this fabric as it appeared to be much stronger than the one in T700. One of the parameter differences was the ply thickness which was 0.375mm higher and compared to 0.281 for the others. At this stage it was questioned if the thickness of the ply would have a great effect on the resistance of the laminate to impact.

6.5.3 Last testing: the effect of the ply thickness

A last experiment on the front face only (same model as Chapter 5.2) was run using the material from Hexcel to check if the ply thickness had any effect.

The front face would have the same thickness of 3 mm and 3 simulations will be run but the number of plies will be changed by changing the ply thickness to see its effect.

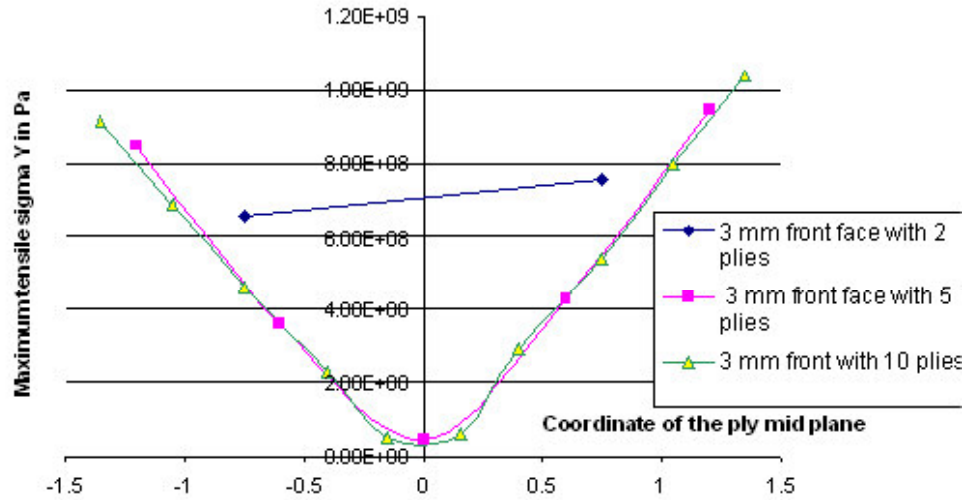


Figure 59: maximum tensile transverse stresses (sigma y) in a 3 mm front face made from different ply thickness at 0.00042 second in the simulation.

Figure 59 is a sample of the results obtained, for more examples please see Appendices 13. Figure 59 showed that a front face with thicker plies (2 plies) will be loaded very differently compared to a front face with a lot of plies (10 plies). Since in our design with woven fabric the outer ply had the tendency to fail first (opposite to UD which had the inner ply failing first), it was important to reduce the maximum compressive stress σ_x on this outer ply. A way to reduce this stress and have a front face more homogenously loaded was to increase the thickness of the plies while keeping the overall laminate thickness the same (reducing overall number of plies).

6.5.4 Safety factor

To avoid our design failing during testing, a safety factor was added in case the design would appear to be too light or if the simplifications made by the model were too important.

The stress σ_x was critical and was initiating failure as seen previously. Hence it is on this stress that a safety factor was added. By looking into various simulation runs it was noticed that increasing the safety factor on UD front face was very difficult due to a lot of plies that had to be added. For woven it was not the case and the design with fabric from Hexcell with a 3.75 mm front face (Figure 58) was believed to have a coefficient of safety of 1.43. The compressive strength was divided by the σ_x stress at impact (maximum) and was set to be the safety factor. It has to be noted that this stress was higher on the compressive form on the outer ply (Figure 60).

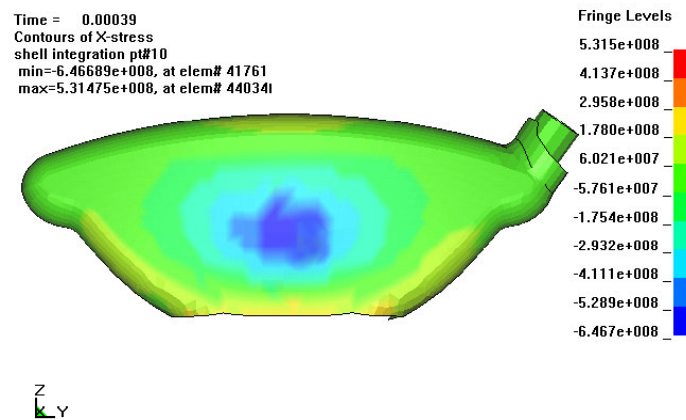


Figure 60: compressive stresses in blue in the outer ply

6.5.5 Moment of inertia

The moment of inertia of the design with a 3.75 mm front face in Hex ply was particularly good. It was superior to the one of the C4 Callaway and to the one with a front face in titanium (table 14).

	Front face	Mass	Ixx	Iyy	Izz	Ixy	Iyz	Ixz	I1	I2	I3
New design (hex ply)	3.75 mm woven carbon	0.195g	0.00036	0.00032	0.00054	2.70E-05	5.70E-05	3.00E-06	0.000372	0.0002965	0.00055
new design Carbon titanium	2.1 mm titanium	0.1936g	0.00027	0.00039	0.00047	7.20E-05	1.33E-05	-5.39E-06	0.00027	0.00029	0.00047
C4 callaway	5mm UD Carbon	0.194g	0.00028	0.00022	0.00037	0.00003	0.00002	0.00001	0.00021	0.00028	0.00038

Table 14: comparing moment of inertia (kg m²)

6.6 Fatigue

No time was available for the study of fatigue, but it is understood that the behaviour of carbon is better than the one of glass and aramid, Matthews [10]. Woven fabrics do not behave as well as unidirectional ones. If the front face was to be subjected to tensile fatigue loading and was made of Carbon epoxy UD it would resist about 5000 cycles before the properties start to diminish slowly. For plain weave loaded in similar conditions the fabric would start degrading rapidly after 100 cycles and the strength will have diminished by half after 1000 cycles. But those results are for tensile fatigue and not impact fatigue and it is understood that they would not be the same therefore further work would need to be pursued in this direction. With Ls-Dyna we only focused on one impact only and not thousands.

6.7 Final design for manufacture

Figure 61 shows the final design lay-up with the HexPly fabric (Appendix 5), the front face does not appear on the picture but was 3.75 mm thick and the lay up was as follow [0/30/60/90/120/150].

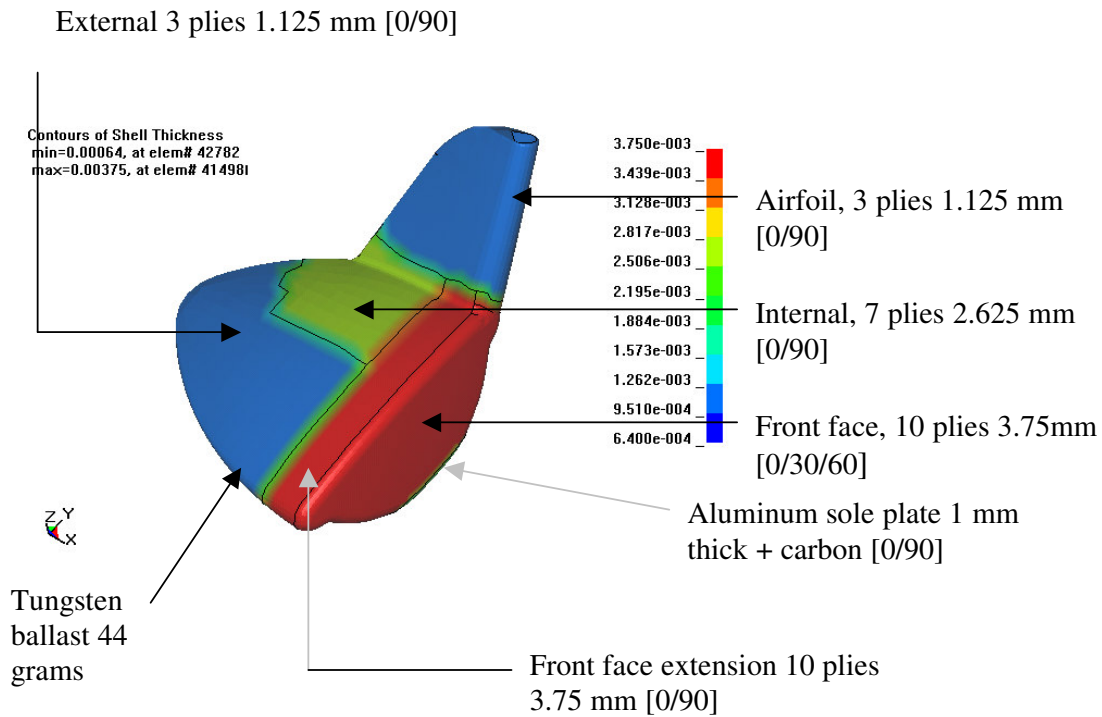


Figure 61: final design for the prototype

In this chapter 6 different choices of carbon fibres have been tested as well as S glass and titanium front faces. The carbon fibres T700 and T800 types were seen to behave best with titanium. It was understood that UD plies failed in tensile matrix mode, and that fabrics was failing in compressive fibres mode. Fabrics are much more resistant than UD and were chosen for the final design which had a coefficient of safety of 1.43 and the highest moment of inertia. It was difficult to investigate fatigue, because the study with Ls Dyna focuses on one shot only. It is understood than woven fabric will behave not as well as UD, this is may be something that could be investigated later by testing or investigations.

The next chapter will deal with the manufacture of two prototypes one in foam in order to visualize the shape from Catia, and a second one slightly different in shape that will be the structural prototype.

Chapter VII Prototypes

This chapter will briefly review the manufacture of a first prototype in high density polyurethane foam which has been used to evaluate the shape and to create moulds for a structural prototype to test the design.

7.1 The foam prototype

7.1.1 Numerical computer controlled cut of the Catia model

The procedure followed was to manufacture 3 blocks of high density polyurethane foam, one for the airfoil, one for the club head and one to be used as a support (figure 62 and 63). The computer program used for the numerical computer cut was Catia 5.8 VR with which the golf club had been first modelled. Miguel Pires doing a PhD in aerospace engineering helped and did most of the computing and machining on Catia to prepare the manufacture. The blocks of foam were first cut virtually with Catia before exporting and converting the file to the numerical controlled cut machine. In general a first roughing path was used by the tool and then another tool was finishing the surface with a smaller feed rate.

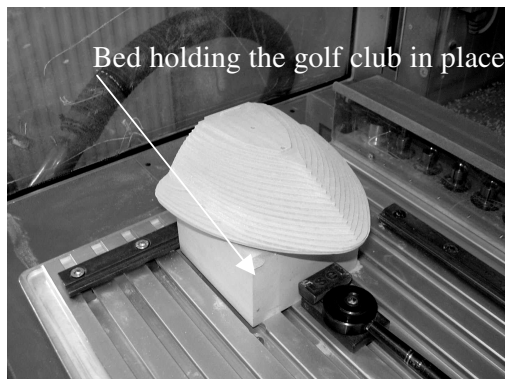


Figure 62: machining the golf club (1)

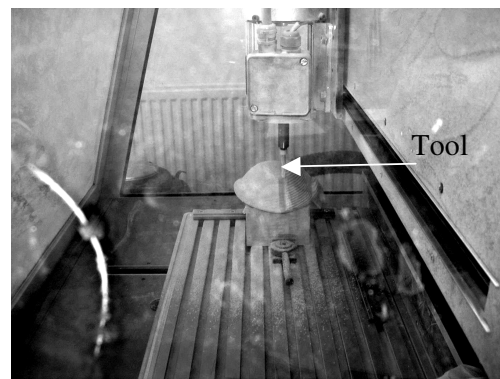


Figure 63: machining the golf club (2)

Note: a “bed” in which the main body could lie had to be modelled and computer cut and was being used as a support when machining the bottom of the club head. The airfoil was shaped out of another block of foam and then stuck to the main body with an epoxy adhesive. The picture of the finished foam model can be seen in figure 64.



Figure 64: final pictures of the golf club numerically computer controlled cut

There is now a computer model that can be used for finite element modelling, but also one that can be used to manufacture moulds and a prototype. In order to validate the design and the results collected from the finite element software, an attempt to manufacture a prototype was made. Further details of the manufacturing and steps involved will be detailed briefly in this chapter.

7.2 Structural prototype

The mechanical properties that were incorporated in the Ls Dyna software in order to design this prototype were simulating a laminate consolidated with 3 atmospheres. The main hypothesis to manufacture this prototype was that a part cooked in an autoclave will be similar to a part cooked under vacuum only. The difference between those two techniques is that an autoclave can apply 3 atmospheres whereas a simple vacuum bagging will only apply one atmosphere. Lower atmosphere consolidation leads to a smaller fibre volume fraction (V_f) reducing the mechanical properties. The design's coefficient of safety was 1.43 for a 3 atmospheres consolidation. It is believed that the coefficient of safety should not decrease too much with one atmosphere because the fibre's volume fraction should not drop below 55%.

