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Optimalisert karbonfiber krasjnese for høyytelses Formula Student racerbil

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Produktutvikling og produksjon
Innlevert: juni 2016
Hovedveileder: Nils Petter Vedvik, IPM

Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Optimized carbon fiber energy absorber for high performance Formula student racecar

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Trondheim, 10.06.16
Norwegian University of Science and Technology

NTNU revolve

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NTNU - NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS SPRING 2016
FOR
STUD.TECHN. EIRIK MONTEAGLE BROWNE

Carbon fiber composite impact attenuator for the Revolve Formula Student car

Revolve NTNU is an independent student organization at the Norwegian University of Science and Technology. The team consists of 50 members who work voluntarily parallel to full time engineering studies. The members are from over 10 engineering fields and all years of study. To develop and build a race car from scratch in one year is a challenging task that demands numerous engineering fields, extraordinary dedication and hard earned resources. Every year a new team of students take on the complex and comprehensive project to make the transition from students to fully capable engineers.

The impact attenuator (crash nose) protects the driver during front collision by limiting the negative acceleration at impact. The structure shall comply with relevant rules for structural integrity and safety as well as being optimized for minimum weight.

The master thesis work will included, but is not limited to:
1. Review of requirements, rules and regulations
2. CAD models of structural components
3. FEA Simulations (buckling and fiber layup)
4. Production and testing methods
5. Physical testing of test panels and crash nose

The work is expected to be an iterative process where redesign, alternative materials and test methods should be continuously assessed with respect to the objectives and possible interference with the rest of the Revolve development team.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site (see https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

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(Signed version can be found in the attachments.)

Acknowledgements

This thesis concludes my one-year participation of the formula student team, Revolve NTNU. Despite the immense workload, it has been an absolute pleasure to take part in such a great project with such a dedicated team. Being able to experience working with such high-end products in such a competitive environment has been fantastic. I want to extend my greatest gratitude to the rest of the team, and especially the monocoque group. They have been a great support throughout these intensive months of long days and hard work.

I would also like to thank the Department of Engineer Design and Materials at NTNU and my supervisor Nils Petter Vedvik for his guidance and help throughout the project.

Finally, I would like to direct a special thanks to Kongsberg Gruppen, for being the main sponsor of the team this year and allowing us to produce the rims, monocoque, back wall and crash nose at their facilities in Kongsberg. Without them, it would have been impossible to achieve such high quality on the items produced.

Summary

This master thesis relates to the design, production and testing of a carbon fiber energy absorber, meant to be used on the Formula Student team Revolve NTNU's racecar of 2016.

Formula Student is the world's largest student competition for engineers. Each team participating creates a car, and competes in the many different events of the competitions around the world. The events reward the engineering parts of car dynamics, like acceleration, steering and traction. Therefore, it is important that the cars are as light as possible, if one wants to perform well in the competition.

The impact attenuator is the part of the car that is supposed to deform during a crash to absorb all the kinetic energy in order to protect the driver. Between the impact attenuator and the chassis of the car there is an anti-intrusion plate, which serves as a barrier to prevent anything from entering the monocoque during a crash and potentially harm the driver.

Several impact attenuator concepts have been investigated in order to land on the concept most suitable in the many different respects. These respects include among other things safety, weight, predictability and access to the pedal box. The chosen concept was the crash nose, which scored best in all respects. The material used was Tencate E745 carbon fiber and Aramid Honeycomb core material. Production took place at the facilities of Kongsberg Defence and Aerospace, and crash testing to get the crash nose approved for the competition took place at Benteler Automotive.

For the anti-intrusion plate, equivalency to the minimum requirement in the competition rule set of 1.5 mm steel or 4 mm aluminum needed to be proved. This has been done through testing, which included 3-point bend, penetration and attachment point tests. The chosen material was Hexply 8552 carbon fiber, and production and testing took place at NTNU.

Sammendrag

Denne masteroppgaven omhandler design, produksjon og testing av en karbonfiber krasjdemper, ment å bli brukt på Formula Student-lag Revolve NTNU's 2016 racerbil.

Formula Student er verdens største ingeniørkonkurranse for studenter. Hvert lag som deltar lager hver sin bil, og konkurrerer i de mange forskjellige øvelsene på de forskjellige konkurransene rundt om i verden. Konkurransene belønner ingeniørdelen av bildynamikk, som akselerasjon, styring og veigrep. Derfor er det viktig at bilene er så lette som mulig, dersom man ønsker å prestere på et høyt nivå.

Støtfangeren er den delen av bilen som skal deformere seg under et krasj og absorbere kinetisk energi for å beskytte sjåføren av bilen. Mellom støtfangeren og chassiset på bilen er det en anti-gjennomtrengningsplate som har som formål å forhindre at noe å trenger igjennom og inn i monocoquen under et krasj og dermed skade føreren.

Mange forskjellige støtfangerkonsepter har blitt undersøkt for å kunne lande på det konseptet som var mest ideelt. Dette inkluderer blant annet sikkerhet, vekt, forutsigbarhet og lett tilgang til pedalboksen på bilen. Det valgte konseptet var krasjnesen, som gjorde de best i alle kategoriene. Materialet brukt til konstruksjon av krasjnesen var Tencate E745 karbonfiber og Aramid Honeycomb kjernemateriale. Produksjon av krasjnesen fant sted i lokalene til Kongsberg Defence and Aerospace, og krasjtesting for å få krasjnesen godkjent for bruk i konkurransen ble utført hos Benteler Automotive.

For anti-gjennomtreningsplaten sin del, måtte ekvivalens til minimumskravet i konkurransereglementet av 1,5 mm stål eller 4 mm aluminium bli bevist. Dette ble gjort gjennom testing, som inkluderte 3-punkts bøy, penetrasjon og festepunktstesting. Det valgte materialet var Hexply 8552 karbonfiber, og produksjonen og testing ble gjennomført på NTNU.

Abbreviations

Abbreviation	Meaning
IA	Impact attenuator
AIP	Anti-Intrusion Plate
CAD	Computer-Aided Design
FSAE	Formula Society of Automotive Engineers
G	The acceleration of gravity
SES	Structural Equivalency Spreadsheet
UTS	Ultimate Tensile Strength
FAQ	Frequently Asked Question
FBH	Front bulkhead
KDA	Kongsberg Defence and Aerospace
IPM	Institutt for Produktutvikling og Materialer (Department for Engineer Design and Materials)
NTNU	Norges Teknisk-Naturvitenskapelige Universitet (Norwegian University of Science and Technology)

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1. Introduction

Revolve NTNU is an independent student project, where the organization creates a new open cockpit, single seat, open wheel, formula style racecar to compete in Formula Student competitions around the world. At the beginning of each school semester, members are recruited and given specific tasks or areas on the car to design and produce. The task presented to the author, was to create an impact attenuator (IA) and the plate behind the IA, the anti-intrusion plate (AIP).

The IA can be a very complicated part, depending on which concept you choose to go for. The IA presented on the picture below, Figure 1, is considered one of the most complex and time consuming concepts, but it also has its advantages, which will be investigated later in the thesis.

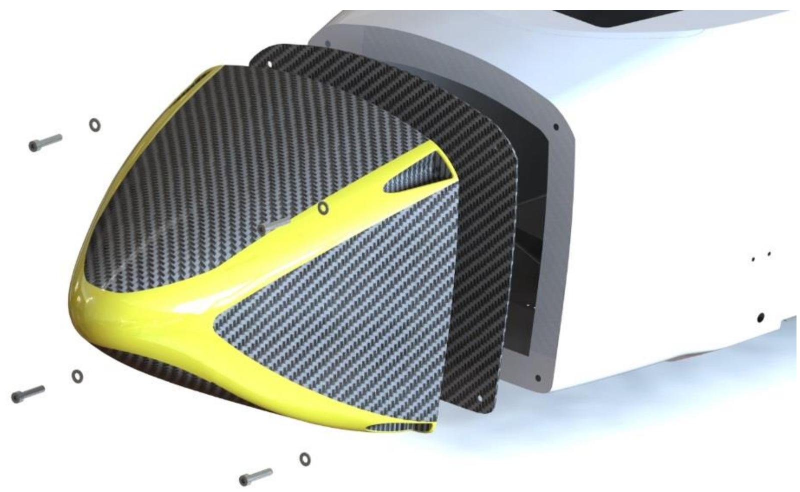


Figure 1 Crash nose and anti-intrusion plate assembly

As this thesis builds further on the work completed in the author's pre-master thesis of autumn 2015, it was natural to include some parts from the thesis. Therefore, parts of the concept chapter have been included, although somewhat modified to better suit this thesis.

2. Background

2.1. Formula Student

The origin of Formula Student dates all the way back to around 1980s, where the first formula student competition was held in 1981 in the United States. Back then, six schools said they would attend, but only four of those showed up at the competition (1). Since then, it has only grown, and last year there were about 3500 participants from nearly 140 different teams. This makes Formula student the world's largest competition for engineering students.

The competition is split into several events, all with their own weighting on the total score. In total, there are three static and five dynamic events (2), which in total may reward 1000 points. These events are:

2.1.1. Static events

Engineering design

The design event is considered the most prestigious event to win. In this event, each team presents their design solutions and the theory and thought behind the choices that were made in order to land on the given design. Highly qualified judges, often from the automotive industry, give out points. The maximum score from this event is 150 points.

Cost and Manufacturing

The cost event of the competition is meant to award cost efficiency when building a racecar. The cost report includes all materials and processes used to produce the car. This event can reward up to 100 points.

Business Presentation

The business presentation is a 10-minute presentation where each team presents a business plan for the car to an assumed manufacturer. The presentation should show that you are reaching your target audience, and that your business plan is economically feasible. A total of 75 points is possible to be awarded from this event.

2.1.2. Dynamic events

Acceleration

The acceleration event is simply a 75-meter stretch, which awards cars with acceleration, good traction and launch control, as well as low drag. The event can give up to 75 points.

Skid Pad

The skid pad is an event performed at an 8-shaped course. This event measures the cars steady state cornering performance and the cars lateral acceleration. The event may reward up to 75 points.

Autocross

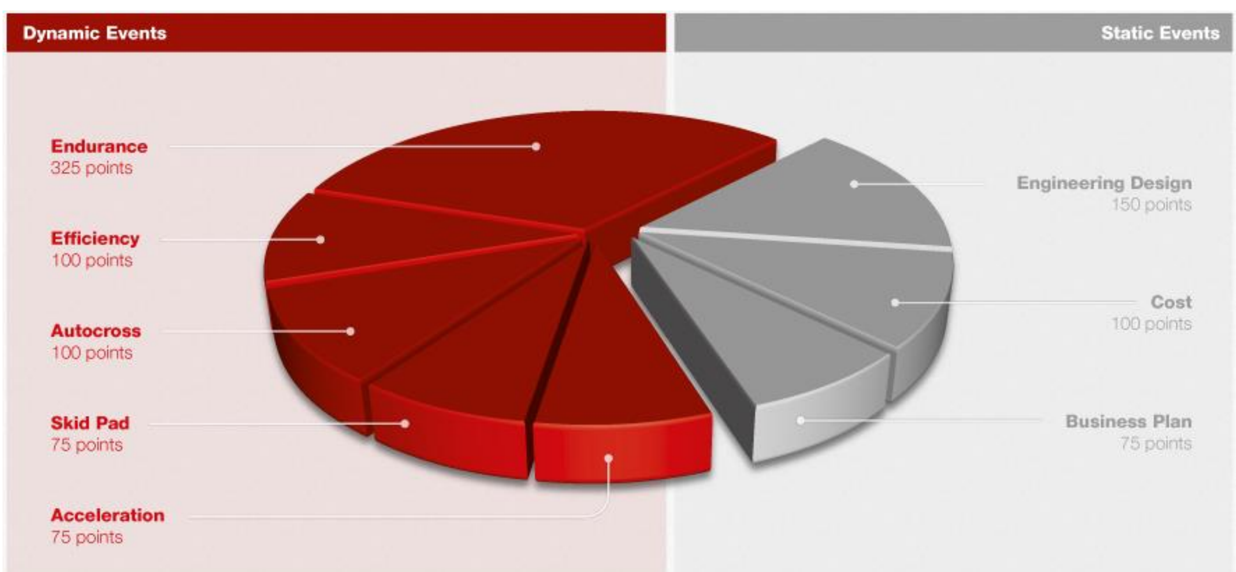
Autocross is race on an about 1 kilometer long course, where the dynamic aspects of the car is tested to its fullest. Unlike most racetracks, the track contains very few long stretches. This rewards the road handling aspects of the car, like acceleration, deceleration and traction, instead of top speed. The event awards up to 100 points.

Endurance

The endurance event is where it is possible to earn the highest amount of points, a staggering 325 points. The event uses the same track as Autocross, but uses 22 laps instead of one. Each team only has one attempt, meaning that this event often is the decider in the competition. All the aspects of the car is present in this competition, ranging from fuel efficiency to vehicle dynamics.

Fuel efficiency

Fuel efficiency is becoming increasingly important in the automotive industry, and this competition is no different. As slow, extremely fuel-efficient cars would have an unfair advantage, the event awards fuel efficiency in relation to lap time. A couple of years ago the maximum amount of points possibly awarded was increased from 50 to todays 100.