The route chosen to manufacture this prototype used the vacuum bagging technique [16]. It used the high density foam model that was computer cut to create two female moulds using the hand lay up technique (details of resin in appendix 4). Then plies of carbon pre-impregnated epoxy were placed in those moulds over which some vacuum bagging consumable is added. Finally the bagged moulds were placed in an oven for 4 hours at 125°C and a vacuum was applied [21] in the bag to consolidate the laminate (this procedure is shown in appendix 14). Parts were then de-moulded and trimmed. Finally the shaft and shaft's insert should be placed in the club head before assembly with a scarf joint [30].

The weight of the two parts in total was 203 grams and the design with Ls Dyna was of 195 grams. The reason why there was a 4% weight difference will be discussed in chapter 8.

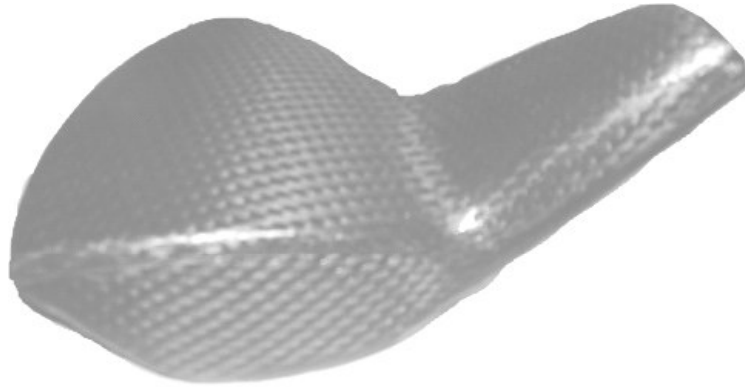


Figure 65: golf club head trimmed and adjusted (1)

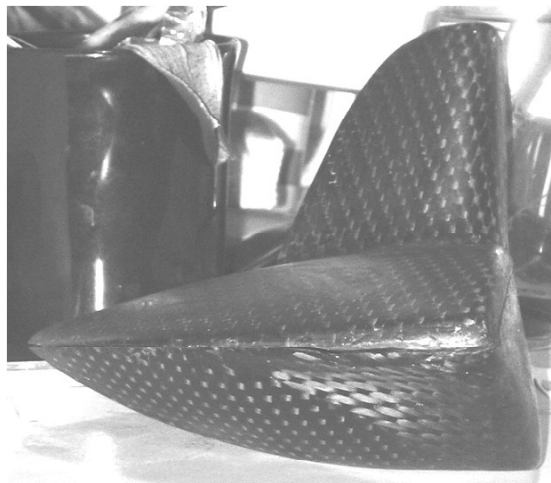


Figure 66: golf club head trimmed and adjusted (2)

The club head had some manufacturing defects and the pressure consolidation was three times lower than in the computer design for those reasons it is not sure this prototype will resist any impact. Figure 65 and 66 shows the prototype.

Chapter VIII Overall discussion

Major golf companies spend a large amount of effort trying to improve the spring effect of their metal drivers and finally obtain coefficients of restitution much higher than permitted by the rules (up to 0.84, 0.92) [32]. So if composite drivers slightly underperform compared to metal ones in term of ball speed it might not be a problem because they need to have the COR value below 0.83 or they would be illegal for the game according to the rules (USGA). Unfortunately not enough time was left to test the coefficient of restitution in Ls-Dyna but the COR of the prototype could be measured experimentally to see how it compared to the rules. Thin metal front faces are known to have a high COR. It is believed for the new composite design it would be very near the maximum permitted and may be above due to the fact that the difference between our best design with a metal front face and the composite one was only 0.2 m/s less ball speed without failure.

Furthermore it is known from the literature and Gorse [5] that front faces with about 2 mm titanium perform very well and have some spring effect. In fact it was noticed that the spring effect was very small (Chapters 5 and 6) and it is understood that the ball speed difference between a very good driver with a spring effect and a bad one without much of it will be in the range of 0.6 m/s (the new driver shape). After a 4 second flight, if the lift of the ball due to its spin is not taken into account, that will make a distance difference of 2.4 meters. This is a small difference and it seems that the spring effect is being brought forward to satisfy marketing needs in order to sell more golf clubs rather than focusing on real distance gain. Originally when starting this project the distance gain was expected to be in the range of 10 to 20 meters.

In the end, the composite design that was finally chosen for manufacture is very different from the C4 Callaway one that was studied. Even if the new design has the same mass (1 g difference) and uses carbon fibre as well, which proved to behave best in term of stiffness and resistance to impact, there are many other differences. As seen in Chapter 3 and 6, UD plies were less resistant to impact and more difficult to mould even if having slightly more resistance to fatigue. For those reasons the new design used

woven fabrics enabling the front face to be thinner, 3.75 mm compared to 5 mm. It is believed as well that the new front face made from plies oriented regularly at 30° from one another (0/30/60) is different from the Callaway front face layup. The new shape designed wide and long with a ballast and an airfoil gave overall a very high moment of inertia. It is much higher than what was measured with the C4 Callaway. Finally the manufacturing process technique is thought to produce less voids (high V_f) but will be more expensive because it requires a lot of vacuum consumable and manual work. Overall if the front face manages to resist the impact as designed, it is believed that the new design will be more accurate (high MOI) stronger (usage of high strength woven fabric) and produce an increased ball speed compared to the C4 Callaway (thinner front face, less stiffness).

In chapter 6 we determined that the composite driver with a thin metal front face (2.1 mm) has less inertia than the one which was made completely in composites with a front face of 3.75 mm. This was due to the high density of titanium which is approximately 3 times carbon epoxy. This result can be extended to a complete titanium club head by saying that on the rear of the club the carbon fibre was under tension and compression and not loaded with impact stresses. Therefore they were behaving at least as well as titanium for the same thickness but were 3 times lighter. The weight saved was added to the ballast and so the composite head's design was having a much higher moment of inertia than the metal driver.

If new composite drivers have a very high moment of inertia it is difficult to see what difference this will make during the game. Will the shot be much more accurate or just a little more? This cannot be answered at the moment as it would probably require running some practical tests in a driving range in order to have a better understanding of what answers might be.

Why can the metal front face be made much thinner than the one in composites? A hypothesis could be that the stresses from an impact propagate much more easily through an isotropic material like metal rather than through a laminate. An isotropic front face was having the same mechanical properties through the thickness

and in every direction. This is absolutely not the case for a composite laminate that usually has weaknesses in some directions where no fibres are aligned and in between the plies. The stresses were very high in those directions and interfaces because the resin only cannot cope with the load. This explains why the proposed final design has plies turned at 30° from one another in order to have the front face approaching an isotropic structure. Therefore the impact load can be carried more appropriately by fibres structured in all directions. The simulations runs confirmed this approach and showed that it was the best lay up found in the front face. It was also understood that for the same reasons, angles between two consecutive layers should not to be too high and that thicker plies was reducing the number of interface between the layers, leading to a more isotropic structure enabling better behaviour at impact. If following the same kind of thinking a 3D fabric should bring great improvements, it could be in heavy T700 and the weave could lock all the plies to gather. The problem is that it could be difficult to model but it might be easy to test.

The structural prototype was slightly different from the design especially in the lay up of the front face due to fibre continuity considerations. The manufactured prototype had the front face thicker than what has been predicted by the software. This could be due to a wrong thickness of the plies supplied or the waviness of the fabric that make the plies thicker. The other difference was that the prototypes weighed 203 g and the computer design value was 195 g. This difference could be due to the fact that more fibres were incorporated in the moulds to create some overlaps in between some layers. The computer design model did not include those overlaps. It is thought that when gluing the parts together, the weight will increase again slightly, therefore in order to match the weight target; less ballast should be added in the prototypes during manufacture. The gluing issue should be resolved by using glue from Vantico, a glue used for cars and plane components. Finally because of an important laminate thickness near the insert, the airfoil was more than 2 cm thick and it was wondered if it will be better than a 1 cm shaft. Also in the rules the shaft had to be constrained at the bottom of the club, so it was proposed that the shaft should be permitted to move freely at the top of the airfoil by putting an elastomeric joint.

Conclusion

The research that has been accomplished for this project was aimed at developing further a new driver geometry proposal. In order to accomplish this, the rules of golf and the spring effect behaviour were carefully reviewed through literature search and the moment of inertia and lay up of the C4 Callaway club head were studied and measured. Based on those findings, a new driver club head with a 400 cm³ volume, a 5.27 mm front face height and a 194 grams weight was designed. This project enabled to take into consideration the structural and inertial properties of this new design.

It was found that the new shape had a very high moment of inertia due to its geometry (airfoil, large and long) and the use of carbon epoxy (low density) which permit the addition of metal ballast (44 grams). The moment of inertia was even superior to the one of the C4 Callaway measured that was known to be already quite high so that it is understood that the new driver is more accurate than actual metal drivers.

Composite materials don't resist impact as well as metal. A front face made with UD fibres will fail because of the poor transverse tensile strength of UD plies. The plies on the inside of the laminate will fail first in the tensile matrix mode. Using a biaxial fabric will partially solve this problem and increase the transverse tensile strength; however the plies on the outside of the laminate will ultimately fail in the compressive fibre mode with this fabric.

Thus the use of thick high strength carbon biaxial fabric (T700 or T800 in 5 harness weave types) with toughened epoxy resin and with plies turned at [0/30/60/90/120/150] can make the front face more resistant. This type of front face (about 3.5mm thick) will only give a 0.2m/s ball speed reduction compare to an optimum titanium front face (2 mm thick) and will be lighter.

It is understood that a higher front face and stronger fibres increases the spring effect. Fibres are getting stronger and weave types more advanced, it may be soon possible to increase the resistance of the composite front face, allowing a thinner design and consequently increasing its spring effect. But this effect was found to have only a very small influence on the ball speed after impact.

Finally the use of composite have the advantages of making prototypes relatively cheap and simple to manufacture which could allow some easy testing to confirm the

design. Golf is an old and very controlled game that takes into consideration a lot of traditions, therefore using new materials and having different approaches will take time to become fully recognized. The results outlined in this project have shown that composite drivers have some very serious advantages that hopefully should soon be acknowledged.

Further work

It will be of interest to design some front faces with different shape and create a quick computer model to compare their performances. Effectively it is believed that the front face of the new driver could still be improved slightly by mainly increasing its height.

Also measuring the COR of the prototype manufactured will bring a lot of information on its performances and will be very interesting to see where it stands from the 0.83 COR limit.

More studies on the effect of the ply thickness in impact resistance and fatigue behaviour of woven fabric and unidirectional would be beneficial.

The aerodynamic of the club head was not part of this project and should be more investigated meanwhile it is clear the airfoil increase the moment of inertia of the club head.

Cutting some metal moulds from a CAD model definitive shape and then cooking some prototypes in autoclaves will make the consolidation of the laminate much better than the consolidation done for the prototype.

It is understood that some 3 D fabric are used on airplane propellers, it is tough it will have very good resistance to impact because all the plies are woven together (interlock) this should make the laminate more isotropic, and increase it's resistance to impact. However it will be very difficult to computer model them. Maybe some investigations could be carried on out in this field.

Finally Mr Gorse [5] just found a driver design with a hole on its base, this design is said to give some spring to the club head during impact giving a higher ball speed after impact.

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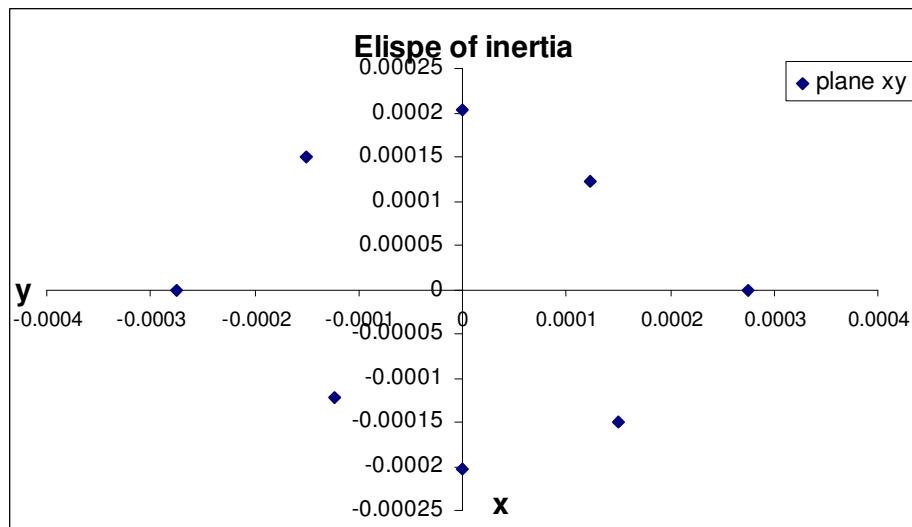
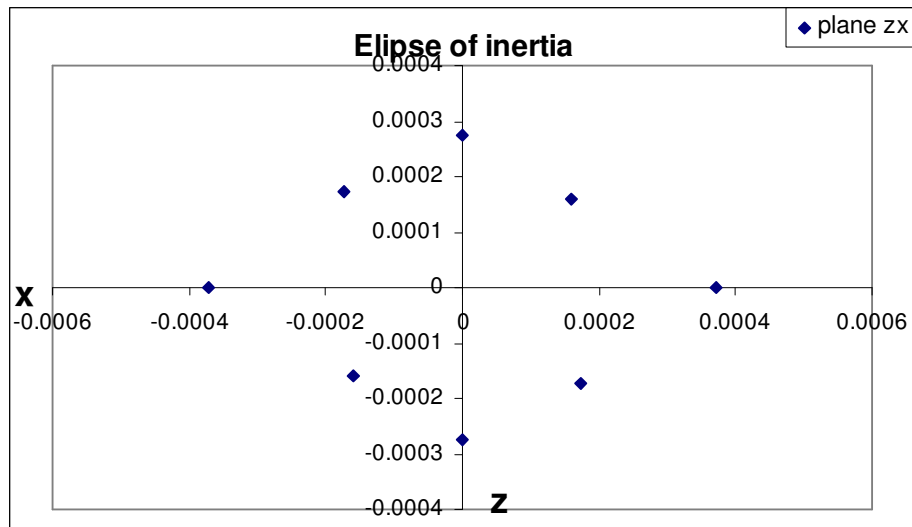
2002

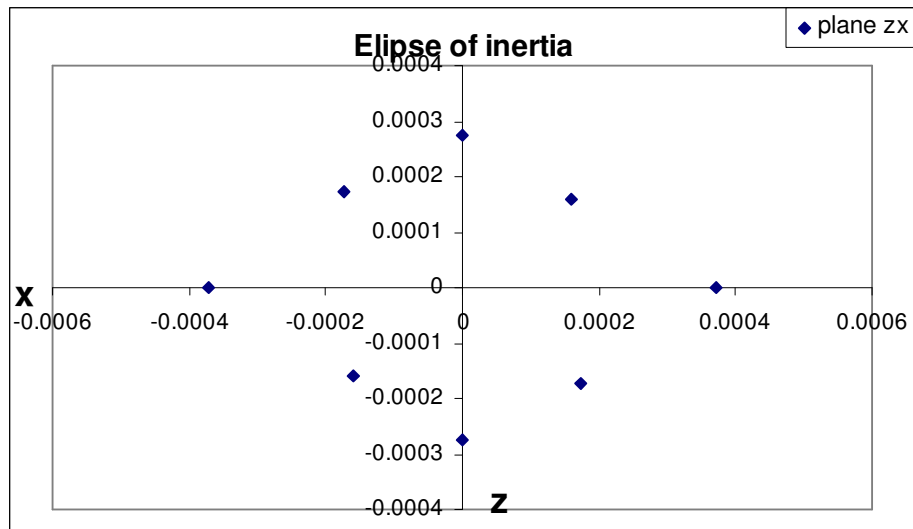
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Appendix 1 Ellipsoids of inertia

Ellipses of inertia from the different measurements of moment of inertia (C4 Callaway ckub head) for three orthogonal planes.





It can be seen that in each graphics we are obtaining nearly an ellipse of inertia which confirm that the results are not too inaccurate.

Appendix 2 Characteristics of some fibers

Source:

http://emedialibrary.com/reader/reader.asp?product_id=23792

36

TABLE 3-1 Typical Properties of Fibers

Fiber	Diameter, μm	Specific Gravity	Modulus, GPa*	Tensile Strength, GPa	Failure Strain, %	CTE, 10 ⁻⁶ /°C
E-glass	3-20	2.4	72.4	3.45		
S2-glass	10-20	2.4	86.9	4.59		
Boron	142	2.5	400	2.80	0.7	
Carbon, PAN based						
High strength		1.8	230	2.5	1.1	-0.4
High modulus		1.9	370	1.0	0.5	-0.5
Ultra-high modulus		2.0	520	1.0	0.2	-1.1
High strain		1.8	230-260	3.0-4.8	1.6-2.0	
Intermediate modulus		1.8	290	5.2	1.8	
Carbon, pitch based						
P25	10	1.8	140	1.4	1.0	-0.9
P55	10	2.02	380	1.4	0.4	-1.3
P75	10	2.00	520	1.4	0.3	-1.6
P100	10	2.15	700	1.4	0.2	-1.6
P120			820	1.4	0.2	-1.6
P140			960	1.4	0.2	-1.8
Silicon carbide						
SCS	140	3.0	430	3.4	0.8	
Nicalon	15	2.6	180-210	2.5-3.3	1.5	3.1
AVCO	6-10		300	2.8		
MPDI	10-15	2.3	180-210	1.8-2.1		
HPZ	10	2.35	140-175	2.1-2.5		
MPS	10-15	2.6-2.7	175-210	1.1-1.4		
Alumina						
FP	20	3.9	345-380	1.4	0.36-0.4	
Sumitomo	9-17	3.2	210-260	1.8-2.6	0.86	
Saffil	3	3.3	300	2.0	0.67	
PRD-166		4.2	385	2.1-2.5		
Alumina-silica						
Fiberfrax		2.7	100	1.0		
Fibermax		3.0	150	0.8	0.5	
Alumina-boria-silica						
Nextel 312	11	2.7	150	1.4-1.7		
Nextel 440	10-12	3.1	200-240	1.4-2.0	0.9	
Nextel 480	10-12	3.1	224	2.3	0.9	
Si, Ti, C, O						
Tyranno	8-10	2.3-2.5	200	3.0	1.5	
Aramid						
Kevlar 49	12	1.44	124-131	3.6	2.8	-2.0
Kevlar 29	12	1.44	83	3.6	4.0	
Kevlar 149	12	1.47	186	3.4	2.0	
HM-50	12	1.3	81	3.1	4.4	
Polyethylene						
Spectra 900	38	0.97	117	2.6	3.5	
Spectra 1000	27	0.97	172	3.1	0.7	
Tungsten	13	19.4	410	4.0		

*1 GPa = 1.45 x 10⁵ psi.

Appendix 3 LS Dyna input file from T700 epoxy

(with a front face in UD [0/30/60/90/120/150] (5.1mm).

```
*KEYWORD
$$ HM_OUTPUT_DECK created 10:47:44 11-26-2003 by HyperMesh Version 6.0
$$ Ls-dyna Input Deck Generated by HyperMesh Version : 6.0
$$ Generated using HyperMesh-Ls-dyna Template Version : 6.0
*CONTROL_TERMINATION
$$ ENDTIM      ENDCYC      DTMIN      ENDENG      ENDMAS
      0.002
*CONTROL_TIMESTEP
$$ DTINIT      TSSFAC      ISDO      TSLIMIT      DT2MS      LCTM      ERODE
MSIST
      0.0      0.9      0      0.0
$$DATABASE_OPTION -- Control Cards for ASCII output
*DATABASE_NODOUT
1.0000E-06
*DATABASE_GLSTAT
1.0000E-06
*DATABASE_MATSUM
1.0000E-06
*DATABASE_BINARY_D3PLOT
$$ DT/CYCL      LCDT      BEAM      NPLTC
3.0000E-05
*DATABASE_EXTENT_BINARY
$$ NEIPH      NEIPS      MAXINT      STRFLG      SIGFLG      EPSFLG      RLTFGL
ENGFLG
      6      18
$$ CMPFLG      IEVERP      BEAMIP      DCOMP      SHGE      STSSZ      N3THDT
      1
*NODE
      38989      0.031      0.0      -0.008
      38990      0.031      0.00266875      -0.008      4
571720.00429214844783-0.0281072091897-0.0235144013644
571730.00452869130785-0.0262519528338-0.0247326971637
57174 0.0043686496158-0.0240833324968-0.0274649538937
571750.00461242527708-0.0248118453728 -0.026037954731
571760.00498585819563-0.0221018329732-0.0273060490116
*MAT_ELASTIC
$HMNAME MATS      23tungstenmoi
      23      19300.04.0000E+11      0.28
*MAT_PLASTIC_KINEMATIC
$HMNAME MATS      5titanium
      5      4400.01.0500E+11      0.31.2000E+09
      0.5
*MAT_PLASTIC_KINEMATIC
$HMNAME MATS      6polypropylene
      6      936.0372000000.      0.3130000000.0
*MAT_PLASTIC_KINEMATIC
$HMNAME MATS      8aluminium
      8      2800.07.5000E+10      0.3450000000.
*MAT_BLATZ-KO_RUBBER
$HMNAME MATS      9POLYBUTADIENE
      9      1210.022000000.0
```

```

*MAT_COMPOSITE_DAMAGE
$HMNAME MATS      11kevlarwoven
      11

*MAT_COMPOSITE_DAMAGE
$HMNAME MATS      12spectrabiaxial
      12      970.08.1000E+109.0000E+094.5000E+09      0.3175      0.4
0.4
3.1000E+091.5000E+091.5000E+09

*MAT_COMPOSITE_DAMAGE
$HMNAME MATS      13spectrabiaxial2
      13      970.04.5000E+104.5000E+104.5000E+09      0.31      0.35
0.35
3.1000E+091.6000E+093.5000E+09

*MAT_ENHANCED_COMPOSITE_DAMAGE
$HMNAME MATS      14biaxial kevlar epoxy
      14      1450.02.5000E+102.5000E+109.0000E+09      0.06
2.0000E+091.6000E+091.6000E+09      2.0
                                0.0      1.0      0.0
                                0.0      1.0      1.0      0.04
140000000.380000000.140000000.380000000.57000000.0      54
*MAT_ENHANCED_COMPOSITE_DAMAGE
$HMNAME MATS      16woven glassfibres
      16      1992.02.3000E+102.3000E+104.5000E+09      0.31      0.4
3.3000E+09

450000000.260000000.450000000.260000000.140000000.      54
*MAT_ENHANCED_COMPOSITE_DAMAGE
$HMNAME MATS      17carbon woven epoxyy
      17      1600.01.3400E+119.4000E+099.0000E+09      0.023      0.0
0.0
4.0000E+094.0000E+094.0000E+09      3.0
      0.0      1.0      0.0

1.4000E+092.4200E+09138000000.48000000.082000000.0      54
*MAT_ENHANCED_COMPOSITE_DAMAGE
$HMNAME MATS      18carbonudepoxy
      18      1600.01.3000E+111.0300E+105.0000E+09      0.02      0.0
0.0
5.5000E+09      0.0      0.0      3.0
      0.0      1.0      0.0

2.0680E+091.5170E+09148000000.48000000.087000000.0      54      0.0
*MAT_ENHANCED_COMPOSITE_DAMAGE
$HMNAME MATS      19topexternalcarbonwoven

```

19	1600.01.3400E+119.5000E+099.0000E+09	0.023
4.0000E+094.0000E+094.0000E+09	3.0	
-1.0	0.0	0.0
1.4000E+092.4200E+091.3800E+0948000000.082000000.0		54
*MAT_ENHANCED_COMPOSITE_DAMAGE		
\$HNAME MATS	20airfoilcarbonwoven	
20	1600.01.3400E+119.0000E+099.0000E+09	0.023
4.0000E+094.0000E+094.0000E+09	0.0	3.0
0.0	0.58	0.81
1.4000E+092.4200E+091.3800E+0948000000.082000000.0		54
*MAT_ENHANCED_COMPOSITE_DAMAGE		
\$HNAME MATS	22steel	
22	7800.02.0500E+11	0.0
*MAT_ENHANCED_COMPOSITE_DAMAGE		
\$HNAME MATS	24moiringcarbone	
24	1600.01.3400E+119.4000E+099.0000E+09	0.023
4.0000E+094.0000E+094.0000E+09		
1.4000E+092.4200E+091.3800E+0948000000.082000000.0		54
*PART		
\$HNAME COMPS	7clubhead	
\$HMCOLOR COMPS	7	12
7	7	16
\$HNAME COMPS	8insert	
\$HMCOLOR COMPS	8	9
8	1	8
\$HNAME COMPS	9front face	
\$HMCOLOR COMPS	9	14
9	9	17
\$HNAME COMPS	11ball	
\$HMCOLOR COMPS	11	11
11	2	9
\$HNAME COMPS	12airfoil	
\$HMCOLOR COMPS	12	1
12	17	20
\$HNAME COMPS	13frontface4udcarbon	
\$HMCOLOR COMPS	13	1
13	9	18
\$HNAME COMPS	14topinternal	0
\$HMCOLOR COMPS	14	13
14	14	19