Before participating in all the different events, the car must pass "Scrutineering". During scrutineering, all the systems of the car are extensively checked to see if they are in accordance to the competition rule set. The rules are mainly used to ensure driver safety, but also as a restrictive measure on the students during design to make sure students do not exaggerate their designs. As an example, cars were using increasingly larger aero packages (back wing, front wing, undertray etc.), and as such restrictions were imposed on the size.

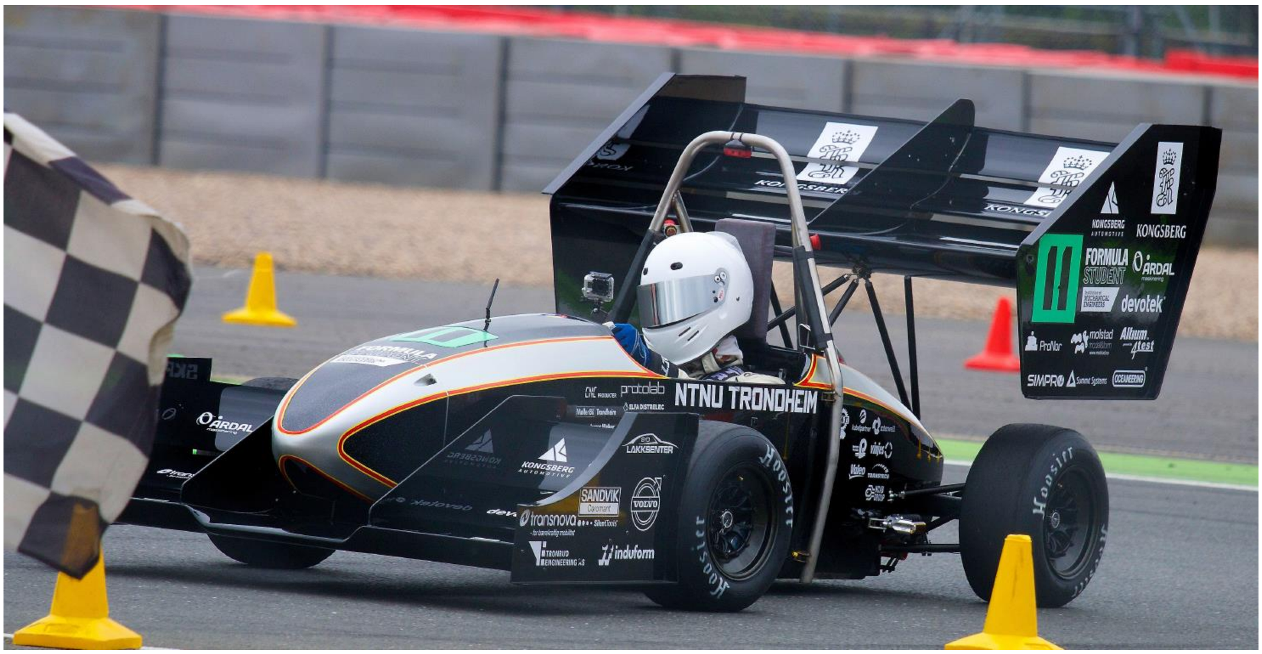


Figure 2 Revolve NTNU 2014 racecar using a large back wing prior to new restrictions regarding size

A common denominator for all the events is that they reward low weight. Therefore, it is important that the impact attenuator is as light as possible, while still complying with the rules set by the competition organizers. This means choosing the right design, proper materials and correct manufacturing methods.

2.2. Revolve NTNU

Revolve NTNU has participated several times before, and 2016 will be the fifth year the team participates in the competition. This makes Revolve one of the youngest teams in the competition, competing against teams who have experience from almost 30 years of participation.

Revolve has managed to make themselves noted in the competitions, due to huge innovative steps each year. The cars have gone from weighing 260kg with an acceleration from 0-100 km/h in 4.0 seconds in 2012, to weighing 175kg and doing 0-100 km/h in 2.8s in 2015 (3). This year is no different, as we are going for a four-wheel drive electric racecar, having a weight of about 170 kg. As this year's car will have four motors instead of one, as well as four gearboxes, reducing the overall weight from last year's car will be a challenge. It is vital that everyone on the team tries to save weight wherever possible.

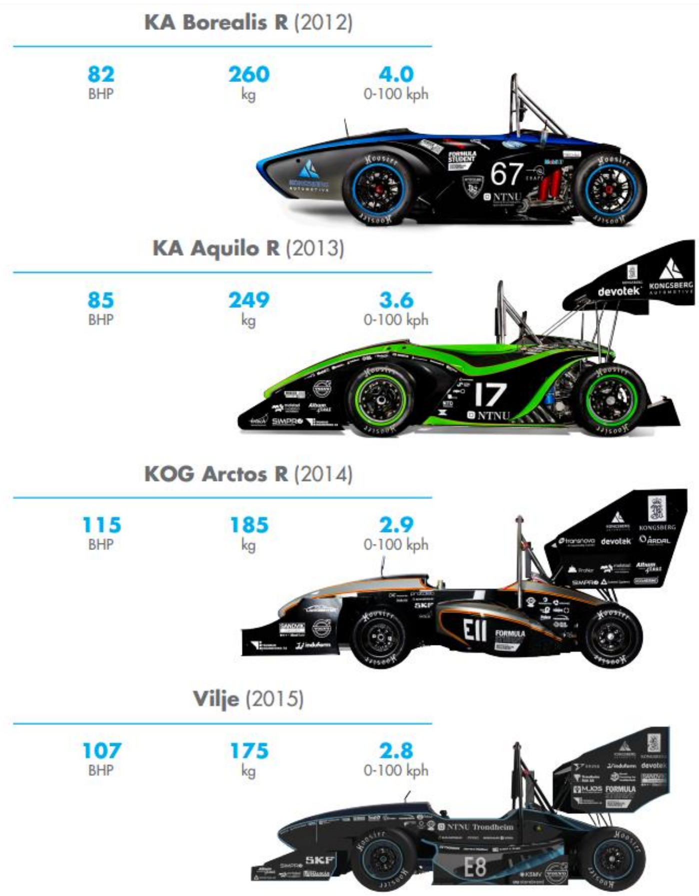


Figure 3 Revolve NTNU car history

2.3. Structural Equivalency Spreadsheet (SES)

SES is an Excel spreadsheet that all teams, both teams using steel spaceframe and monocoque chassis', must get approved. A monocoque is a "self-bearing chassis", meaning that wheel bracings, suspension, aero package etc. is constrained directly to the chassis without the use of support structure from f. ex steel tubes. A more commonly used alternative is to use a steel spaceframe, as this requires significantly less effort and money. This was originally the only used solution in the first years of Formula Student, but as the competition has grown and sponsors have shown an increasing interest in the competition, most of the top teams are now using a monocoque. The SES serves as a tool to prove that the different composite panels on the monocoque are as strong, or stronger, than the equivalent amount of steel tubes required in the rule set for steel spaceframe cars. All test results from every composite panel test is included in the SES. As an example, Figure 4 shows that the test panel for the side impact zone must be as stiff as or stiffer than two steel tubes, with the same amount or higher absorbed energy during 3-point bend testing.

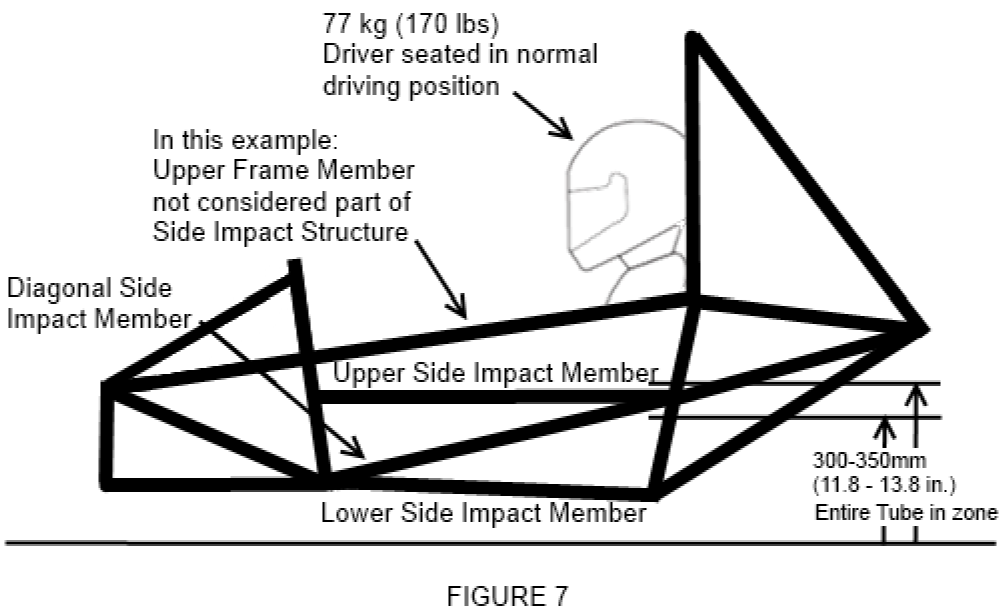


Figure 4 Required setup for side impact zone.

2.4. Software

To achieve our goal of creating a light impact attenuator and anti-intrusion plate, we need a set of tools. These tools come in the shape of several modeling and simulation tools, which were used to both create the shape of the impact attenuator, as well as confirm the calculations and presumptions that were made for the different designs. As it is extremely tedious and imprecise to cut each of the carbon fiber plies used for the impact attenuator, a program to create the flat patterns for each ply was also needed.

2.4.1. SolidWorks 2015

SolidWorks 2015 is a computer aided design (CAD) software published by Dassault Systèmes. SolidWorks has its advantages in that it is very user friendly and has a very low beginner threshold to start using. It deploys a parametric feature-based approach to modeling, meaning that parameters such as width, depth etc. are used to create models. This allows the user to rapidly create sketches and splines in order to form the different features of the model.

The software was chosen over other CAD-programs because of the huge user base and equally huge collection of learning material on the internet. SolidWorks however does not have advanced enough composite simulations, and therefore other more specialized software was used.

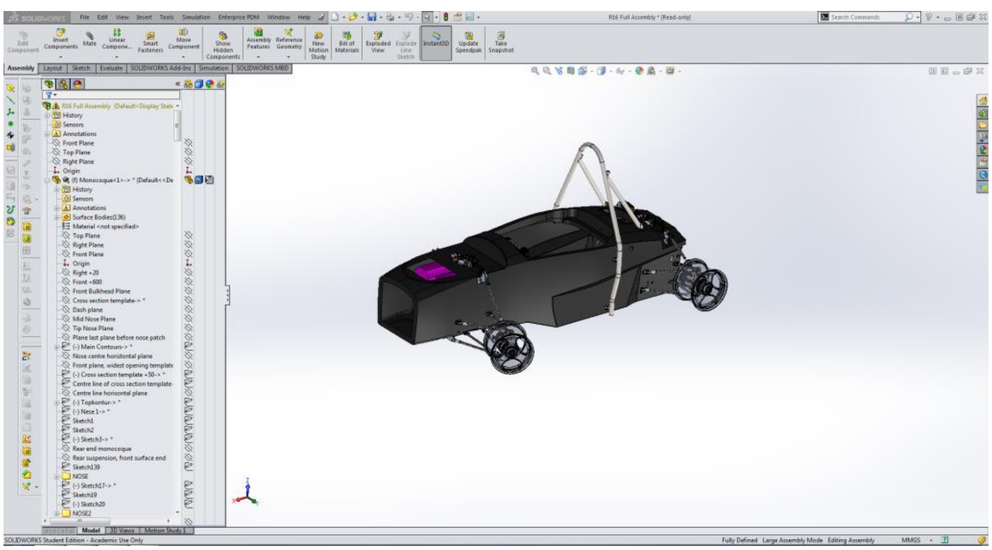


Figure 5 SolidWorks user interface

2.4.2. Abaqus FEA

Abaqus FEA is a Finite Element Analysis (FEA) program from the same author as SolidWorks, used for both modeling and analysis of mechanical components and assemblies. The software is commonly used in the automotive and aerospace industry, due to its wide material modeling capability. Among other things, Abaqus is able to consider loads, dynamic forces, nonlinear static problems and thermal coupling.

The program has been used by Revolve NTNU earlier years with relatively high success on composite simulations, meaning that the simulations were close to the actual test results. Unlike SolidWorks, Abaqus is more difficult to learn and become proficient with. The workflow is very different from other CAD-programs and it takes a while to get the hang of in order to work efficiently. Therefore, all models were imported as STEP-files from SolidWorks, before they were processed and simulated on in Abaqus.