\$HNAME COMPS	15	topexternal				
\$HMCOLOR COMPS	15	11				
	15	11	19			
\$HNAME COMPS		16	frontfaceextension			
\$HMCOLOR COMPS		16	7			
	16	19	19			
\$HNAME COMPS		18	moiringcarbone			
\$HMCOLOR COMPS		18	5			
	18	20	17			
\$HNAME COMPS		19	moiringsteel			
\$HMCOLOR COMPS		19	4			
	19	22	23			
\$HNAME COMPS		20	frontcarboneyunderallu			
\$HMCOLOR COMPS		20	2			
	20	30	17			
\$HNAME COMPS		21	midlecarbonunderallu			
\$HMCOLOR COMPS		21	9			
	21	35	17			
\$HNAME COMPS		22	backcarbonunderallu			
\$HMCOLOR COMPS		22	2			
	22	34	17			
\$HNAME COMPS		23	frontallu			
\$HMCOLOR COMPS		23	1			
	23	24	8			
\$HNAME COMPS		24	middleallu			
\$HMCOLOR COMPS		24	5			
	24	27	8			
\$HNAME COMPS		25	backallu			
\$HMCOLOR COMPS		25	7			
	25	28	8			
\$HNAME COMPS		26	ballcover			
\$HMCOLOR COMPS		26	7			
	26	44	6			
*SECTION_SHELL						
\$HNAME PROPS		1	properties			
	1		2		0.0	
	1.0000E-03	1.0000E-03	1.0000E-03	1.0000E-03		
\$HNAME PROPS		3	Compositespectra			
	3	2	0.83	10	0.0	-4
	0.003	0.003	0.003	0.003		0
\$HNAME PROPS		5	sectionshellglass			
	5	2	0.83	30	0.0	-6
	0.009	0.009	0.009	0.009		
\$HNAME PROPS		7	sectionshell carbon			
	7	2	1.0	15	0.0	-8
	0.0045	0.0045	0.0045	0.0045		
\$HNAME PROPS		9	sectionshellfrontface			
	9	2	0.83	18	0.0	-10
						1

0.005058	0.005058	0.005058	0.005058			
0.0	30.0	60.0	90.0	120.0	150.0	180.0
30.0						
60.0	90.0	120.0	150.0	180.0	30.0	60.0
90.0						
120.0	150.0					
\$HNAME PROPS	11	2	1.0	5	-12	1
0.001405	0.001405	0.001405	0.001405			
0.0	90.0	0.0	90.0	0.0		
\$HNAME PROPS	14	2	1.0	10	0.0	-13
0.00281	0.00281	0.00281	0.00281			1
0.0	90.0	0.0	90.0	0.0	90.0	0.0
90.0						
0.0	90.0					
\$HNAME PROPS	16			10	-15	
\$HNAME PROPS	17	2	1.0	5	0.0	-15
1.4050E-041.4050E-041.4050E-041.4050E-04						1
0.0	90.0	0.0	90.0	0.0		
\$HNAME PROPS	19	2	1.0	14	0.0	-18
0.003934	0.003934	0.003934	0.003934			1
0.0	90.0	0.0	90.0	0.0	90.0	0.0
90.0						
0.0	90.0	0.0	90.0	0.0	90.0	
\$HNAME PROPS	20			5	-21	1
0.001405	0.001405	0.001405	0.001405			
0.0	90.0	0.0	90.0	0.0		
\$HNAME PROPS	22			1	-23	
5.0000E-045.0000E-045.0000E-045.0000E-04						
\$HNAME PROPS	24			1	-25	
1.0000E-031.0000E-031.0000E-031.0000E-03						
\$HNAME PROPS	27			1	-26	
1.0000E-031.0000E-031.0000E-031.0000E-03						
\$HNAME PROPS	28			1	-29	
1.0000E-031.0000E-031.0000E-031.0000E-03						
\$HNAME PROPS	30			19	-31	1
0.005339	0.005339	0.005339	0.005339			
0.0	30.0	60.0	90.0	120.0	150.0	180.0
30.0						
60.0	90.0	120.0	150.0	180.0	30.0	60.0
90.0						
120.0	150.0	180.0				
\$HNAME PROPS	34			5	-33	1
0.001405	0.001405	0.001405	0.001405			
0.0	90.0	0.0	90.0	0.0		
\$HNAME PROPS	35			14	-32	1

0.003934	0.003934	0.003934	0.003934			
0.0	90.0	0.0	90.0	0.0	90.0	0.0
90.0						
0.0	90.0	0.0	90.0	0.0	90.0	
\$HMNAME	PROPS	43fibersmoisections	shell			
43			4		-41	
0.0012	0.0012	0.0012	0.0012			
\$HMNAME	PROPS	42steelmoisections	shellshell			
42			1		-40	
1.0000E-031	0.0000E-031	0.0000E-031	0.0000E-03			
*SECTION_SOLID						
\$HMNAME	PROPS	2properties	4ball			
2		1				
\$HMNAME	PROPS	44sectsolid	ballcover			
44						
*INTEGRATION_SHELL						
\$HMNAME	PROPS	4integration	shellpectra			
4	10		1			
\$HMNAME	PROPS	6integrationshell	glass			
6	15		1			
\$HMNAME	PROPS	8integrationshell	carbon			
8	30		1			
\$HMNAME	PROPS	10integrationshell	frontface			
10	18		0			
0.94	0.111					
0.8425	0.111					
0.722	0.111					
0.611	0.111					
0.5	0.111					
0.389	0.111					
0.278	0.111					
0.1674	0.111					
0.056	0.111					
-0.056	0.111					
-0.1674	0.111					
-0.278	0.111					
-0.389	0.111					
-0.5	0.111					
-0.611	0.111					
-0.722	0.111					
-0.833	0.111					
-0.94	0.111					
\$HMNAME	PROPS	12integrationshell	topexternal			
12	5		0			
0.8	0.4					
0.4	0.4					
0.0	0.4					
-0.4	0.4					
-0.8	0.4					
\$HMNAME	PROPS	13integration	rultopinternal			
13	10		0			
0.9	0.2					
0.7	0.2					
0.5	0.2					
0.3	0.2					
0.1	0.2					
-0.1	0.2					
-0.3	0.2					
-0.5	0.2					

-0.7	0.2	
-0.9	0.2	
\$HNAME PROPS	15	integrationshellairfoil
15	5	0
0.8	0.4	
0.4	0.4	
0.0	0.4	
-0.4	0.4	
-0.8	0.4	
\$HNAME PROPS	18	integrationshellffextension
18	14	0
0.9285	0.143	
0.7855	0.143	
0.642	0.143	
0.5	0.143	
0.3565	0.143	
0.2135	0.143	
0.0705	0.143	
-0.07	0.143	
-0.2135	0.143	
-0.3565	0.143	
-0.4995	0.143	
-0.6425	0.143	
-0.7855	0.143	
-0.9285	0.143	
\$HNAME PROPS	21	linegationshellmoiring
21	5	0
0.92	0.308	
0.52	0.308	
-0.37	0.308	
-1.15	0.308	
-1.69	0.308	
\$HNAME PROPS	23	integrationrulessteel
23	1	0
0.49	0.52	
\$HNAME PROPS	25	frontalluintshell
25	1	0
5.34	0.315	
\$HNAME PROPS	26	middlealluintshell
26	1	0
3.947	0.4	
\$HNAME PROPS	29	backalluintshell
29	1	0
1.39	0.83	
\$HNAME PROPS	31	intrulesalucarbo
31	19	0
0.81	0.0886	9
0.71	0.0886	9
0.6	0.0886	9
0.49	0.089	9
0.39	0.089	9
0.266	0.089	9
0.181	0.089	9
0.076	0.089	9
0.023	0.089	9
-0.13	0.089	9
-0.23	0.089	9
-0.33	0.089	9
-0.439	0.089	9

```

-0.546      0.089      9
-0.65      0.089
-0.76      0.089
-0.866     0.089
-0.97      0.089
-1.0683    0.089
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      32      14      0
      0.68     0.113     9
      0.538    0.113     9
      0.395    0.113     9
      0.252    0.113     9
      0.109    0.113     9
     -0.033    0.113     9
     -0.176    0.113     9
     -0.32     0.113     9
     -0.46     0.113     9
     -0.605    0.113     9
     -0.748    0.113     9
     -0.89     0.113     9
     -1.034    0.113     9
     -1.177    0.113     9
$HMNAME PROPS      33intrulesalucarboback
      33      5
      0.083    0.233
     -0.31     0.233
     -0.71     0.233
     -1.11     0.233
     -1.51     0.233
$HMNAME PROPS      41fibersmoiintrules
      41      4
      1.53     0.2
      0.92     0.2
     -0.92     0.2
     -1.53     0.2
$HMNAME PROPS      40steelmoiintrules
      40      1
      0.0      0.2
*INITIAL_VELOCITY_GENERATION
$HMNAME LOADCOLS      2insertvelocitygood
$HMCOLOR LOADCOLS      2      16
      15      1      42.0

*CONTACT_NODES_TO_SURFACE
$HMNAME GROUPS      19inserthead
$HMCOLOR GROUPS      19      6
$HMFLAG GROUPS SLAVE MASTER
      16      2      4      0

*SET_NODE_LIST
      16
      56754      56755      56756      45563      49047      56671      56677
56680
      46460      56748      56747      56749      56684      56683      56685
56678
      56682      56679      56676      56673      56670      56674      56672
56669
      56668      56665      56667      56666      56681      56675

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*SET_SEGMENT

2

56755	49051	56756	56756
56665	49049	56666	56666
56668	49052	56669	56669
56748	56749	49023	49023
56669	49052	56670	56670
56673	55595	55490	55490
56754	49047	56749	56749
49024	56747	56685	56685
48871	56681	56680	56680
48871	56682	56681	56681
48871	56682	56683	56683
56673	55489	55490	55490
56754	49051	56755	56755
56753	46460	49121	49121
56674	56675	56676	56676
56756	56665	49049	49051
56756	56755	56748	56747
56665	56756	56747	56685
56666	56665	56685	56684
56667	56683	56684	56666
56667	56666	49049	49053
56668	56667	49053	49052
56668	56682	56683	56667
56669	56681	56682	56668
56670	56680	56681	56669
49009	46460	56749	49023
56755	56754	56749	56748
56749	49047	56753	46460
56671	56670	49052	48883
56672	55596	48883	56671
56673	55595	55596	56672
49024	56685	56684	48846
56674	55524	55489	56673
56674	56675	55525	55524
49023	56748	56747	49024
56676	56675	55525	55521
56677	56676	55521	55519
55516	55493	56677	55519
48843	55493	56677	56678
48869	56679	56678	48843
48871	56680	56679	48869
48846	56684	56683	48871
56754	49047	49046	49051
56671	56679	56680	56670
56671	56679	56678	56672
56673	56672	56678	56677
56674	56673	56677	56676
45563	54615	54641	54639
54636	54633	54601	49121
49121	45563	54639	54636
54615	45563	49047	49046
46460	49121	54601	49009

*CONTACT_AUTOMATIC_GENERAL

\$HNAME GROUPS 3contact

\$HMCOLOR GROUPS 3 6

0

5

0

0

0.27

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*ELEMENT_SHELL
  44626      8    56783    56788    56785    56785
  44619      8    56778    56780    56783    56783
  44608      8    56775    56773    56769    56769
  44603      8    56766    56770    56768    56768

.....

30331      26    41651    41353    41289    41284    41676    41328    41243
41248
  30447      26    41769    41764    41763    41768    41721    41726
41727    41722
  30475      26    41769    41768    41853    41858    41721    41722
41807    41812
  30587      26    42091    41853    41768    41763    42116    41807
41722    41727
  30703      26    42290    42285    42284    42289    42242    42247
42248    42243
  30731      26    42290    42289    42353    42358    42242    42243
42328    42333
  30843      26    42651    42353    42289    42284    42676    42328
42243    42248
$$
$$ Sets Defined In HyperMesh
$$
*SET_PART_LIST
$HMSSET
$HMNAME SETS      15velocityset
      15
      7          8          9          12          13          14          15
16
      18          19          20          21          22          23          24
25
*BOUNDARY_SPC_NODE
$HMNAME LOADCOLS      2insertvelocitygood
$HMCOLOR LOADCOLS      2      16
      56829          0          1          1          1          1
1
.....

*END

```

Appendix 4 Scott Bader Resin and Catalyst

Source: Scott Bader

Introduction

Crystic 471PALV is a pre-accelerated, low viscosity polyester resin with rapid hardening characteristics. It combines rapid impregnation of reinforcements and fillers with a very short mould release time, and is suitable for hand-lay or spray applications. Crystic 471PALV is recommended for automotive, marine and resin concrete applications.

Approvals

Crystics 471PALV is approved by Lloyd's Register of Shipping for use in the construction of craft under their survey. It also meets the requirements of BS 3532:1990, Type A.

Product Characteristics

FORMULATION

Crystic 471PALV should be allowed to attain workshop temperature (18°C - 20°C) before use. It requires only the addition of a catalyst to start the curing reaction. The recommended catalysts are Catalyst M (or Butanox M50) or, where ambient temperatures are high, Catalyst O (or Interlox LA3). Either catalyst should be added at 1% or 2% into the resin and thoroughly dispersed. The geltime of the resin can be approximately determined from the table below.

POT LIFE

Parts of Catalyst M to 100 Parts Resin	2.0
Pot life in Minutes at 15°C	18
Pot life in Minutes at 20°C	12
Pot life in Minutes at 25°C	8

The resin, mould and workshop should be at, or above, 15°C before curing is carried out.

ADDITIVES

Crystic 471PALV may be pigmented by the addition of up to 10% of Crystic Pigment Paste. The addition of fillers may change the hardening rate of the resin, and should be evaluated before large scale use.

POST CURING

Satisfactory laminates for many applications can be made with Crystic 471PALV by curing at workshop temperature (20°C). For optimum properties and long term performance, however, laminates should be post cured before being put into service. Mouldings should be allowed to cure for 24 hours at 20°C, and then be oven cured for 3 hours at 80°C or 16 hours at 40°C.

Catalyst M *Source: Scott Badder*

Introduction

Catalyst M is a clear, colourless liquid comprising Methyl Ethyl Ketone Peroxides in dimethyl phthalate.

Applications

This general purpose MEKP is used for the curing of Cobalt accelerated Unsaturated Polyester Resins at room temperature. It can be used in Hand lay-up and various mechanised production methods. The low water content of Catalyst M makes it particularly suitable for curing Gelcoat resins.

Dosage levels

- 2 % for Gelcoat resins
- 1 – 2 % for Laminating and Casting resins.

TYPICAL PROPERTIES

Property	
Appearance	Colourless liquid
Active oxygen content	9.0 %
Density at 20° C	1.18
Self accelerating decomposition temperature	60° C
Maximum storage temperature	25° C

Typical gel time data

Parts of Catalyst M to 100 parts Crystic 2-406 PA	1.0	2.0
gel time at 25 ° C	17	12

Typical hardening rate at 20° C

(of 3 layers of 450 g/m² mat with Crystic 2-406 PA and 2 % Catalyst M)

Barcol hardness (GYZJ 934-1)	1 – 5	15	30
Time	3.5 hours	4.5 hours	6 hours

Packaging

30 kg containers

Storage and Health & Safety

Please see separate Material Safety Data Sheet.
31 August 2001



Appendix 5 HEXPLY 920 CX-926-42%

The pre-impregnated fabric used for the prototype



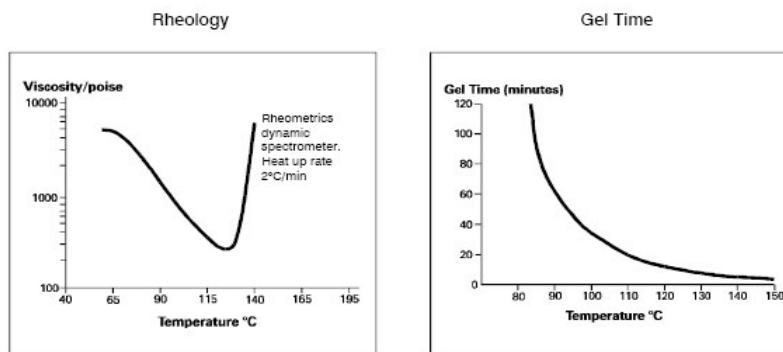
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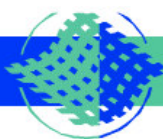
920 is a very tough advanced resin matrix, ideally suited to the single-shot production of honeycomb sandwich structures and the manufacture of solid laminates. It is highly tolerant of a variety of production techniques and equipment, making it easy to process. The high toughness of 920 makes it ideal for industrial applications and performance cars. It is available preimpregnated into carbon, glass or aramid fibres.

Benefits and Features

- Very tough matrix
- Excellent adhesive properties
- Tolerant to many production techniques
- High melt viscosity, giving easy processing characteristics
- Suitable for low to medium pressure laminating and moulding
- Variable cure cycles
- Long shelf life at -18°C and out life at 23°C
- Excellent surface finish

Resin Matrix Properties





920

Cured Matrix Properties (cured at 125°C)

		Method
Tensile strength	34.9 MPa	ISO R527 type 1
Tensile modulus	3.76 GPa	ISO R527 type 1
Tensile strain	8.41%	ISO R527 type 1
Poisson's ratio	0.39	ISO R527 type 1
Flexural modulus	3.51 GPa	ISO 178
Compression strength	290 MPa	ISO 604
Compression strain	7.40%	ISO 604
Toughness K_{1c}	1.55 MPa $\sqrt{m}$	Tested in accordance with
Toughness G_{1c}	541 J/m ²	EGF Task Group on Polymers
		and Composites protocol.
Glass transition temperature (T _g)	107°C	DMTA
Cured density	1.22 g/cm ³	
Vol. shrinkage	1.59%	

Prepreg Curing Conditions

1 hour at 125°C and 300kN/m² (3 bar) pressure.

Heat up rate 2°C to 10°C

920 is very versatile and can cure much quicker at high temperatures

Temperature °C	Time (Mins)
140	30
150	15
160	10
170	5

Performance testing should accompany the alternative cure cycles to ensure they are suitable for the particular application. Thick components require a dwell in the cure cycle of 2-3 hours at 90°C to avoid the risk of an exotherm in the matrix.

Cured Prepreg Properties (cured at 125°C)

Test	Method	920CX-FM40J-6-42%	920CX-EP2015-47.5%	920KX-285-52%	920CX-950-42%
		High modulus carbon, unidirectional, 165 g/m ²	Intermediate modulus 6K carbon, 2 x 2 twill, 193 g/m ²	Kevlar, 4H satin, 171 g/m ²	Intermediate modulus 6K carbon, 5H satin, 285 g/m ²
Tensile strength * MPa	pr EN 2561	1760	1337	442	1434
Tensile modulus * GPa	Type B	215	87	33	87
Compression strength * MPa	EFA TP-003	894	901	278	912
Compression modulus * GPa		199	79	30	78
ILSS MPA	pr EN 2563	76	71	44	70
CAI @ 6.6 J/mm * MPa	pr EN 6038	240	369	140	361

*Results normalised to 60% fibre volume for Carbon, 50% fibre volume for Kevlar.

180°C curing epoxy matrix

Prepreg Storage Life

- | | | |
|-------------------------|---------|---------------------|
| ■ Tack Life | @ 23°C | 30 days |
| ■ Guaranteed Shelf Life | @ -18°C | 12 months (minimum) |

■ Storage conditions.

920 prepregs should be stored as received in a cool dry place or in a refrigerator. After removal from refrigerator storage, prepreg should be allowed to reach room temperature before opening the polythene bag, thus preventing condensation. (A full reel in its packaging can take up to 48 hours).

Precautions for Use

The usual precautions when handling uncured synthetic resins and fine fibrous materials should be observed, and a Safety Data Sheet is available for this product. The use of clean disposable inert gloves provides protection for the operator and avoids contamination of material and components.

Appendix 6 Laminate analysis

The final, or ultimate, failure load of an angle ply laminate is often coincident with, or only slightly higher than, the load to cause initial failure. This is not necessarily the case for other lay-ups and final failure can be at a considerably higher load than that to cause first ply failure.

It is clear that once a ply has sustained failure its stiffness in certain directions will have been reduced. However, unless the damaged ply has completely delaminated from the rest of the laminate it will still contribute to the overall stiffness of the plate. The magnitude of this contribution depends on the amount of damage, the fibre/matrix combination and the nature of the loading on the ply.

In general an iterative method is adopted, successively applying the approach described in section 9.3.1 until final failure has occurred. As a starting point the relative value of the forces and moments (N_x , N_y , N_{xy} , M_x , M_y , M_{xy}) acting on the laminate will be known from, say, a structural analysis of the component being designed. Alternatively a parametric study of a range of lay-ups could be carried out for an arbitrary set of load values. The steps taken are as follows.

1. Apply, in the previously-determined ratio, a small value of the loads to the laminate under consideration.
2. Using laminate analysis determine the plate strains and curvatures and hence the stresses and strains in each ply (in the principal directions).
3. Apply the chosen failure criterion to each ply.
4. If no failure has occurred increase the loads (maintaining their relative magnitudes) by the appropriate factor to give first ply failure.
5. Reduce the stiffnesses in the damaged plies and recalculate the **A**, **B** and **D** matrices.
6. Repeat steps 2 and 3 until no further failures occur.
7. Repeat steps 4, 5 and 6.
8. Repeat step 7 until failure (i.e. fibre fracture) of the last ply takes place. This defines the ultimate strength of the laminate.

Source: Matthews [10]

Appendix 7 Metal matrices

METAL MATRIX COMPOSITE PROCESSING		
Table 3.1 MMCs for aerospace applications. (Source: Wei, 1992)		
<i>Matrix</i>	<i>Fibre</i>	<i>Application</i>
Cu base	C	combustion chamber
	SiC	nozzle (rocket, space shuttle)
	W	NASP ^a heat exchanger
Fe base	W	tubing
Ni base and intermetallics	Al ₂ O ₃	blades, discs
	W	
Ti base and intermetallics	SiC	housings, tubing
	TiB ₂	blades, discs
	TiC	shafts, honeycomb
Al base	SiC	housings (pumps, instrumentation), mechanical connectors, satellite, structures
	Al ₂ O ₃	fuselage
	C	structural members
	SiC	wings, blades
Mg base	Al ₂ O ₃	structural members
Directionally solidified eutectics		blades, cable, NASP ^a heat exchanger, superconductors
Cu base	Nb	
Ni base	Carbide	
Ti base	Silicide	

^aHypersonic American National Aerospace Plane.

Source [10]: Matthews

Appendix 8 Mechanical properties of some composites plies computed from “micro-mechanics”.

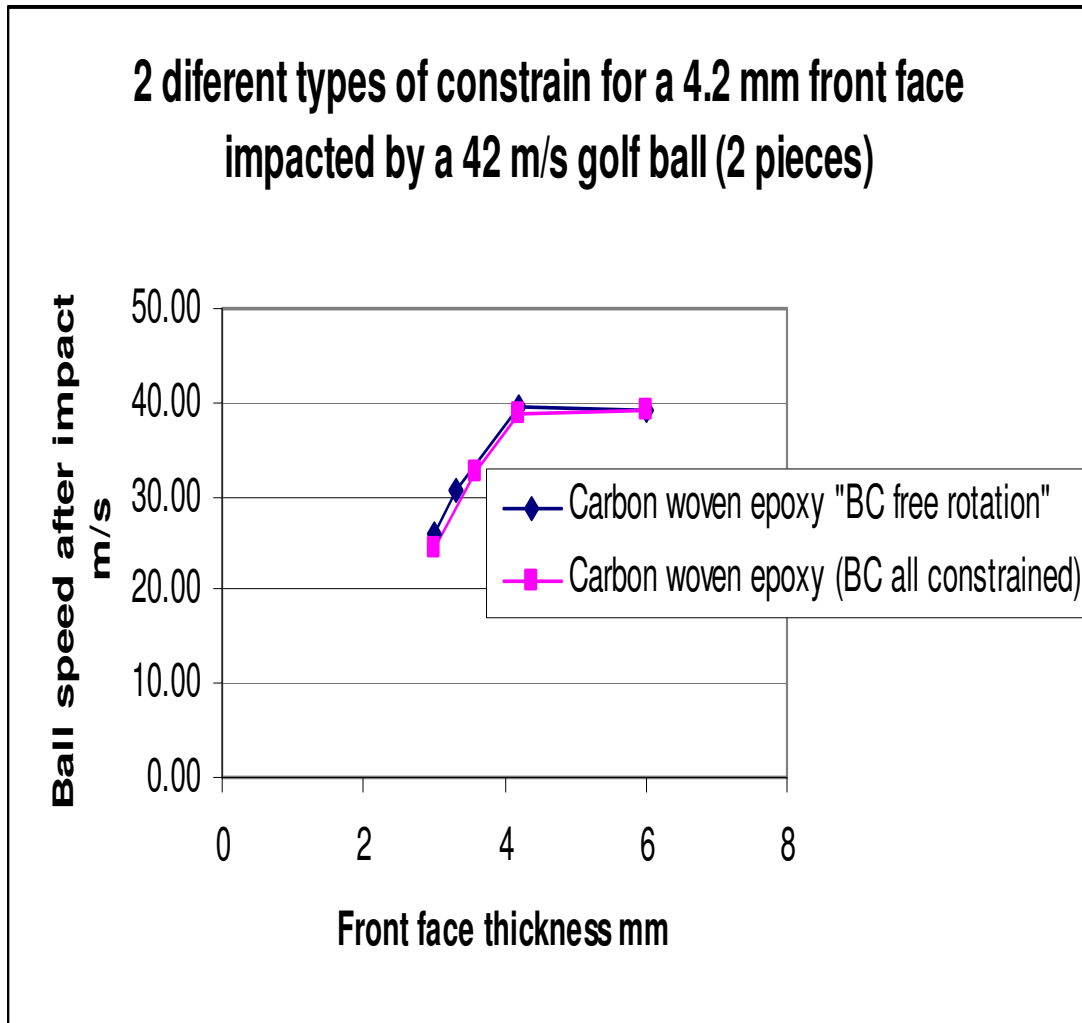
Micromechanics for strenght and stiffness