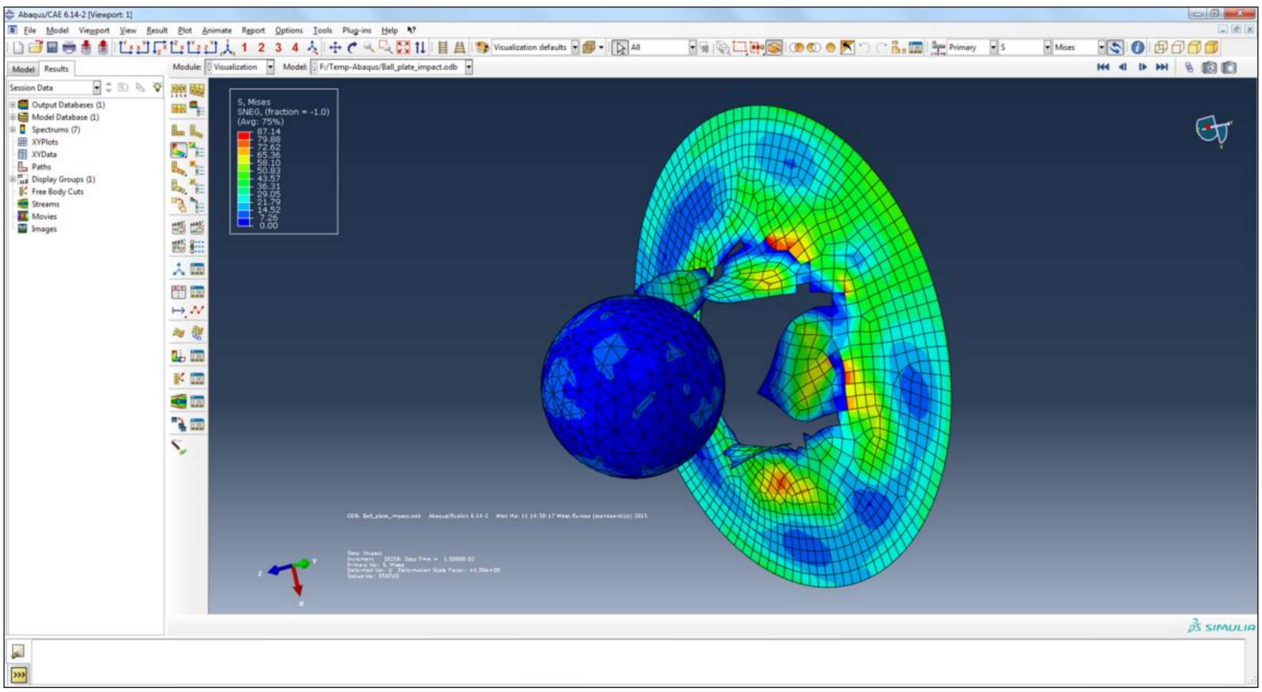


Figure 6 Abaqus user interface

2.4.3. Siemens NX Fibersim

Siemens NX is another CAD and simulation package, and just like Abaqus it is difficult to learn and use. Siemens NX as a modeling tool was not used too much in this thesis, but rather the extension to NX called Fibersim. Fibersim is one of the only, if not the only, composite programs on the market which allows you to create flat patterns from models. It allows you to mark an area on your model, and it will then tell you both how the area would look if you laid it flat out, as well as if there is too much curvature on you model to lay the ply. This will be explained more thoroughly later in the thesis.

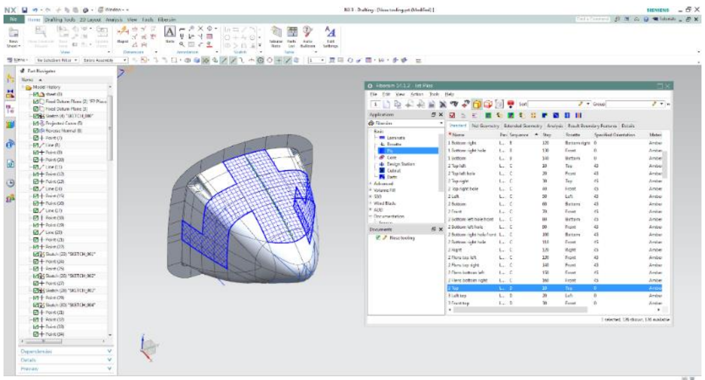


Figure 8 Carbon fiber ply

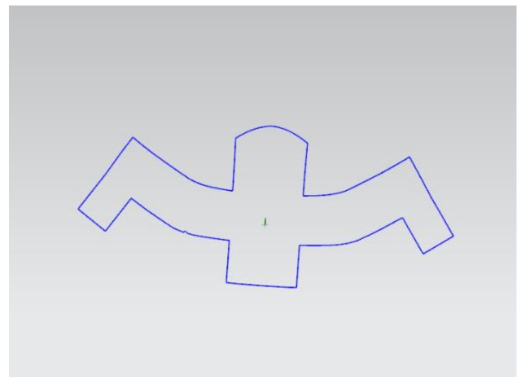


Figure 7 Corresponding flat pattern

3. Methodology

3.1. Introduction

Throughout the thesis, as will be discussed later, many different concepts were investigated. They all differed in complexity and finding valuable information about the concepts varied accordingly. Composite crash noses, for example, have been commonly used in Formula 1, but as this is a very competitive field, the information is not openly available. There is information easily available about impact testing where the panels are loaded transversely, but not longitudinally as would be our case when creating a crash nose (see Figure 9). Simulations, basic composite theory and experience from the two proceeding crash noses in Revolve NTNU have therefore supported most of the work.

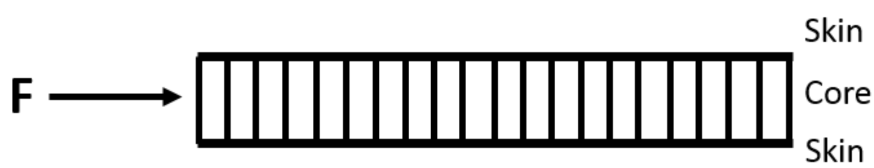


Figure 9 Illustration of laminate load direction

The production window for the impact attenuator was also limited. The less complicated concepts did not present much of a time constraint, as much of the work could be done before arriving at the production facilities of Kongsberg Defence and Aerospace (KDA), where the team only had 4 weeks available for the manufacture of all the composite parts. This was because the impact attenuators themselves were readily available directly from the producer, which will become apparent later in the thesis.

For the more complex concepts, the time constraint on the production facilities presented a challenge and induced a lot of uncertainty, as the concepts were entirely dependent on being able to use the utilities at Konsgsberg AS. This included both equipment and machines, as well as practical assistance from the employees there. Only 4 weeks were allocated for creation of the crash nose mold, production of 3-4 impact attenuators as well as crash testing the attenuators. This left little wiggle room for experimentation and failure and therefore increased the importance of being well prepared before arriving at the facilities.

3.2. Problem solving strategy

At Revolve NTNU, the process of building a formula student racecar is split into four different phases:

1) Concept phase
2) Design phase
3) Production phase
4) Finalizing phase

3.2.1. Concept phase

During the concept phase, the team members explore different concepts and ways of solving their given tasks. The idea is to look at the problem from as many different angles as possible to try to find the best solution. By the end of the concept phase, each member should have found which solution to go further with. Sometimes several concepts seem feasible, and it is therefore possible to work further with several concepts in order to properly investigate which one is the best.

3.2.2. Design phase

The design phase is where you further develop your chosen concept. For the mechanical groups, this includes amongst other things shape, material and cost. It is important that all the team members cooperate so that the different systems fit together.

3.2.3. Production phase

During this phase, every member produce their assigned parts. The production phase started in January, and production at the composite facilities of Kongsberg Defence Systems started in the middle of February 2016. As production of impact attenuators and testing will take place interchangeably, there was no time to create anti-intrusion plates in-between. As the AIPs needs to be present during the crash test, it was important that at least two AIPs were ready before the team left from Trondheim heading to Kongsberg.

3.2.4. Finalizing phase

The finalizing stage is where the last few touch-ups for the parts are being made before they are mounted on the car. The earlier this phase is over, the sooner testing can start. The longer a team has to test, the more time they have to fix problems that occur when driving, so they do not occur during the competition. This also allows small adjustments on for example the aero package of the car, which may have a huge impact on the overall performance of the car. The different sensors on the car also logs data, which is then analyzed by the team to help make the correct adjustments more apparent.

All testing on the impact attenuator and anti-intrusion plate will be complete by this time, and the only thing remaining is paint and some small adjustments in order to make the transition over to the monocoque as smooth as possible.

4. Concept phase

During the concept phase, several different concepts were investigated in order to find to optimal solution. The method used to find concepts was primarily to extract information from the impact attenuator alumni from the last two years. They provided valuable information about what aspects to assess and areas that were important to highlight while designing a new IA. Using the internet and looking at what other teams had done to complete the task proved helpful as well.

4.1. Concept limitations

Before looking at concepts, it is important to properly investigate the criteria and limitations for the impact attenuator. These are both imposed by the ruleset of the competition, as well as practical and physical limitations such as size, weight and producibility. Certainty of success was also a huge factor, as a failure to create an IA that is approved for the competition would result in immediate disqualification from all Formula Student competitions. A collection of the rules regarding the crash nose can be found in section 13.1 in the appendix.

To get the IA approved for the competition, it has to fulfill the following requirements:

1. Dimensions: minimum 200 mm long, 100 mm high and 200 mm wide (T3.20.2).
2. Acceleration: withstand crash at 7 m/s and not exceed 40 G's (the acceleration of gravity) peak and 20 G's average deceleration with a moving mass of 300 kg. This is the equivalent of a peak force below 120 kN and an average force below 60 kN (T3.21.3).
3. Energy absorption: minimum 7350 Joules (T3.21.2).
4. Fixture: Unless the AIP is integral with the frame (i.e. welded), it needs to be able to be fastened with four 8 mm Metric Grade 8.8 bolts to the front bulkhead (T3.20.5).

The main design criteria for selecting a concept in this thesis, was that the combination of IA and AIP had to have the overall minimum weight. As you will see, many of the concepts have a very light IA, but the AIP has to be very strong and heavy to support the IA. The process of getting the AIP approved (allowed to use in the competition) also vary depending on the load case during the crash, which will be discussed later.

4.2. Previous year's solutions

The impact attenuators on the first and the second car were made out of foam and aluminum honeycomb respectively. The aluminum honeycomb crash box weighed about 1.9 kg, with the support structure around it included. The huge downside of these two solutions were that they had to be mounted on the anti-intrusion plate (AIP). According to rule T3.20.3, the AIP must be either 1.5 mm solid steel or 4.0 mm solid aluminum (4). Combined with rule T3.21.11, which says that the AIP must never deflect more than 25.4 mm after crash testing, this means that the AIP had to be heavily strengthened.

The same year the team decided to build a monocoque, it was also decided to create the crash nose in carbon fiber. Therefore, the noses of two subsequent years were made out of a carbon fiber and Kevlar honeycomb composite sandwich. They both weighed about 750 grams, meaning that they weighed less than half of the previous solutions. The advantages of this solution were that it was a lot lighter, and the forces were transferred directly to the front bulkhead (the frame supporting the anti-intrusion plate). The arrangement resulted in the AIP not needing additional supporting structure and in this way saved a lot of weight.

Figure 10 Revolve NTNU 2013 aluminum crash box mounted directly on the anti-intrusion plate

4.3. Carbon fiber crash nose (shell structure)

The concept the two previous years has been to create a hollow crash nose out of carbon fiber and core material sandwich. This solution has it's upsides in that it is lightweight and will not put much load on the AIP, which will in turn limit the need for a strong AIP. The solution is however extremely complex. It requires extensive knowledge of the analytical software to get an even close to correct simulation. No one on the team has any knowledge from doing such a simulation, and it would be way too time consuming to put a lot of time into a simulation that could only be somewhat correct. This means that if this solution is chosen, one would have to rely on simplifications and experience from previous years. Secondly, the manufacturing process is complex, requiring very expensive machines like auto-claves (pressurized curing ovens) and CNC cutting machines to produce efficiently and with high enough quality. The overall price is high compared to other solutions. The solution is however safer than many of the other concepts in the event of a sideways impact.

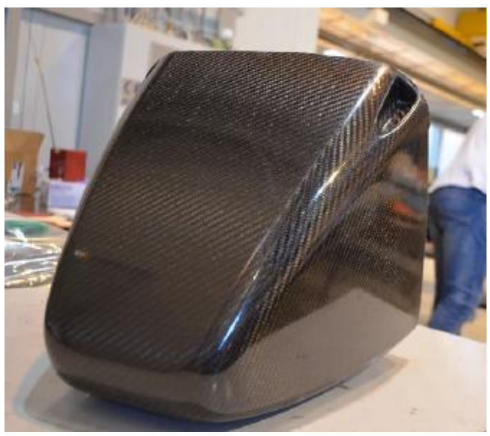


Figure 11 Crash nose from the 2015 car

4.4. Honeycomb crash box

The concept revolves around creating a crash box out of honeycomb material and mount it onto the AIP. It is possible to create a very light IA this way. As mentioned, this would require the AIP to receive extra strengthening to be able to pass the requirements of the rules and regulations of the competition. The weight gained from using a honeycomb crash box will probably be lost while strengthening the AIP. You would also need to create a carbon fiber casing that would enclose the honeycomb crash box in order to maintain optimal aerodynamic properties and aesthetics. The upsides of the concept is that the crash box itself is cheap and comes readily available from the manufacturer. An illustration of the concept can be seen on the 2013 car in **Feil! Fant ikke referansekilden.**, where the outer casing is missing.