Materials	E1 Pa	E2 Pa	1/E2	E2 Pa	vf	E3	Ef	Em	Gf	Gm	1/G12
S Glass / epoxy	4.93E+10		1.06E-10	9.40E+09	0.55		8.60E+10	4.50E+09	4.00E+10	1600000000	2.95E-10
Kevlar 49 ud / epoxy	7.90E+10		1.04E-10	9.62E+09	0.55		1.40E+11	4.50E+09	1.20E+10	1600000000	3.27E-10
Steel ud / epoxy	1.15E+11		1.03E-10	9.74E+09	0.55		2.05E+11	4.50E+09	7.90E+10	1600000000	2.88E-10
Carbon ud high strength / epoxy	1.29E+11		1.02E-10	9.77E+09	0.55		2.30E+11	4.50E+09	5.00E+10	1600000000	2.92E-10
Carbon woven epoxy	6.29E+09		#DIV/0!	6.29E+09	0.55	9.00E+09		4.50E+09	5.00E+10	1600000000	2.92E-10
Steel	6.29E+09	2.05E+11	#DIV/0!	6.29E+09	0.55			4.50E+09	5.00E+10	1600000000	2.92E-10
Titanium AU4G	6.29E+09	1.05E+11	#DIV/0!	6.29E+09	0.55			4.50E+09	5.00E+10	1600000000	2.92E-10
Ball cover	6.29E+09	3.72E+08	#DIV/0!	6.29E+09	0.55			4.50E+09	5.00E+10	1600000000	2.92E-10
Polybutadiene	6.29E+09		#DIV/0!	6.29E+09	0.55			4.50E+09	5.00E+10	1600000000	2.92E-10
	6.29E+09		#DIV/0!	6.29E+09	0.55			4.50E+09	5.00E+10	1600000000	2.92E-10
carbon IM t700	1.34E+11		1.02E-10	9.40E+09	0.55		2.35E+11	4.50E+09	5.00E+10	1600000000	2.92E-10

Materials	G13	G32	V12	vf	vm	V21
S Glass / epoxy	2.00E+09	2.00E+09	0.29	0.2	0.4	5.53E-02
Kevlar 49 ud / epoxy	2.00E+09	2.00E+09	0.4	0.4	0.4	4.87E-02
Steel ud / epoxy	2.00E+09	2.00E+09	0.345	0.3	0.4	2.93E-02
Carbon ud high strength / epoxy	2.00E+09	2.00E+09	0.345	0.3	0.4	2.62E-02
Carbon woven epoxy	2.00E+09	2.00E+09		0.3	0.4	6.00E-02
Steel	2.00E+09	2.00E+09	0.3	0.3	0.4	3.00E-01
Titanium AU4G	2.00E+09	2.00E+09	0.31	0.3	0.4	0.31
Ball cover	2.00E+09	2.00E+09	0.33	0.3	0.4	0.033
Polybutadiene	2.00E+09	2.00E+09	0.33	0.3	0.4	
	2.00E+09	2.00E+09	0.33	0.3	0.4	
carbon IM t700	2.00E+09	2.00E+09	0.33	0.3	0.4	2.31E-02

Materials	sigm1t	sigm1f	sigm1c	sigm2t	sigm m	sign 2 c	t	df	dm	Density
S Glass / epoxy	1.76E+09	3.20E+09	3.56E+09	21219362	1.30E+08	7.00E+08	1.60E+07	2.50E+03	1.25E+03	1.94E+03
Kevlar 49 ud / epoxy	1.60E+09	2.90E+09	3.56E+09	21219362	1.30E+08	5.50E+07	3.45E+07	1.45E+03	1.25E+03	1.36E+03
Steel ud / epoxy	6.60E+08	1.20E+09	3.56E+09	21219362	1.30E+08	5.50E+07		7800	1.25E+03	4.85E+03
Carbon ud high strength / epoxy	1.8E+09	3.20E+09	3.56E+09	4.80E+07	1.30E+08	1.38E+08	8.20E+07	1.75E+03	1.25E+03	1.53E+03
Carbon woven epoxy	1.56E+09		2.68E+09	4800000	1.30E+08	1.48E+08				1600
Steel	1.56E+09				1.30E+08					7800
Titanium AU4G	1.56E+09				1.30E+08					4400
Ball cover	1.56E+09				1.30E+08					936
Polybutadiene	1.56E+09				1.30E+08					1210
	1.56E+09				1.30E+08					
carbon IM i700	2.42E+09	5.30E+09	1.40E+09	4.80E+07	1.30E+08	1.38E+08	8.20E+07			

Appendix 9 two types of constraints



Appendix 10 Material 54

source [26]: *Ls- Dyna keyword user's manual*

Full details of how material number 54 works.

Card 4

Variable	V1	V2	V3	D1	D2	D3	DFAILM	DFAILS
Type	F	F	F	F	F	F	F	F

Card 5

Variable	TFAIL	ALPH	SOFT	FBRT	YCFAC	DFAILT	DFAILC	EFS
Type	F	F	F	F	F	F	F	F

Card 6

Variable	XC	XT	YC	YT	SC	CRIT	BETA	
Type	F	F	F	F	F	F	F	

<u>VARIABLE</u>	<u>DESCRIPTION</u>
MID	Material identification. A unique number has to be chosen.
RO	Mass density
EA	E_a , Young's modulus - longitudinal direction
EB	E_b , Young's modulus - transverse direction
(EC)	E_c , Young's modulus - normal direction (not used)
PRBA	ν_{ba} , Poisson's ratio ba
(PRCA)	ν_{ca} , Poisson's ratio ca (not used)
(PRCB)	ν_{cb} , Poisson's ratio cb (not used)
GAB	G_{ab} , shear modulus ab
GBC	G_{bc} , shear modulus bc

VARIABLE	DESCRIPTION
GCA	G_{c2} , shear modulus ca
(KF)	Bulk modulus of failed material (not used)
AOPT	Material axes option (see MAT_OPTION TROPIC_ELASTIC for a more complete description): EQ. 0.0: locally orthotropic with material axes determined by element nodes 1, 2, and 4, as with *DEFINE_COORDINATE_NODES. EQ. 2.0: globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR. EQ. 3.0: locally orthotropic material axes determined by rotating the material axes about the element normal by an angle (MANGLE) from a line in the plane of the element defined by the cross product of the vector v with the element normal.
A1 A2 A3	Define components of vector a for AOPT = 2.
V1 V2 V3	Define components of vector v for AOPT = 3.
D1 D2 D3	Define components of vector d for AOPT = 2.
MANGLE	Material angle in degrees for AOPT = 3, may be overridden on the element card, see *ELEMENT_SHELL_BETA or *ELEMENT_SOLID_ORTHO.
DFAILM	Maximum strain for matrix straining in tension or compression. The layer in the element is completely removed after the maximum strain in the matrix direction is reached. The input value is always positive.
DFAILS	Maximum shear strain. The layer in the element is completely removed after the maximum shear strain is reached. The input value is always positive.
TFAIL	Time step size criteria for element deletion: ≤ 0: no element deletion by time step size. The crashfront algorithm only works if t _{fail} is set to a value above zero. 0 < t _{fail} ≤ 0.1: element is deleted when its time step is smaller than the given value. > 1: element is deleted when the quotient of the actual time step and the original time step drops below the given value.
ALPH	Shear stress parameter for the nonlinear term, see Material 22.
SOFT	Softening reduction factor for material strength in crashfront elements (default = 1.0). TFAIL must be greater than zero to activate this option.

VARIABLE	DESCRIPTION
FBRT	Softening for fiber tensile strength: EQ.0.0: tensile strength = $\bar{X}_t$ GT.0.0: tensile strength = X_t , reduced to $X_t * FBRT$ after failure has occurred in compressive matrix mode.
YCFAC	Reduction factor for compressive fiber strength after matrix failure. The compressive strength in the fiber direction after compressive matrix failure is reduced to: $X_c = YCFAC * Y_c$ (default: $YCFAC = 2.0$)
DFAILT	Maximum strain for fiber tension. (Maximum 1 = 100% strain). The layer in the element is completely removed after the maximum tensile strain in the fiber direction is reached.
DFAILC	Maximum strain for fiber compression (Maximum -1 = 100% compression). The layer in the element is completely removed after the maximum tensile strain in the fiber direction is reached. The input value must have a negative sign.
EFS	Effective failure strain.
XC	Longitudinal compressive strength
XT	Longitudinal tensile strength, see below.
YC	Transverse compressive strength, b-axis, see below.
YT	Transverse tensile strength, b-axis, see below.
SC	Shear strength, ab plane, see below.
CRIT	Failure criterion (material number): EQ.54.0: Chang matrix failure criterion (as Material 22) (default), EQ.55.0: Tsai-Wu criterion for matrix failure.
BETA	Weighting factor for shear term in tensile fiber mode ($0.0 \leq BETA \leq 1.0$)

Remarks:

The Chang/Chang (mat_54) criteria is given as follows:

for the tensile fiber mode,

$$\sigma_{aa} > 0 \quad \text{then} \quad e_f^2 = \left(\frac{\sigma_{aa}}{X_t} \right)^2 + \beta \left(\frac{\sigma_{ab}}{S_c} \right) - 1 \quad \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}$$

$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0,$$

for the compressive fiber mode,

$$\sigma_{aa} < 0 \quad \text{then} \quad e_c^2 = \left(\frac{\sigma_{aa}}{X_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$E_a = \nu_{ba} = \nu_{ab} = 0.$$

for the tensile matrix mode,

$$\sigma_{bb} > 0 \quad \text{then} \quad e_m^2 = \left(\frac{\sigma_{bb}}{Y_t} \right)^2 + \left(\frac{\sigma_{ab}}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$E_b = \nu_{ba} = 0. \rightarrow G_{ab} = 0,$$

and for the compressive matrix mode,

$$\sigma_{bb} < 0 \quad \text{then} \quad e_d^2 = \left(\frac{\sigma_{bb}}{2S_c} \right)^2 + \left[\left(\frac{Y_c}{2S_c} \right)^2 - 1 \right] \frac{\sigma_{bb}}{Y_c} + \left(\frac{\sigma_{ab}}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases},$$

$$\nu = \nu_{ba} = \nu_{ab} = 0. \rightarrow G_{ab} = 0$$

$$X_c = 2Y_c \quad \text{for 50\% fiber volume}$$

In the Tsai-Wu (mat_55) criteria the tensile and compressive fiber modes are treated as in the Chang-Chang criteria. The failure criterion for the tensile and compressive matrix mode is given as:

$$e_{nd}^2 = \frac{\sigma_{bb}^2}{Y_c Y_t} + \left(\frac{\sigma_{ab}}{S_c} \right)^2 + \frac{(Y_c - Y_t) \sigma_{bb}}{Y_c Y_t} - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}$$

For $\beta = 1$ we get the original criterion of Hashin [1980] in the tensile fiber mode. For $\beta = 0$ we get the maximum stress criterion which is found to compare better to experiments.

Failure can occur in any of four different ways:

1. If DFAILT is zero, failure occurs if the Chang-Chang failure criterion is satisfied in the tensile fiber mode.
2. If DFAILT is greater than zero, failure occurs if the tensile fiber strain is greater than DFAILT or less than DFAILC.
3. If EFS is greater than zero, failure occurs if the effective strain is greater than EFS.
4. If TFAIL is greater than zero, failure occurs according to the element timestep as described in the definition of TFAIL above.

When failure has occurred in all the composite layers (through-thickness integration points), the element is deleted. Elements which share nodes with the deleted element become "crashfront" elements and can have their strengths reduced by using the SOFT parameter with TFAIL greater than zero.