4.5. Carbon fiber crash cone

The crash box can also be made out of carbon fiber parts arranged in a favorable geometry. This will allow a huge amount of flexibility when it comes to shape and energy absorption. Just like the carbon fiber crash nose (shell), this will be difficult to simulate on and will also require extensive testing of the AIP in CAD. The concept should be moderately difficult to manufacture. Just like the aluminum honeycomb crash box, you will also have the same problem with having to strengthen the AIP and you will need an outer carbon fiber cover.

Another problem with this concept is that there is a very large uncertainty of whether or not it is going to work, as it has not been done before. There is a risk of the concept failing completely, leaving the team unable to compete.

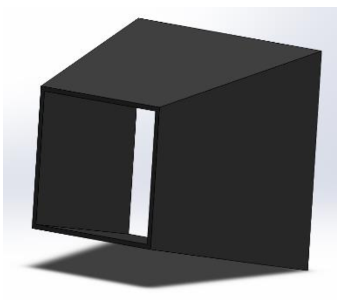


Figure 13 Example 1 carbon fiber crash box

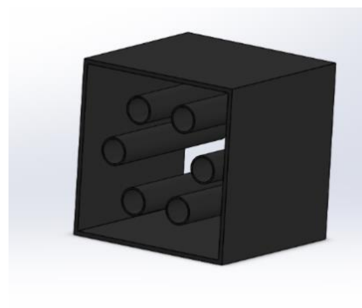


Figure 12 Example 2 carbon fiber crash box

4.6. Carbon fiber crash nose with wall structure

The thought behind the concept was that you could probably reduce wall thickness of the nose if you included some sort of inner geometry. Seeing that the previous crash noses caved inwards during crashes, forces applied directly onto carbon fiber plates in the longitudinal direction inside the nose should provide valuable support. Straight walls also increases the chances that the carbon fiber sandwich will be pulverized, which is favorable in a crash test. This concept will also limit the problem of having to strengthen the AIP, as the forces would be more evenly distributed across the AIP.

There are several huge downsides to this concept. To start with, the concept is extremely difficult to manufacture. It is also very difficult to simulate on, expensive and the AIP will need extra stiffening in order to not deflect.

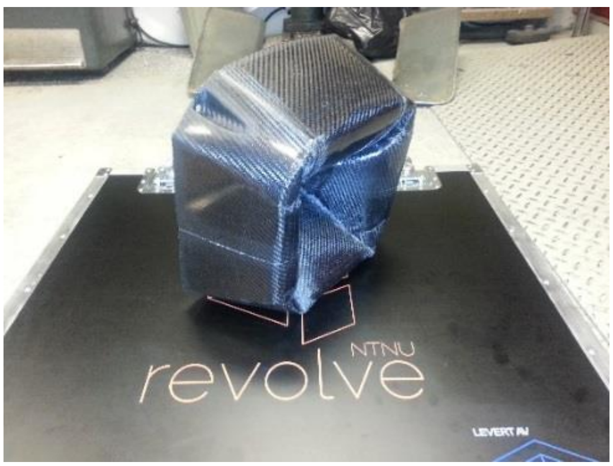


Figure 15 Second crash nose made in 2014

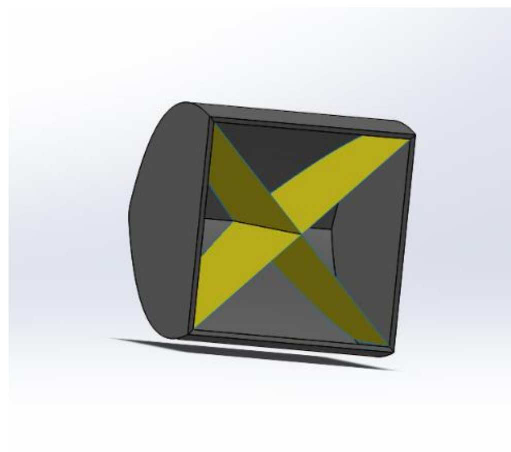


Figure 14 Example of inner structure

4.7. Concept evaluation

The ultimate weight goal given by the team captain, Roy Andreas Iversen, was 500 grams. This is an extremely ambitious goal, as it would mean a 30% weight decrease from last year. For comparison, the 2015 year's nose was 4.8% lighter than the one from 2014, which was mainly attributed to the use of lighter paint. Seeing that this year's nose is also longer and wider than in 2015, makes the 500 gram target an even more ambitious goal. The only consolation here is that the nose being bigger means that the monocoque becomes smaller and consequently lighter. The goal was therefore adjusted back up to 700 grams, which is still an improvement over last year, but not as much as the team captain would have hoped for. In order to achieve this goal, an analysis of optimal fiber, core material, lay-up and production methods needs to be conducted.

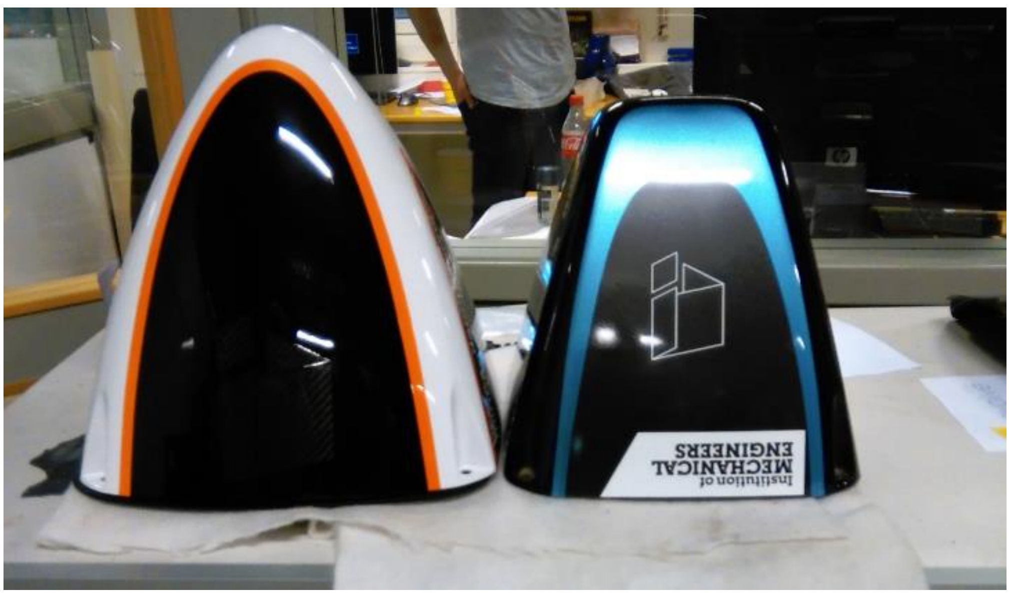


Figure 16 2016 crash nose as it turned out compared to 2015

As previously mentioned, it is new this year that the team makes a composite anti-intrusion plate. The standard practice is to use a 1.5 mm thick steel AIP or 4 mm thick aluminum AIP, which automatically is approved as long as it does not deflect more than 25.4 mm during the crash test. If the AIP is to be made out of composite, the process of getting it approved is considerably more difficult.

There are two rules regarding getting a composite AIP approved (see Figure 17) and since the rules does not mention anything else one would assume that as long as one of them was within the rules, the AIP would be approved. Due to the uncertainty, a judge[1] was consulted, who explained that the rules depended on whether or not the AIP was directly inflicted by the impact attenuator during the crash.

If the impact attenuator is mounted directly on the anti-intrusion plate, it is approved as long as it does not deflect more than 25.4 mm during the crash. However, if the plate is not directly stressed during the crash, it needs to be able to withstand 120 kN in a 3-point bend test and 20 kN in an attachment point test. This seemed excessive, as the intention of the rule is to prove that the AIP is a least as strong, or stronger, than the minimum requirement of a 1.5 mm steel or 4 mm aluminum AIP[2]. Several more e-mails and weeks of waiting went by before a clear answer on how to proceed was received. The final verdict was that as long as it was possible to prove equivalency to 1.5 mm steel or 4 mm aluminum with three point dynamic bend test, perimeter shear test, equivalent strength in each attachment point and pass the physical crash test, the composite AIP would be approved. The conversation has been added in attachment 13.2.

T3.38.2 Strength of composite AI plates may be verified by physical testing under rules T3.21.2 and T3.21.3.

T3.38.3 Strength of composite AI plates may be verified by laminate material testing and calculations of 3 point bending and perimeter shear analysis. Composite laminate materials must be tested under T3.30.3 and T3.30.5. Analysis of the AI plate under 3-point bending must show the AI plate does not fail under a static load of 120 kN distributed over 150mm of length, and perimeter shear analysis must show each attachment can hold 20 kN in any direction.

Figure 17 The two different rules concerning approval of the anti-intrusion plate

[1] Ulf Steinfurth

[2] A 4 mm aluminum plate was used as AIP last year, which weighed about 1400 grams.

4.8. Concept criteria

When choosing what concept to go for, several different criteria need to be evaluated. Apart from the security aspect which is taken care of by the competition rules, one of the most important properties of the nose is of course weight. Seeing that the car is always either accelerating or decelerating, a lower mass enables the car to accelerate or brake more effectively, as well as giving it superior traction. In the FSEA competition, the course is mapped out so there are not a lot of long stretches. As such, top speed is not really a priority, but handling and acceleration is.

Other important criteria are predictability/safety and ease of production. If the chosen concept behaves differently from one test to the other the concept will be ruled out, as it is difficult to know if the concept would actually work in the event of a crash. Ease of production is also very important, seeing that there are probably theoretically better solutions, but they would be impossible to produce.

Last on the list is esthetics and cost. Even though they are listed last, they are of course important to the project. The esthetics are also closely linked to the aerodynamic properties of the car. A nose that creates a smooth transition over to the monocoque will in turn look esthetically pleasing. Cost is listed last, as the concepts are fairly equal in terms of production cost. This is because even though the crash boxes will be a lot cheaper as a standalone impact attenuator, you will need a carbon fiber cover around it, as mentioned earlier.

Table 1 Criteria used to choose concept

Selection criteria (ranked from most important to least)	
1.	Predictability/Safety
2.	Weight
3.	Appearance
4.	Ease of production
5.	Cost

4.9. Concept comparison

The most important deciding factor is the combined weight of the anti-intrusion plate, the AIP concept itself, and if the concept needs to be surrounded by an outer casing. The concepts that need an outer casing are the aluminum honeycomb crash boxes and the carbon fiber crash cones.

The same fiber and honeycomb material will be used when simulating the different concepts and finding out how much each concept will weigh. The fiber used to simulate the anti-intrusion plate is Hexply M18/1 (datasheet in attachment 13.3) and the core used was Aramid/paper/phenolic honeycomb 0.05. It later turned out that the team was forced to change both the core material and the fiber, but for the sake of comparison this has little effect.

All numerical simulations on the AIP were carried out using the finite element software Abaqus. The material data used for the calculations were derived from the datasheet of the material and can be found in table below. An explanation of what the abbreviations mean can be found in attachment 13.4.

Table 2 Material properties used in simulations

Material	E1	E2	v12	G12	G13	G23	S1T	S1C	S2T	S2C	Shear
Hexply M18/1	65000	67000	0.04	3800	900	900	800	800	800	800	100
Aramid Honeycomb	0.01	0.01	0	0.01	58	38					

4.10. Abaqus setups

The Abaqus setups for the concepts were considerably different, because the requirements to get the anti-intrusion plates approved for the competition was inherently different as well. The concepts were split into crash nose (shell) concept(s) where the AIP was not directly loaded, and the crash box/cone concepts where the AIP was directly loaded. The difference in getting the two approved for the competition was discussed in Chapter 4.7.

4.10.1. Crash nose (shell) concept setup

For the crash nose (shell) concept, equivalence to an aluminum or steel AIP needs to be proved. Test panels of 500x275 mm has to be produced both in 4 mm aluminum or 1.5 mm steel for simulation (measurements and thickness set by the rules of the competition), as well as test panels of the same size in carbon fiber.

The panels used for simulation were made using shell models in Abaqus. This made it easy to test different materials, as you can easily define the shell as a given material or a composite lay-up. This meant that you would not have to apply new boundary conditions to the test panel for each material tested.

Following the directions from a clarification email sent to one of the judges in Germany, the test setup described was copied (attachment 13.5). The analysis type used was General, Static. General static was used because 3-point bending tests are time independent and quasi-static, meaning that the test is rate dependent, but does not include inertia.

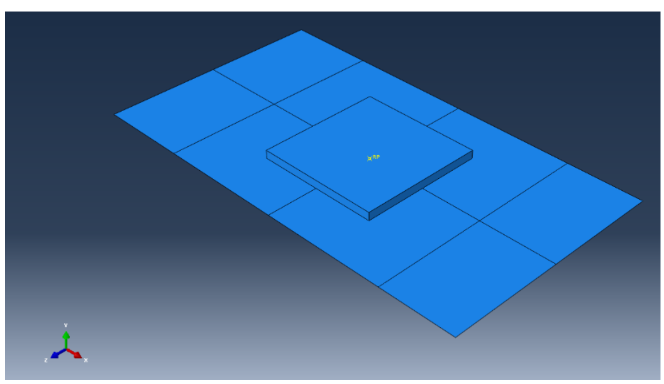


Figure 18 Test panel simulation setup

Seeing that this is a composite, normal failure criterion does not apply. Therefore, Tsai-Wu's failure criterion and deflection will be used to determine whether the lay-up is acceptable, as the maximum allowed deflection is set to 25.4 mm. Tsai-Wu is a criterion widely used to determine the safety factor for composite orthotropic shells (5). It considers the total strain energy in all the different directions of the material, and uses it to predict failure. As long as the Tsai-Wu criterion is less than one, the fibers will not fail under the given load situation.

4.10.2.Crash box/cone concepts setup

As the crash box/cone concepts only have to fulfill rule T3.38.2, which says that the AI plate only has to pass the physical crash test, we can simulate directly on the AIP. The AIP surface model was imported as STEP-file from SolidWorks and defined as a shell in Abaqus. The different materials were defined using the inputs listed in Table 2 and the shell was defined as a lamina. Looking at the front bulkheads from previous years, the monocoque appears to cover about 30 mm of the AIP surface around the edge. As such, the edge is constrained in the Z-direction. All the bolt holes are constrained in the X-, Y- and Z-direction. The same criteria of a maximum deflection of 25.4 mm and Tsai-Wu criterion has been used here.

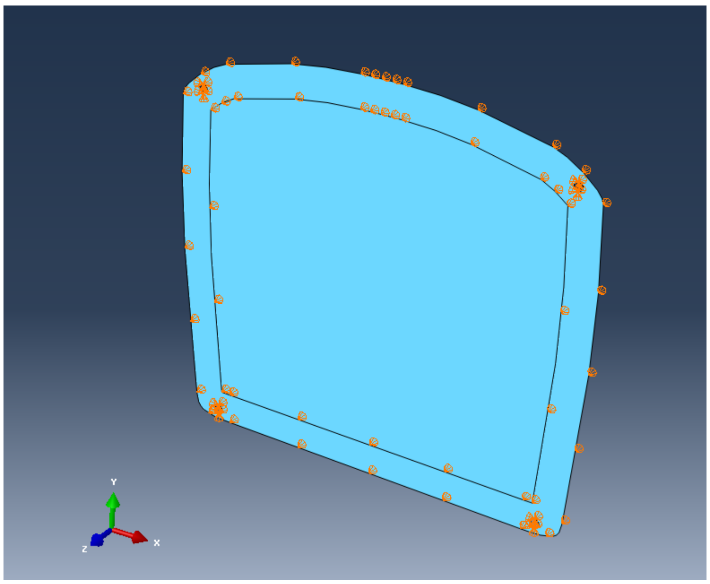


Figure 19 Crash box simulation setup

A general static analysis was used here as well. It was considered whether or not to use a Dynamic, explicit one, but this suggestion was ruled out. A dynamic explicit simulation would allow you to perform simulations where models undergo highly non-linear, transient dynamic forces, with inertia included. Seeing that the mass of the plate is low and only needs to withstand a given load it was decided that a general static simulation would be more suitable.

4.11. Evaluation of carbon fiber crash nose concept

The total weight of this system will be the concept itself and the AIP. For this concept, as mentioned earlier, there are four different tests that need to be performed in order to get the AI plate for the concept approved for the competition:

Test	Description
3-point bend test	Must prove equivalency in three point bending*
Penetration test	Must prove equivalency in penetration*
Attachment point test	Must prove equivalency* in strength for each attachment point* in any direction, or 20 kN (as per rule T3.38.3)
Pass physical crash testing	Must not fail during the physical crash test
	* = Equivalency to 1.5 mm steel or 4 mm aluminum

3-point bend[3]

Equivalent strength to the minimum requirement of a 4 mm aluminum or 1.5 mm steel AIP must be proved. To do so, test panels will be created in both aluminum and steel in Abaqus, which will then be bent down the maximum of 25.4 mm. The reaction force this deflection produces from the plate will then be analyzed. Afterwards, the composite lay-up needed to withstand the same amount of force can be found.

Aluminum test panel

Material data

E-modulus: 70000 MPa

Poisson's ratio: 0.3

Plate thickness: 4 mm

Reaction force: 1263 N

Plastic data (6)[4]:

Yield stress	Plastic strain
200	0
250	0.005
260	0.01
270	0.015

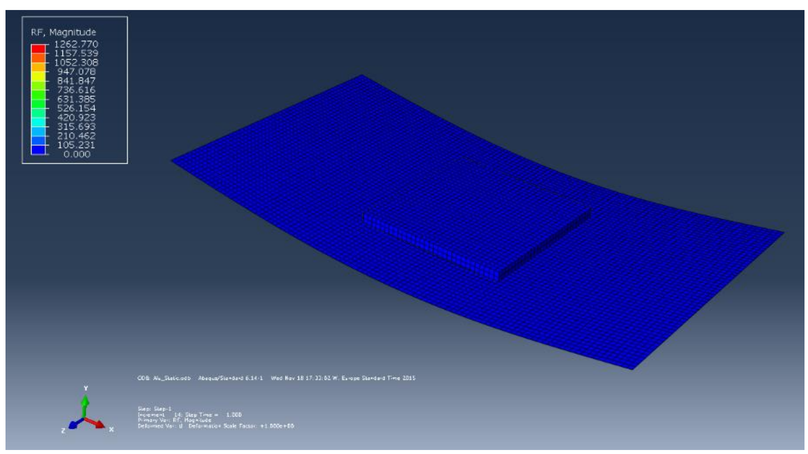


Figure 20 Aluminum test panel simulation setup

[3] Although this is not exactly a 3-point bend, this is the setup that was provided to the team by the judges. It will be referred to as a 3-point bend test in this thesis.
[4] Material data for steel and aluminum has been chosen to come as close to or better than what is specified in the Structural Equivalency Spreadsheet (SES) as possible (see attachment 13.6).

4.11.1.Steel test panel

Material data

E-modulus: 200000 MPa

Poisson's ratio: 0.3

Plate thickness: 1.5 mm

Reaction force: 195 N

Plastic data (7):

Yield stress	Plastic strain
305	0
350	0.005
380	0.01
400	0.015

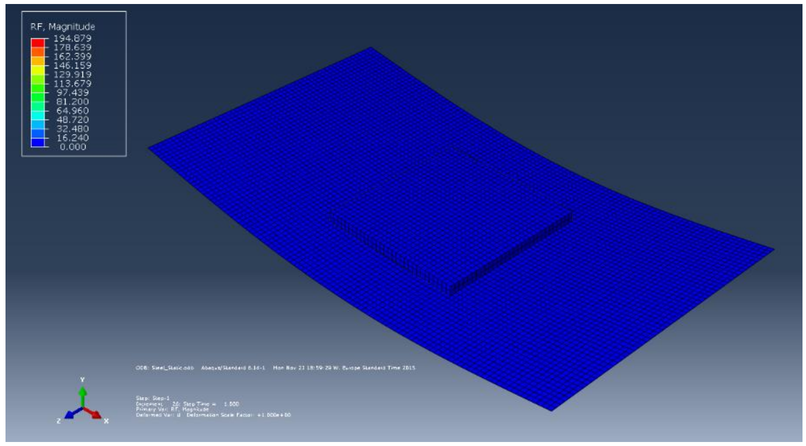


Figure 21 Steel test panel simulation setup

As a double check of the results, some simple calculation can be performed by using panels that are loaded by concentrated forces:

$$\delta_{aluminum} = \frac{F \times l^3}{48EI} \rightarrow F = \frac{\delta \times 48EI}{l^3} = \frac{25.4 \times 48 \times 70000 \times \frac{275 \times 4^3}{12}}{500^3} = 1001\ N$$

$$\delta_{steel} = \frac{F \times l^3}{48EI} \rightarrow F = \frac{\delta \times 48EI}{l^3} = \frac{25.4 \times 48 \times 210000 \times \frac{275 \times 1.5^3}{12}}{500^3} = 158\ N$$

Where:

δ = Deflection

F = Force

L = Length of panel

E = E-modulus

I = Second area moment

The numbers are close (Aluminum: 1263 N vs 1001 N / Steel: 195 N vs 158 N) and we can therefore accept the results from Abaqus.

4.11.2.Carbon fiber test panel 3-point bend test

Seeing that the rules clearly state "1.5 mm (0.060 in) solid steel or 4.0 mm (0.157 in) solid aluminum ", choosing the weakest result is allowed. As the results from the simulations show, choosing to test with the weaker steel panel would enable us to create a lighter AIP, while still being within the rules of the competition. The load case for the carbon fiber panel will be the same as for the steel panel, and therefore:

$$[EI]_{steel} = [EI]_{carbon}$$

$$200000 \times \frac{w \times 1.5^3}{12} = 65000 \times \frac{w \times t_{carbon}{}^3}{12}$$

$$t_{carbon} = \sqrt[3]{\frac{200000}{65000} \times 1.5^3} = 2.2\, mm$$

Where:

E = E-modulus

I = Second area moment

w = Width of panel

t = Thickness of panel

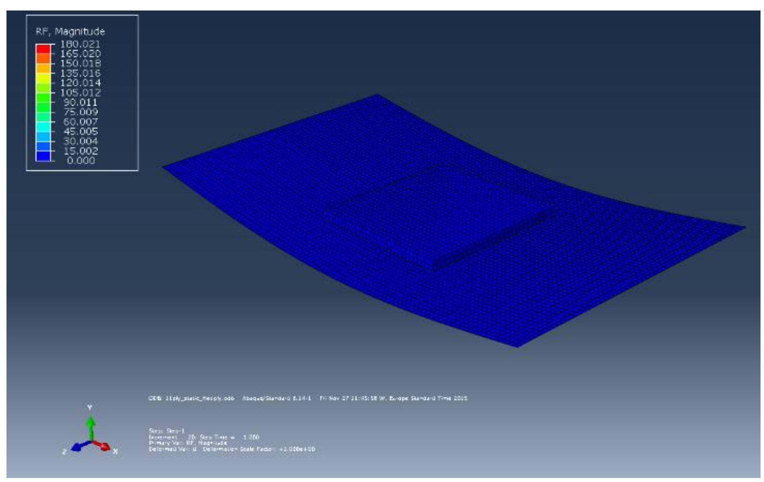


Figure 22 Test panel 11 plies

2.2 mm of carbon fiber means that about 11 plies of carbon fiber are needed to fulfill the requirement of bending stiffness, as each ply is about 0.2 mm thick. A quick Abaqus simulation, using the material properties of Hexply M18/1, shows that 11 plies would give us a reaction force of 180 N. This is insufficient, meaning 12 plies are needed to pass the equivalency in bending requirement, giving a reaction force of 240 N at a deflection of 24.8 mm. The lay-up used was $[0]_{12}$, as this gave the highest reaction force under the given deflection in Abaqus. Here, [0] denotes the fiber direction for each ply, and the 12 tells us how many times this pattern is stacked.

4.11.3.Penetration Test

In order to calculate how much force the composite Al plate must be able to withstand, a 1.5 mm steel plate will be investigated using von Mises yield criterion for pure shear:

$$\sigma_e = \sqrt{3}|\sigma_{12}| \rightarrow \; F_{shear} = \frac{UTS \times h \times O}{\sqrt{3}} = 25224N$$

Where:

UTS = Ultimate tensile strength

H = Plate thickness

O = Circumference of mandrel

To find out how many plies are needed, results from the penetration tests performed last year will be investigated. According to the results, you will need about 10 plies to pass the penetration test of approximately 25 kN (see attachment 13.7). It should also be mentioned that our composite panel should be even stronger, as there is no use of a core material that can fail.

4.11.4.Attachment point/bolted joint

To calculate how much force each attachment point must be able to withstand to prove equivalency to 1.5 mm steel, Eurocode 3.1-8 for steel design of joints will be used (8):

$$F = k \times \alpha \times UTS \times \frac{d \times t}{\gamma} = 19200\ N$$

$$\alpha = \frac{UTS_{bolt}}{UTS_{plate}} = \frac{800}{365} = 2.2$$

$$k = 2{,}8 \times \frac{e}{d} - 1{,}7 = 2{,}5$$

Where:

F = Attachment point force

k = UTS ratio

d = Hole diameter

t = Plate thickness

γ = Safety factor

e = Distance from bolt hole center to edge (minimum 1.5*Diameter due to rule T11.1.3)

Investigating the attachment point tests performed by the team ION Racing UiS, they needed about six plies to pass a 20kN bearing load with a twice as high density composite as Hexply M18/1 (see attachment 13.8). As such, it is fair to assume that 12-14 plies of Hexply should be able to pass the requirement for attachment point strength.

Physical test

All forces will be transferred directly to the front bulkhead, as shown in Figure 23, and therefore the physical test will not be a dimensioning factor.