Information about the status in each layer (integration point) and element can be plotted using additional integration point variables. The number of additional integration point variables for shells written to the LS-DYNA database is input by the *DATABASE_BINARY definition as variable NEIPS. For Models 54 and 55 these additional variables are tabulated below (i = shell integration point):

History Variable	Description	Value	LS-TAURUS Component
1. $ef(i)$	<i>tensile fiber mode</i>	1 - elastic 0 - failed	81
2. $ec(i)$	<i>compressive fiber mode</i>		82
3. $em(i)$	<i>tensile matrix mode</i>		83
4. $ed(i)$	<i>compressive matrix mode</i>		84
5. $efail$	$max[ef(ip)]$		85
6. dam	<i>damage parameter</i>	-1 - element intact 10^{-8} - element in crashfront +1 - element failed	86

These variables can be plotted in LS-TAURUS as element components 81, 82, ..., 80+NEIPS. The following components, defined by the sum of failure indicators over all through-thickness integration points, are stored as element component 7 instead of the effective plastic strain:

Description	Integration point
$\frac{1}{nip} \sum_{i=1}^{nip} ef(i)$	1
$\frac{1}{nip} \sum_{i=1}^{nip} ec(i)$	2
$\frac{1}{nip} \sum_{i=1}^{nip} em(i)$	3

Appendix 11 Different fiber types

Source: http://www.azom.com/details.asp?ArticleID=984#_Carbon

Glass

By blending quarry products (sand, kaolin, limestone, colemanite) at 1600°C, liquid glass is formed. The liquid is passed through micro-fine bushings and simultaneously cooled to produce glass fibre filaments from 5-24µm in diameter. The filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a “size” to provide filament cohesion and protect the glass from abrasion.

By variation of the “recipe”, different types of glass can be produced. The types used for structural reinforcements are as follows:

- a. E-glass (electrical) - lower alkali content and stronger than A-glass (alkali). Good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance relatively poor. Depending on the type of E-glass the price ranges from about £1-2/kg. E-glass is the most common form of reinforcing fibre used in polymer matrix composites.
- b. C-glass (chemical) - best resistance to chemical attack. Mainly used in the form of surface tissue in the outer layer of laminates used in chemical and water pipes and tanks.
- c. R, S or T-glass – manufacturers trade names for equivalent fibres having higher tensile strength and modulus than E-glass, with better wet strength retention. Higher ILSS (interlaminar shear strength) and wet out properties are achieved through smaller filament diameter. S-glass is produced in the USA by OCF, R-glass in Europe by Vetrotex and T-glass by Nittobo in Japan. Developed for aerospace and defence industries, and used in some hard ballistic armour applications. This factor, and low production volumes mean relatively high prices. Depending on the type of R or S-glass the price ranges from about £12-20/kg.

E-Glass Fibre Types

E-glass fibre is available in the following forms:

- a. Strand - a compactly associated bundle of filaments. Strands are rarely seen commercially and are usually twisted together to give yarns.
- b. Yarns - a closely associated bundle of twisted filaments or strands. Each filament

diameter in a yarn is the same, and is usually between 4-13µm. Yarns have varying weights described by their 'tex' (the weight in grams of 1000 linear metres) or denier (the weight in lbs of 10 000 yards), with the typical tex range usually being between 5 and 400.

c. Rovings - a loosely associated bundle of untwisted filaments or strands. Each filament diameter in a roving is the same, and is usually between 13-24µm. Rovings also have varying weights and the tex range is usually between 300 and 4800. Where filaments are gathered together directly after the melting process, the resultant fibre bundle is known as a direct roving. Several strands can also be brought together separately after manufacture of the glass, to give what is known as an assembled roving. Assembled rovings usually have smaller filament diameters than direct rovings, giving better wet-out and mechanical properties, but they can suffer from catenary problems (unequal strand tension), and are usually higher in cost because of the more involved manufacturing processes.

It is also possible to obtain long fibres of glass from short fibres by spinning them. These spun yarn fibres have higher surface areas and are more able to absorb resin, but they have lower structural properties than the equivalent continuously drawn fibres.

Glass Fibre Designation

Glass fibres are designated by the following internationally recognised terminology: Table 1
Table 1. Demonstrates the internationally recognised terminology for glass fibre designation.

Glass Type	Yarn Type	Filament Diameter (µ)	Strand Weight (tex)	Single Strand Twist	No. of Strands	Multi-strand Twist	No. Turns/metre
E	C	9	34	Z	X2	S	150
E = Electrical S = High Strength	C = Continuous			Z = Clockwise S = Anti- Clockwise			

Aramid

Aramid fibre is a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. The bright golden yellow filaments produced can have a range of properties, but all have high strength and low density giving very high specific strength. All grades have good resistance to impact, and lower modulus

grades are used extensively in ballistic applications. Compressive strength, however, is only similar to that of E-glass.

Although most commonly known under its Dupont trade name 'Kevlar', there are now a number of suppliers of the fibre, most notably Akzo Nobel with 'Twaron'. Each supplier offers several grades of aramid with various combinations of modulus and surface finish to suit various applications. As well as the high strength properties, the fibres also offer good resistance to abrasion, and chemical and thermal degradation. However, the fibre can degrade slowly when exposed to ultraviolet light.

Aramid fibres are usually available in the form of rovings, with texes ranging from about 20 to 800. Typically the price of the high modulus type ranges from £15-to £25 per kg.

Carbon

Carbon fibre is produced by the controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursors, which are already in fibre form. The most common precursor is polyacrylonitrile (PAN), because it gives the best carbon fibre properties, but fibres can also be made from pitch or cellulose. Variation of the graphitisation process produces either high strength fibres (at $\sim 2600^{\circ}\text{C}$) or high modulus fibres (at $\sim 3000^{\circ}\text{C}$) with other types in between. Once formed, the carbon fibre has a surface treatment applied to improve matrix

Appendix 12 UD an Fabric mechanical properties with the same fibers an resin

Source Gorse [5]

MECHANICAL PROPERTIES

M46J Unidirectional Tape (cont)

Property	Orien- tation	Test Temp	Cure	2020-36%-M46J-140-300		
				Actual 54.9% vf	Normalise 60% vf	Retention %
Flexural Strength (MPa) Crag 200	0°	RT	135°C 60 mins	1377	1511	
	0°	120°C	135°C 60 mins	1138	1248	83
	0°	150°C	135°C 60 mins	803	881	58
	0°	177°C	135°C 60 mins + 180°C 120 mins P/C	802	877	58
Flexural Modulus (GPa) Crag 200	0°	RT	135°C 60 mins	198	218	
	0°	120°C	135°C 60 mins	194	213	98
	0°	150°C	135°C 60 mins	177	195	89
	0°	177°C	135°C 60 mins + 180°C 120 mins P/C	176	193	89
Tensile Strength (MPa) Crag 300	0°	RT	135°C 60 mins	1882	2057	
	0°	120°C	135°C 60 mins	1914	2092	102
	0°	150°C	135°C 60 mins	1827	1997	97
	0°	177°C	135°C 60 mins + 180°C 120 mins P/C	1588	1736	84
	90°	RT	135°C 60 mins	30.4		
Tensile Modulus (GPa) Crag 300	0°	RT	135°C 60 mins	233	255	
	0°	120°C	135°C 60 mins	237	259	102
	0°	150°C	135°C 60 mins	240	262	103
	0°	177°C	135°C 60 mins + 180°C 120 mins P/C	237	259	102

	90°	RT	135°C 60 mins	6.6		
Poisson's Ratio	0°	RT	135°C 60 mins	0.28		

MECHANICAL PROPERTIES M46J 2X2T Fabric

Property	Orien- tation	Test Temp	Cure	2020-42% -6KM46J-2X2T-200	
				Actual 47.4% vf	Normalise 55% vf
Compressive Strength (MPa)	Warp	RT	135°C 60 mins	415	482
<i>ASTM D695</i>	Weft	RT	135°C 60 mins	374	434
Compressive Modulus (GPa)	Warp	RT	135°C 60 mins	87	101
ASTM D695	Weft	RT	135°C 60 mins	86	100
Tensile Strength (MPa)	Warp	RT	135°C 60 mins	639	742
<i>CRAG 300</i>	Weft	RT	135°C 60 mins	598	694
Tensile Modulus (GPa)	Warp	RT	135°C 60 mins	106	123
CRAG 300	Weft	RT	135°C 60 mins	99	114
Poisson's Ratio	Warp	RT	135°C 60 mins	0.04	
Interlaminar Shear St (MPa)	Warp	RT	135°C 60 mins	64	
CRAG 100					
Interlaminar Shear St (MPa)	Weft	RT	135°C 60 mins	57	
CRAG 100					
In-Plane Shear Strength (MPa)	±45°	RT	135°C 60 mins	82	
CRAG 101					
In-Plane Shear Modulus (MPa)	±45°	RT	135°C 60 mins	3.7	
CRAG 101					
Poisson's Ratio	±45°	RT	135°C 60 mins	0.72	
Flexural Strength (MPa)	Warp	RT	135°C 60 mins	762	884
CRAG 200					
Flexural Modulus (GPa)	Warp	RT	135°C 60 mins	98	114
CRAG 200					

Appendix 13 Parametric study of a 3mm carbon epoxy front face impacted by a ball

Number of plies	Ply position in the laminate	Max Sigma X Pa	Min Sigma X Pa	Max Sigma Y Pa	Min Sigma Y Pa
2	0.75	7.79E+08	-5.80E+08	7.60E+08	-8.20E+08
	-0.75	4.70E+08	-8.80E+08	6.60E+08	-8.35E+08
5	1.2	9.50E+08	-7.10E+08	9.50E+08	-8.90E+08
	0.6	4.40E+08	-3.90E+08	4.30E+08	-6.06E+08
	0	6.10E+07	-1.08E+08	4.67E+07	-1.20E+08
	-0.6	2.60E+08	-6.40E+08	3.60E+08	-6.80E+08
	-1.2	5.90E+08	-9.15E+08	8.50E+08	-9.50E+08
10	1.35	1.06E+09	-7.90E+08	1.04E+09	-8.20E+08
	1.05	8.10E+08	-6.30E+08	8.00E+08	-8.80E+08
	0.75	5.50E+08	-4.70E+08	5.40E+08	-6.87E+08
	0.405	2.90E+08	-3.00E+08	2.90E+08	-4.56E+08
	0.15	6.40E+07	-1.42E+08	6.20E+07	-2.20E+07
	-0.15	6.20E+07	-2.20E+08	4.90E+07	-2.10E+08
	-0.405	1.70E+08	-4.78E+08	2.30E+08	-4.60E+08
	-0.75	3.30E+08	-7.38E+08	4.60E+08	-7.12E+08
	-1.05	4.97E+08	-9.00E+08	6.90E+08	-9.01E+08
	-1.35	6.50E+08	-9.40E+08	9.20E+08	-9.12E+08

Appendix 14 Manufacture of the structural prototype

A Mould making

The high density foam model was coated with 2 coats of paint then sanded by hand in order to have a good surface finish. Some plaster was added on the airfoil to make it thicker and change the shape, enabling the shaft to pass through and fixed in the insert even with an airfoil wall thickness above 3 mm as designed in chapter 2.

In order to create the edges of the moulds some plaster was added again on the joint line (Figure 67). The part was then waxed 10 times making sure all solvents were evaporated between each coat before polishing. The resin used was polyester resin A and a gel-coat with a catalyst MEK (appendix 4).

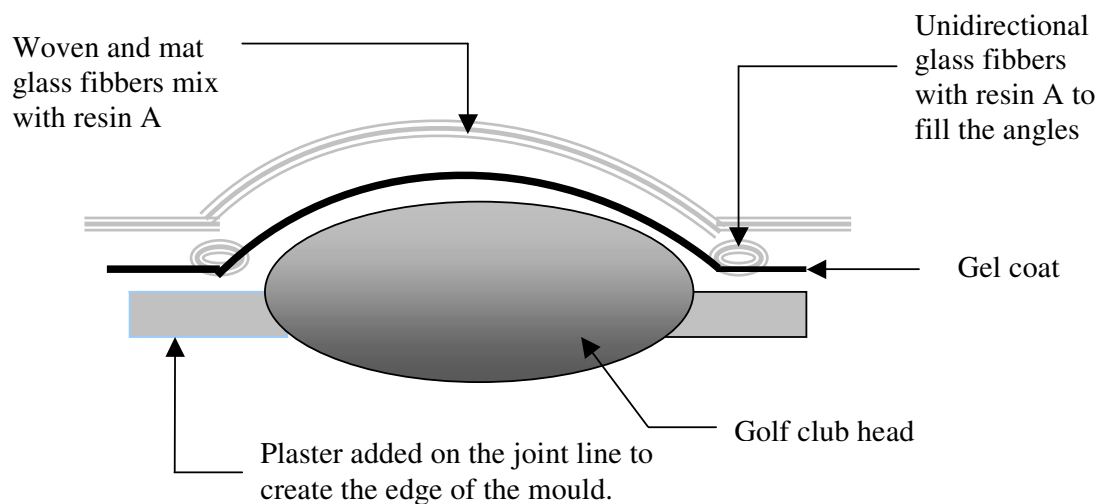


Figure 67: hand lay up technique for making the mould

A gel coat of 1 mm thickness was applied on the golf club head model after being mixed with 1% of catalyst MEK. Once the gel coat starts to crosslink, the resin A, the reinforcement made out of chopped fibres mat (650g/m²) and twill woven (300g/m²) both in glass fibres are hand lay up on the moulds when the desired thickness is achieved (+/- 4 mm). Then the part is left to set.