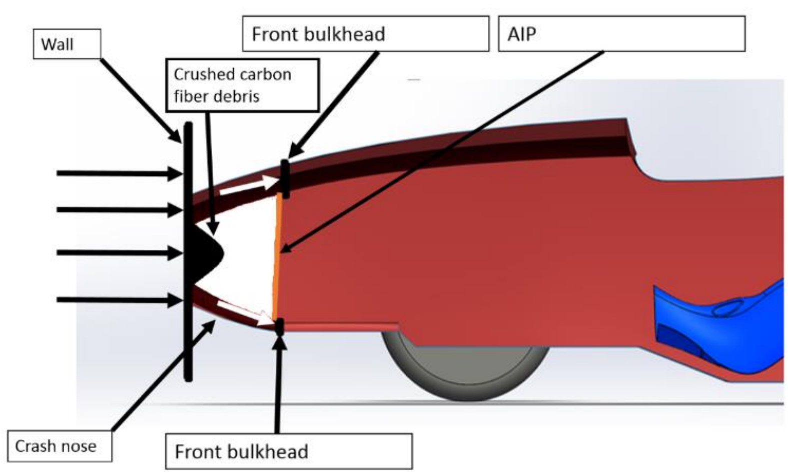


Figure 23 Front bulkhead force distribution during crash

4.11.5.Crash nose (shell structure)

To calculate how much fiber is needed in the nose to absorb the needed amount of energy, namely 7350 Joule, the specific energy absorption (SEA) number of the Tencate E745 (the carbon fiber, datasheet in attachment 13.9) will be used. By calculating the circumference every 5 mm of the nose and multiplying this with the thickness of the plies in that area and the length of the interval (5 mm), it is possible to calculate an approximate volume of fiber. By using the density of the fiber, finding the weight of the fiber in each section afterwards is easy. Then, using the SEA number of the fiber listed as Joule/gram, one can figure out how much energy each section will absorb.

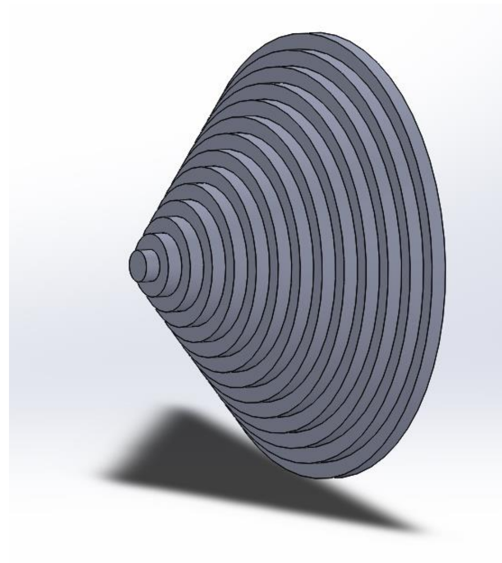


Figure 24 Illustration of simplification made in order to determine how much carbon fiber is needed

For the areas of the nose where there is no core material, a crush factor of 5% was used, as the fiber will buckle due to lack of stiffness, and for the places with core material a crush factor of 55% was used. The percentage is an estimate of how much of the fiber volume that is actually used to absorb energy. The numbers have been derived from comparing the calculations with actual test results from previous years. Only the last 185 mm of the nose will contain core material. The suggested layup calculations can be found in attachment 13.10.

With the suggested lay-up, and adding 100 gram to account for the extra fiber needed to limit buckling, as well as adhesive film, the nose will weigh in at about 550 grams.

4.11.6. Crash nose (shell) summary

By investigating all of the four tests that need to be performed, we can see that the dimensioning factor is the attachment point test, which tells us that 14 plies of carbon fiber are needed. This would bring the weight of the anti-intrusion plate up to a weight of 600 grams. Adding the weight of the crash nose (shell) itself of 550 grams, puts the whole concept at a total weight of 1150 grams.

4.12. Evaluation of honeycomb crash box concept

The total weight of this system will include the concept itself, the AIP, and an outer casing to cover the crash box. The outer casing will only consist of two plies of carbon fiber. One ply would probably suffice, but seeing that the nose needs to survive transportation etc. two plies will be used for added strength. The area of the nose is in total about 0.41m^2, which brings the weight of the casing up to about 263 grams using the same fiber density as before.

The load case for this concept is distinctly different from the previous concept, in that the AIP must withstand all the forces exerted onto the honeycomb crash box. The rules state that the impact attenuator must be at least 200x100x200 mm big according to the rules, meaning that the foot of the crash box would be 200x100 mm, as can be seen in Figure 25.

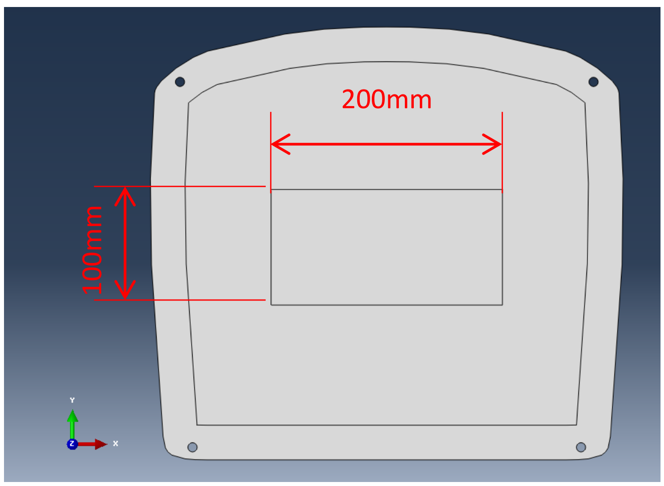


Figure 25 Aluminum honeycomb crash box simulation setup

In order to determine how much force the AIP must sustain, several reports from other Formula Student teams were investigated. The highest number an aluminum honeycomb crash box sustained was about 90kN.

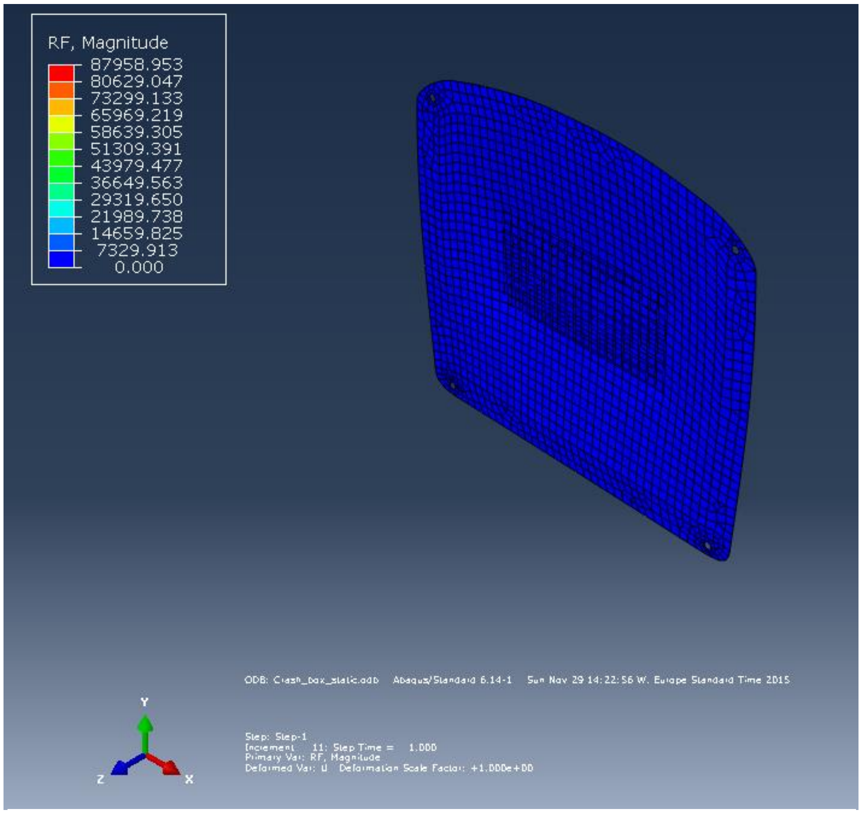


Figure 27 Reaction force aluminum crash box

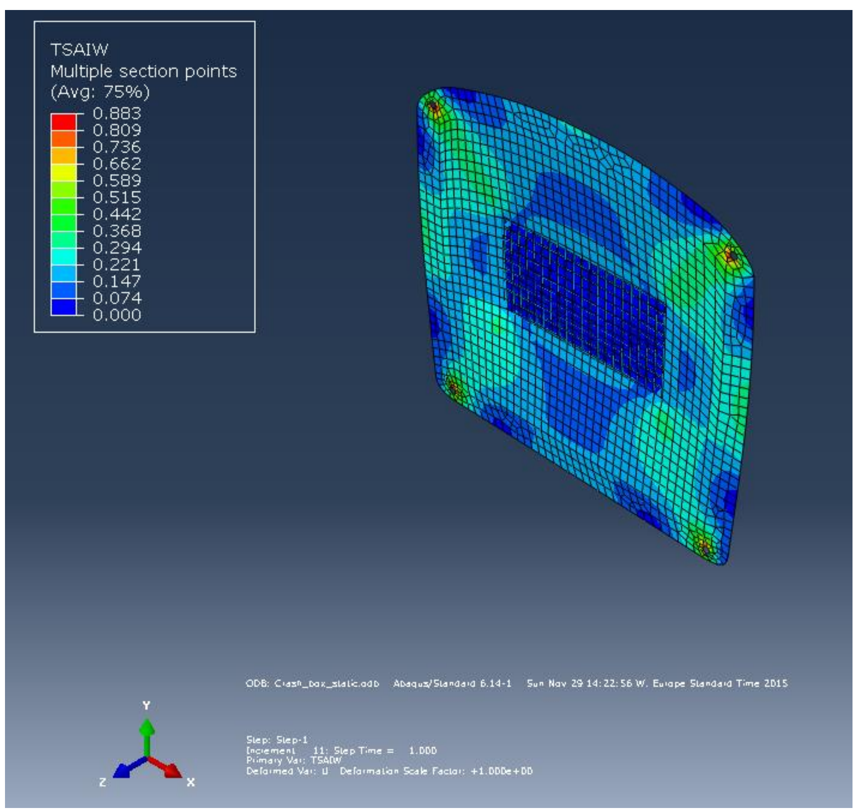


Figure 26 Tsai-Wu aluminum crash box

The 200 mm x 100 mm rigid surface was set to move about 10 mm into the AI plate, and the reaction force from the plate was studied to find out how much force the given lay-up could withstand. The maximum deflection allowed is 25.4 mm as mentioned earlier, but a deflection that large would most likely result in a failure for the carbon fiber.

A large amount of iterations were performed in order to find the most optimal lay-up. The final lay-up was $[0/0/45/-45]_4$ (the 4 being the number of times the layup is repeated) with a 20 mm core in the middle of the lay-up. The lay-up passes both the Tsai-Wu failure criterion and the maximum allowed deflection, at a minimal amount of carbon fiber used. It would probably be possible to use less fiber and a thicker core, but this would in turn cause curvature problems between the nose, the AI plate and the chassis of the car. Sixteen plies of fiber and 20mm of aramid honeycomb core would weight about 850 grams. This puts the total weight of the AIP and the outer casing up to about 1100grams.

Lastly, the weight of the aluminum honeycomb must be added. A typical aluminum crash box, including the one used by the 2013 Revolve NTNU team, weighs about 450 grams. Additionally, you would need glue to constrain the crash box to the AIP. This would add up to about 50 grams, putting the total weight of the whole concept at about 1600g.

4.13. Evaluation of carbon fiber crash cone concept

As with the aluminum crash box concept, the weight of the system will be the combined weight of the casing, the concept itself and the AI plate. The shape chosen is a cone, as this would limit the chances of having weak areas, as you would have on the edges of a square crash box.

The constraints are the same as with the aluminum crash box; the bolt holes are constrained in X, Y and Z, and the border constrained in Z. The circle that can be seen in Figure 28 is ment to simulate the foot of the crash box cone pressing against the AI plate.