Note: on a sharp angle some unidirectional fibre tows were added and impregnated before placing the mat and fabric because they couldn't follow the shape in this area (too stiff).

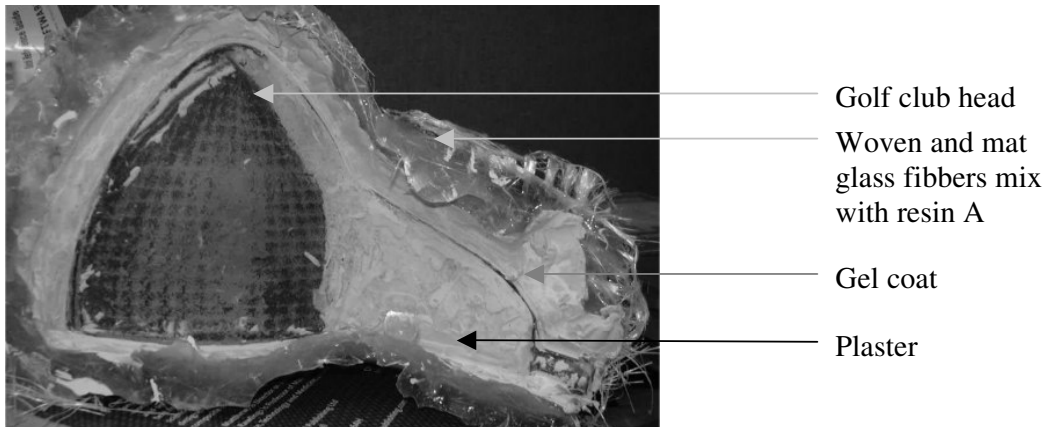


Figure 68: picture of the model and the mould after hand lay up

After the resin was set up the part and the mould were hammered releasing the mould from the golf club model (figure68). The mould was then sanded with waterproof silicon carbide paper ranging from 240 to 1200 in order to achieve a good surface finish (figure 69).

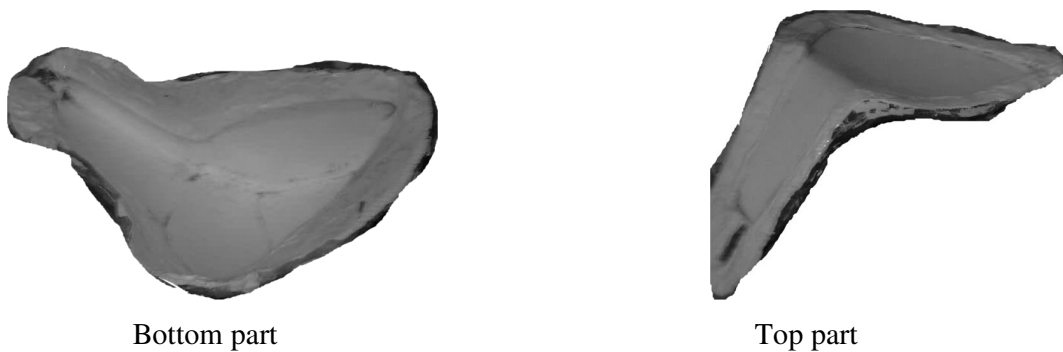


Figure 69: the polyester moulds

B Placing the various layers and metallic parts in the moulds

Fabric pre-impregnated with resin epoxy is characterized by a resin system which is contained within the fibres and maintained at low temperature (-18°C) to avoid the resin to set. This material is usually usable for 2 or 3 years after being manufactured if kept in a freezer. Before using this material it must be pull out of the freezer 24 hours to allow

any moisture to evaporate. This fabric has the advantage that it is easy to cut and to place in the mould with the right amount of resin.

Again prior to placing the fibres in the mould, it must be waxed with 10 coats of wax (maximum mould release wax from Meguiar's). Prior to add each coat sufficient time is necessary (1 to 2 hours) to let the solvent contained in the wax evaporate. Then the wax can be polished with a tissue and the next coat applied.

Another important detail was if the laminate was thicker than 5 layers, one operation called de-bulking must take place in order to suck the air trapped in between the layers. If this was not done while the laminate continues to be built up, it is highly probable that the air will not be sucked out completely creating a weak area where the air was trapped. The de-bulking operation was done once half the layers needed were in the moulds. This was accomplished by placing some sealant tape on the edges of the moulds, a plastic bag over it and by pumping the air out of the plastic bag with a vacuum pump.

In order to show the sequence of the fabric layers in the moulds the golf club head was split in different area (figure 70).

The laminate sequence for the prototype where as follow:

Legend for the nomenclature lay up of the prototype.

Complete: the reinforcement cover all the mould (including the airfoil area)

Front face extension: reinforcement near the front face.

Front face: reinforcement on the front face.

Internal: reinforcement on the inside of the club head where the insert for the shaft is located.

Ballast: one millimetre of led to increase the moment of inertia.

Layers/ reinforcements	Orientations/ angles in degrees
Sole plate/ Aluminium	
Complete	0
Front face extension	0
Front face	30
Internal	0
Front face extension	0

Front face	60
Internal	0
Front face extension	0
Front face	90
Complete	90
Ballast / Led	
Front face	90
Front face extension	0
Internal	0
Front face	60
Front face extension	0
Internal	0
Front face	30
Front face extension	0
Complete	0

Figure 70: layers sequence in the bottom mould

Note:

- The front face lay up is slightly different from the original design as it was extremely difficult to have the layers in the front face orientated at 30° from one another. This was due to the use of 3 layers covering the whole golf club (“complete” reinforcement) which needed to be oriented at 0° in some other part of the club head. Fibers continuity was preferred to the front face layers orientation defined initially. The angles in between the layers remained relatively small and similar to the initial design. Figure 71 shows the ballast in the mould.



Figure 71: the ballast in the prototype

C Placing vacuum bagging consumables

The vacuum bag consolidation (figure 72) of the laminate improve the fibres volume fraction ($V_f=55-60\%$) compared to a simple hand lay up laminate (40%), enhancing a lot the mechanical properties (strength and stiffness). The needs for numerous consumables make the process more expensive due to the extra time required to set the process in place.

This technique and pre-preg fabric requires:

- a plastic bag to cover the mould
- a sealant tape to seal the bag to the mould
- some peel ply just over the laminate
- breather (plastic bag with holes)
- bleader (absorbing the excess of resin)
- vacuum gage
- oven (125 °C)
- copper pipe linking the pump to the bag

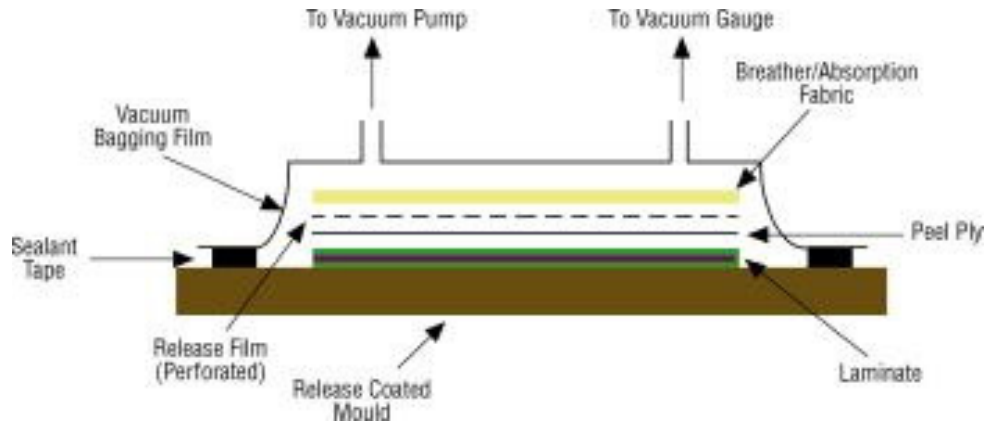


Figure 72: vacuum bagging technique, [16]

D Curing the parts

The golf club being cured can be seen in picture 73.

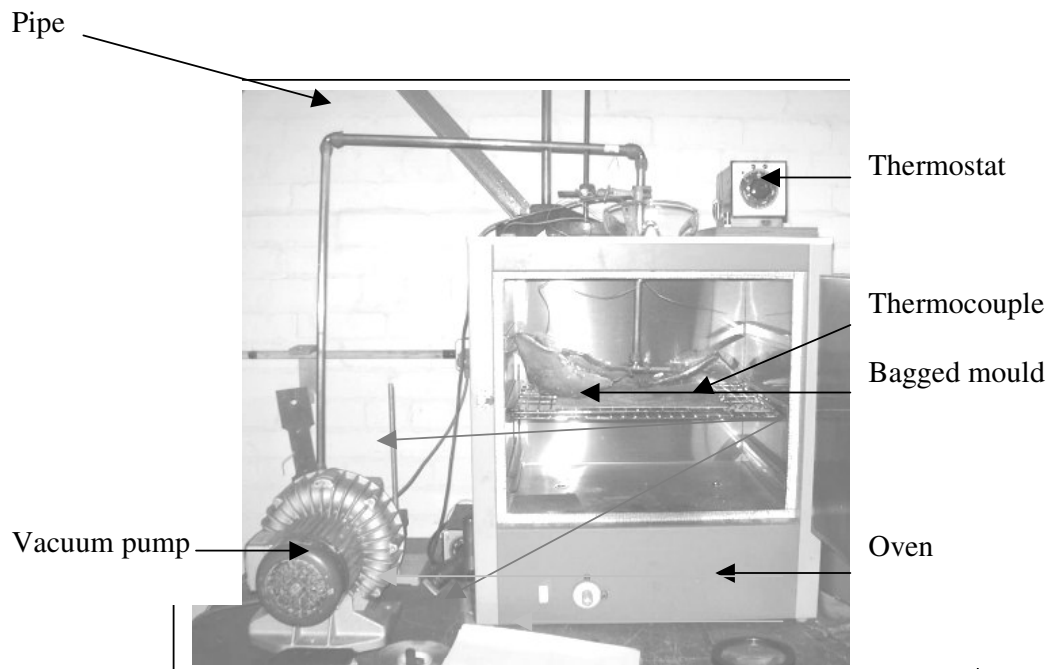


Figure 73: curing the prototype

The temperature of the mould was recorded with a thermocouple placed on the mould and linked to the thermostats which regulate the temperature of the moulds. The adequate curing cycle time is proposed by Hexcell composites in appendix 5.

The mould started to become very soft after 37 minutes in the curing process when the temperature was reaching 115°C. This was due to the fact that the mould's resin was not

completely set at ambient temperature, and that no post cure had been done on the moulds to try to correct this. This problem is common with the usage of polyester resin and is more significant if the resin and catalyst are not mixed in the right proportion. To try to save the mould from complete distortion the oven's door was open to cool the mould down to 80°C where it regained strength and stiffness. The temperature was risen back up very slowly as the mould was becoming stronger and its resin completely setting.

After 330 minutes at an average temperature of 98°C, it was assumed that the parts were cured and the oven was switch off while the pump was sucking the air. When the parts were cold the vacuum pump was shut down and the parts were released from the moulds. Both part needed to be trimmed with fills so that the parts matches each other and could be glued to gather after placing the shaft and shaft insert inside. It was proposed to glue the part using a simple scarf joint (figure 74).

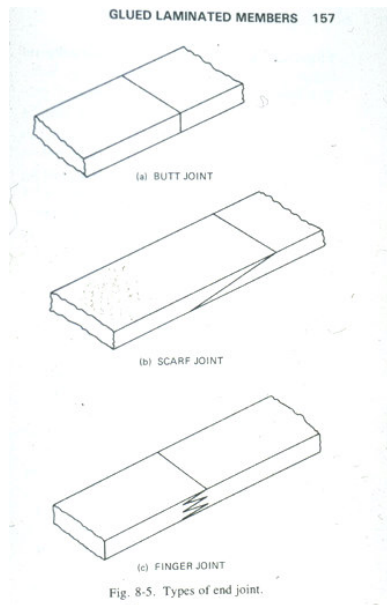


Figure 74: scarf joint, [www document \[30\]](#)

D Health and safety

During the hand laminating, sanding and handling of the pre-impregnated epoxy fabric gloves, mask and protective glasses were worn in order to prevent any skin sensitizations and respirations from the chemical components