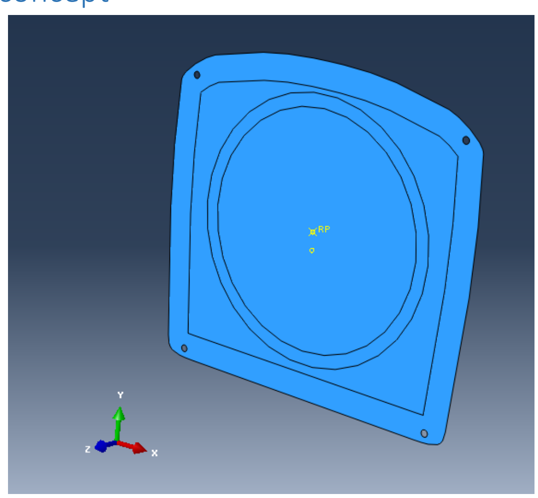
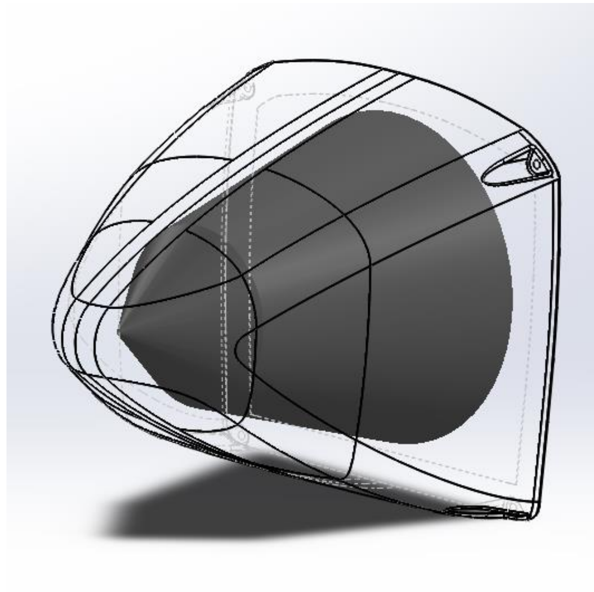


Figure 28 Abaqus setup crash cone

To calculate the weight of the crash cone itself, the same method of calculating fiber volum as with the crash nose has been used. Here, the circumference calculations were considerably easier, as the circumference increase was linear. Adding the weight of the adhesive needed to attach it to the AI plate, puts the total weight of the system at about 400 grams. The suggested lay-up can be found in attachment 13.11.



The size and shape of the crash cone was chosen to fill as much of the nose as possible, in order to distribute most of the forces close to the edges of the front bulkhead. It was also made as long as the outer casing would allow, so that when you run the crash test the average deceleration will be low. The cone at the end will consist of only two plies of fiber, but the rest will contain core material.

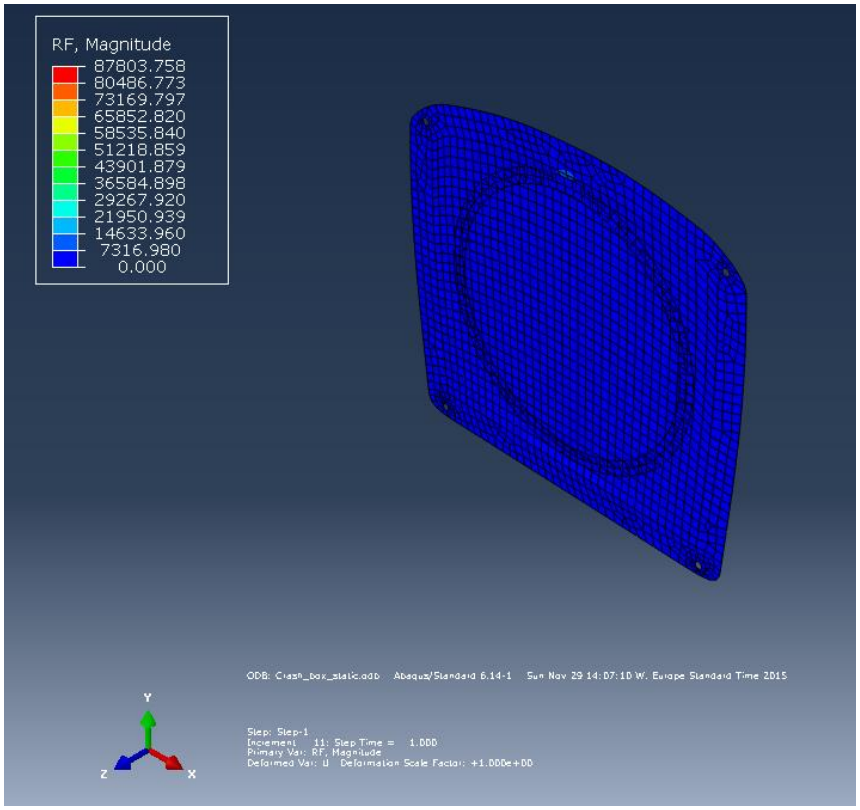


Figure 29 Reaction force crash cone

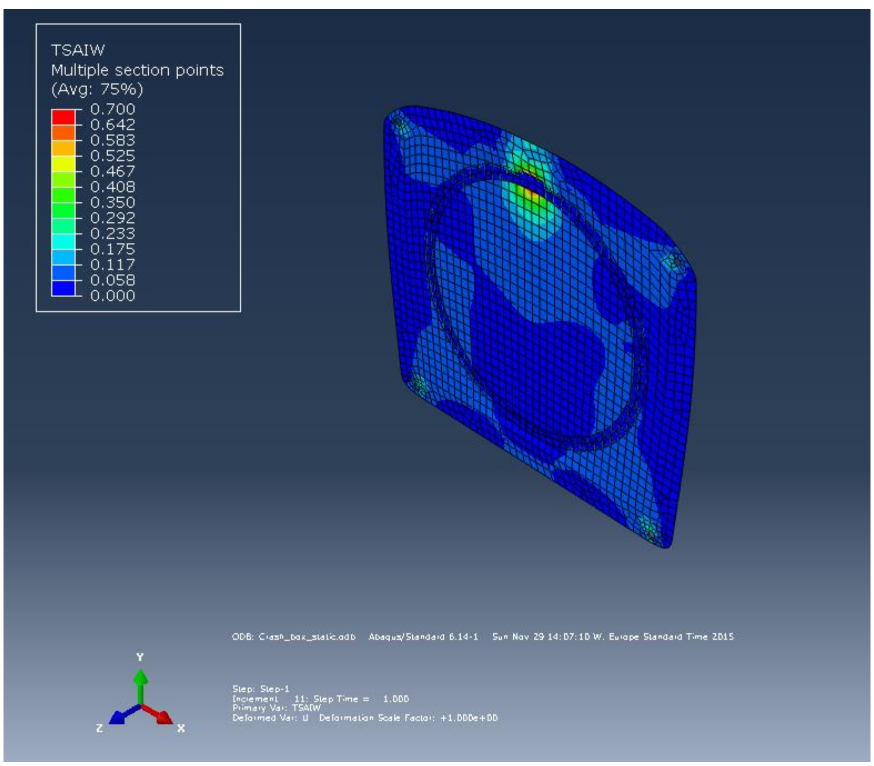


Figure 30 Tsai-Wu crash cone

The lay-up was $[0/0/45/-45/0/0]_2$ with a 15 mm core in the middle. 12 plies of Hexply and 15 mm of core puts the weight of the AI plate of this concept up to about 650 grams. Adding the weight of the crash box itself and the outer casing brings the total weight of this system up to 1300 grams.

4.14. Evaluation of carbon fiber crash nose with inner walls

After consulting alumni from previous years about the different concepts, it was decided that this concept was too difficult to manufacture. Additionally, it would be extremely difficult to simulate how much fiber was needed, you would need to strengthen the AIP, and the concept has a high chance of buckling and therefore failing completely. Thus, this concept was not been investigated further, seeing there were clearly better solutions.

4.15. Chosen concept

Both the crash box/cone concepts only work well if the car crashes perfectly perpendicularly into a wall. If a sideways crash occurs, as is highly likely, the glue holding the crash boxes/cones onto the AI plate would probably break and the monocoque would have to absorb most of the energy from the crash. As the monocoque is not designed to deform, this would likely cause the driver to be severely harmed in high speed crashes. Therefore, the crash nose (shell) concept is safer, as it will absorb energy even if the crash is at an angle.

Testing of the AI plate for the crash boxes/cones will be limited compared to the crash nose (shell), as you will only need to pass the physical crash test compared to having to pass the 3-point bend, penetration, attachment point and physical crash test. This also limits the need for producing test panels for these tests, giving more time in the production phase to design or help other team members with production.

Looking at estimated weight, the concept of the crash nose (shell) comes in best, at a weight of only 1150 with the AI plate included. Compared to last year, where the nose weighed 700 grams and the AI plate 1400 grams, this is a huge weight reduction.

An added benefit of choosing the crash nose concept (shell) is that it allows the team to create a much smaller front bulkhead on the car. The size of the front bulkhead is decided in the SES depending on how well the front bulkhead test panels do in 3-point bend and penetration tests. As the forces are transferred directly to the outer 20-25 mm of the chassis perimeter, the crash nose concept (shell) would allow the team to not have to worry about the torque generated by the crash box/cone concepts and use the minimum required sized front bulkhead dictated by the SES (See Figure 31). Seeing that the front bulkhead last year consisted of 24 plies of carbon fiber with a 20 mm core, the ability to remove a lot of material will cause a noticeable weight reduction overall on the car.

For comparison, a small front bulkhead would cause problems for the crash box/cone concepts, as the distance to the nearest free edge would be rather large, causing the anti-intrusion plate to suffer massive deformation due to the large torque generated during a crash.

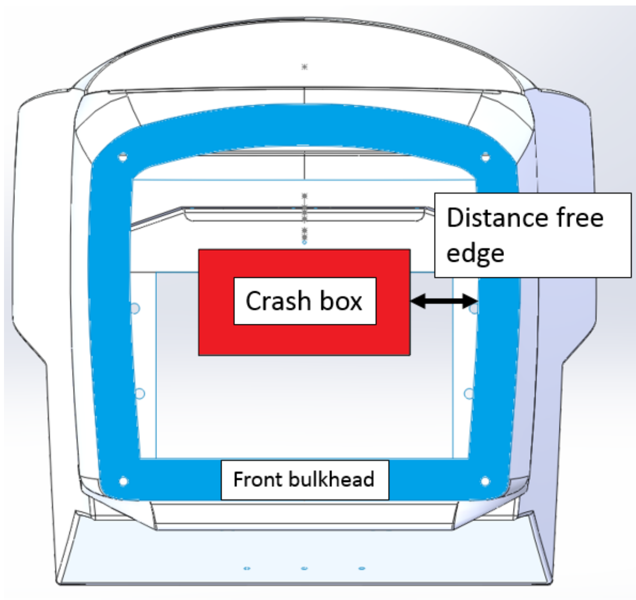


Figure 31 Distance to nearest free edge for the crash box concept

Overall, the crash nose (shell) concept appears to be the best. The only real downside is the amount of test panels that have to be produced, but this should not present too much of a problem.

5. Design phase

During the design phase, the chosen concept is refined and readied for production. This includes shape, lay-up, analysis and fiber simulation of both the chosen concept and the anti-intrusion plate. As production time is very limited, it is important that everything is as close to perfect before production starts.

5.1. Shape

The shape of the crash nose was created using the solid modeling program SolidWorks. The team member responsible for the computer aided-design (CAD) of the car performed the actual modeling, as it was important that it fit well with the rest of the monocoque. The modeling was of course accompanied by input from the author when it comes to shape relating to the crash nose. For the most part, this included symmetry and having as straight walls as possible. This was done in an effort to limit the chances of buckling, which proved to be an issue last year.

The car will be using four engines this year, one in each tire. Therefore, there is no need for having the engine inside the chassis and the team can create a much shorter car than last year. This in turn means that the crash nose is considerably longer and wider than last year to accommodate the wider chassis. The boundary for where the chassis ends and the nose starts was placed to allow assembly of the pedal box by putting it through the front bulkhead. Otherwise, like last year, it would be very difficult to assemble the pedal box by putting it through the chassis where there are all kinds of cables and steering rods etc.

Work drawings for both the crash nose and the anti-intrusion plate can be found in attachment 13.12 and 13.13

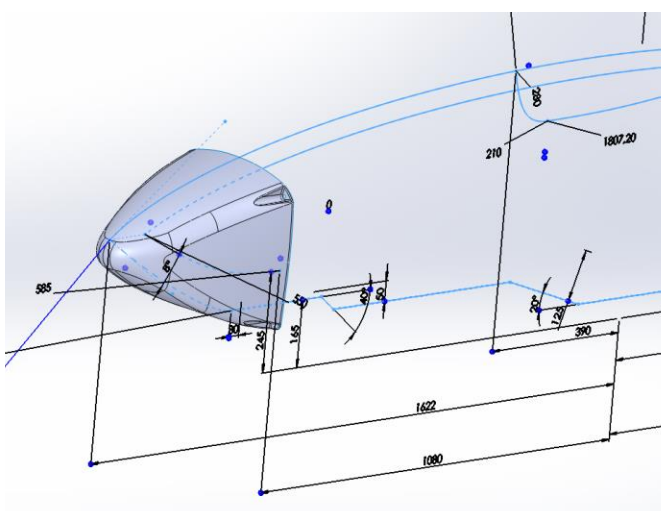


Figure 32 Lines used to build the crash nose

5.2. Layup

In the event of a crash, you would want to come to a complete stop as gradually as possible. The layup for the crash nose was therefore made with this in mind, using more and more fiber through the crash. Using most fiber at the base (shown red in Figure 33) of the crash nose also helped strengthening the corners of the crash nose. The area in and around immersed pits near the bolt holes proved to be an area susceptible for failure last year, being the cause for complete failure in 2 out of 3 tests.

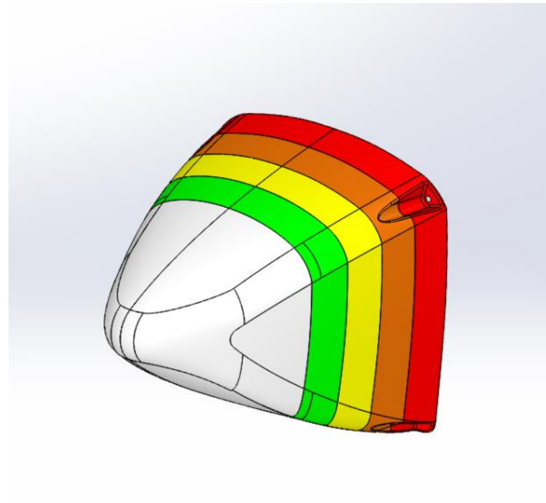


Figure 33 Layup zones

Table 3 Fiber layers and core material areas

Zone	Layers	Core material[5]?
White	2	No
Green	3	Yes
Yellow	4	Yes
Orange	5	Yes
Red	6	Yes

[5] Aramid honeycomb

5.3. Fiber direction

The general idea behind the fiber direction choice of the crash nose is that fibers being loaded parallel to the force direction will absorb more energy than the layers placed transverse to the load direction. As discussed in the beginning of the Methodology chapter, there is very little information available about panels loaded longitudinally, and it is therefore difficulty to reach any conclusion as to what fiber direction to use. This is of course also coupled with the fact that it is impossible to predict with sufficient accuracy what will happen in a crash and how the forces will spread through the layup.

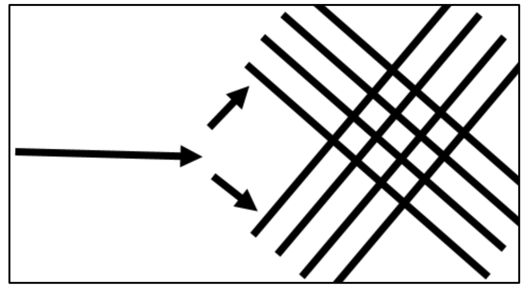


Figure 34 Illustration of force distribution for fibers 45 degrees to load direction

It is however possible to imagine what will happen during a crash, and how a load would behave on a carbon fiber ply. As illustrated in Figure 34, it makes sense to think that using plies placed at an angle to the load direction might cause the fibers to buckle away. Carbon fibers aligned with the load path will be less susceptible to buckling away, and will therefore contribute more to energy absorption. Therefore, most of the plies used in the layup are aligned with the load path of the crash. Based on this train of thought, one could argue that using only plies aligned with the load path would be better, but seeing that the load situation is so complex and difficult to predict, coupled with the rather organic shape of the crash nose, it was assumed safer to include some plies at an angle as well.

Both the inner skin and the outer skin of the crash nose uses a symmetric layup of [0/45/0]. By using a symmetric layup, one limits the possibility for twist in the layup, which will be discussed in chapter 5.4.

5.4. Laminate layup

Using classic laminate theory, we can calculate how much a carbon fiber layer can withstand before failing. Seeing that composites are anisotropic (properties depending on direction), we need a minimum of four different constants to perform calculations:

$E_1 = Elasticity\ modulus\ fiber\ direction\ (GPa)$

$E_2 = Elasticity\ modulus\ transverse\ (GPa)$

$G_{12} = Shear\ modulus\ (GPa)$

$\nu_{12} = Poissons\ ratio$

We also need ν_{21}, which can be found using the constants above:

$$\nu_{21} = \frac{\nu_{12} E_1}{E_2} \qquad \text{(eq. 1)}$$

Each ply in the laminate is described by its stiffness matrix Q in the x-y coordinate system (9), which is given by:

$$[\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \qquad \text{(eq. 2)}$$

For the most part, the inner and outer skin of the crash nose can be considered a gently curved thin plate and we can therefore say that we have a plane stress situation. We can therefore use a reduced stiffness matrix:

$$[\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 \\ \bar{Q}_{21} & \bar{Q}_{22} & 0 \\ 0 & 0 & \bar{Q}_{66} \end{bmatrix} \qquad \text{(eq. 3)}$$

Where:

$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \qquad \text{(eq. 4)}$$

$$Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} \qquad \text{(eq. 5)}$$

$$Q_{12} = Q_{21} = \frac{\nu_{21} E_1}{1-\nu_{12}\nu_{21}} \qquad \text{(eq. 6)}$$

$$Q_{11} = G_{12} \qquad \text{(eq. 7)}$$

Thin laminates are characterized by three stiffness matrices denoted [A], [B] and [D]. Together, these make out the ABD matrix. The ABD matrix is used to combine the properties of a laminate consisting of multiple plies, while also taking fiber orientation and thickness into account:

$$\begin{bmatrix} A_{xx} & A_{xy} & A_{xs} & B_{xx} & B_{xy} & B_{xs} \\ A_{xy} & A_{yy} & A_{ys} & B_{xy} & B_{yy} & B_{ys} \\ A_{xs} & A_{ys} & A_{ss} & B_{xs} & B_{ys} & B_{ss} \\ B_{xx} & B_{xy} & B_{xs} & D_{xx} & D_{xy} & D_{xs} \\ B_{xy} & B_{yy} & B_{ys} & D_{xy} & D_{yy} & D_{ys} \\ B_{xs} & B_{ys} & B_{ss} & D_{xs} & D_{ys} & D_{ss} \end{bmatrix}$$

Since the Q matrix is constant across each ply, we can write that:

$$A_{ij} = \sum_{k=1}^{K} \left(\overline{Q_{ij}}\right)_k (z_k - z_{k-1}) \qquad \text{(eq. 8)}$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{K} \left(\overline{Q_{ij}}\right)_k ({z_k}^2 - (z_{k-1})^2) \qquad \text{(eq. 9)}$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{K} \left(\overline{Q_{ij}}\right)_k ({z_k}^3 - (z_{k-1})^3) \qquad \text{(eq. 10)}$$

Where:

$\left(\overline{Q_{ij}}\right)_k$ = Elements of the stiffness matrix for the *K*th ply

z = Distance from reference plane to the two surfaces of the *K*th ply

k = Number of plies

Using the preceding equations and definitions, the expression for the in-plane forces (N) and moments (M) become:

$$\begin{bmatrix} N_x \\ N_y \\ N_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & A_{xs} & B_{xx} & B_{xy} & B_{xs} \\ A_{xy} & A_{yy} & A_{ys} & B_{xy} & B_{yy} & B_{ys} \\ A_{xs} & A_{ys} & A_{ss} & B_{xs} & B_{ys} & B_{ss} \\ B_{xx} & B_{xy} & B_{xs} & D_{xx} & D_{xy} & D_{xs} \\ B_{xy} & B_{yy} & B_{ys} & D_{xy} & D_{yy} & D_{ys} \\ B_{xs} & B_{ys} & B_{ss} & D_{xs} & D_{ys} & D_{ss} \end{bmatrix} \begin{bmatrix} {\varepsilon_x}^0 \\ {\varepsilon_y}^0 \\ {\gamma_{xy}}^0 \\ k_x \\ k_y \\ k_{xy} \end{bmatrix}$$

Here we have that:

A are the in-plane stiffnesses that relate the in-plane forces N_x, N_y, N_{xy} to the in-plane deformations ${\varepsilon_x}^0, {\varepsilon_y}^0, {\varepsilon_{xy}}^0$.

B are the in-plane-out-of-plane coupling stiffnesses that relate the in-plane forces N_x, N_y, N_{xy} to the curvatures k_x, k_y, k_{xy} and the moments M_x, M_y, M_{xy} to the in-plane deformations ${\varepsilon_x}^0, {\varepsilon_y}^0, {\varepsilon_{xy}}^0$.

D are the bending stiffnesses that relate the moments M_x, M_y, M_{xy} to the curvatures k_x, k_y, k_{xy}.

For a symmetric laminate, the ply located at position +z is identical to the ply at –z (with z being the distance from the reference plane, and therefore the stiffness matrix at +z is identical to the one at –z. By substituting these stiffnesses into equation 8, 9 and 10, we find that:

$$B_{ij} = 0$$

This means that there is no in-plane-out of-plane coupling, which means that we have no twist in the laminate during the crash.

5.5. Buckling analysis

One of the worst things that can happen during a crash test is that the walls buckle. This would mean that you get close to no energy absorption, as the carbon fiber walls would bend away from the load path. The real energy absorption happens when you get a high carbon fiber crush factor. After all, the lay-up was decided using the specific energy absorption number of the carbon fiber and multiplying it with a crush factor based on the previous year's results.

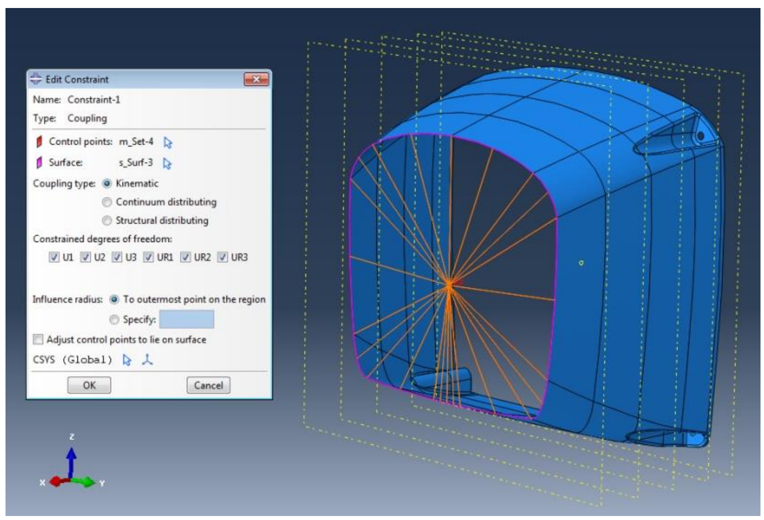


Figure 35 Buckling analysis Abaqus

Using the exact fiber lay of the nose, a buckling analysis was performed using Abaqus. The edge around the nose was constrained with a coupling to a point in the middle, placed approximately at the height of the tip of the nose. This was done for all the different fiber zones, (see Figure 33) with the zone closest to the anti-intrusion plate being investigated first. The result provided was eigenvalues for how much force needed to be applied to cause buckling. According to the rule set of the competition, the nose could never be exerted to more than 120 kN. As such, any value above 120 kN would mean that buckling would not be a dimensioning factor. Only the parts of the nose with core material was analyzed, as this was where most of the energy absorption would take place.

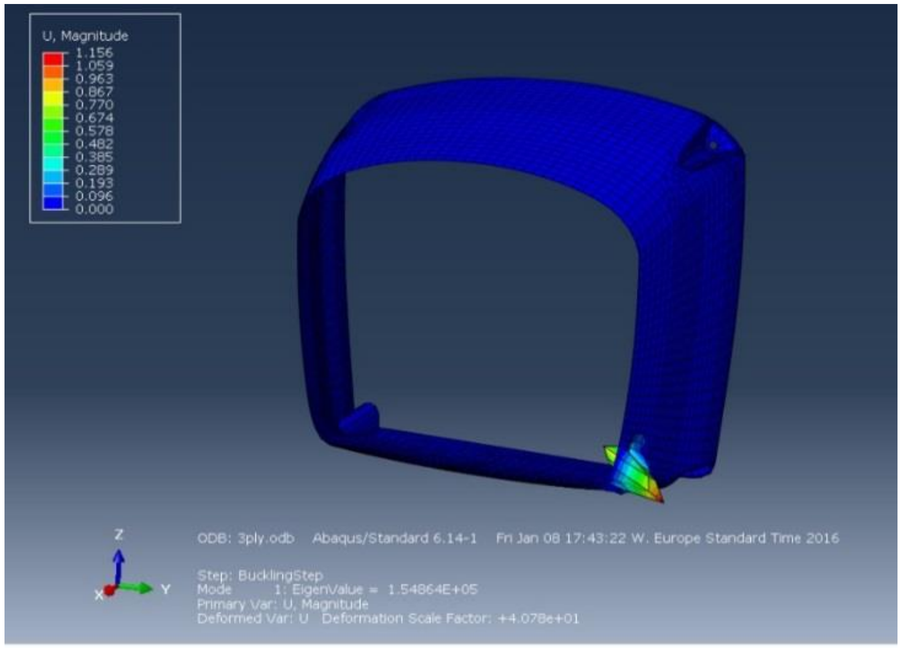


Figure 36 First area that will fail due to buckling

Table 4 Buckling for the different zones

Area (see Figure 33)	**Newton (kN)**
3 ply (green)	155
4 ply (yellow)	415
5 ply (orange)	680
6 ply (red)	755

The table shows that even at the start of the core material there will be no buckling, seeing that all the sections of the crash nose requires more than the maximum allowed force of 120 kN to buckle. Therefore, buckling is not a dimensioning factor and the lay-up can be considered approved for production.

5.6. Fibersim

NX Fibersim works as a CAD-tool for carbon fiber plies. First, you define a rosette from a line and a point. This is the base for the ply, and the program will try to lay the ply in your appointed direction starting from the point. Next, you need to define the outline of the ply. Often times there is too much curvature within the given outline, and you need to make new split lines in order for the ply to drape properly. If the drapability is insufficient (ability to cover/form over a surface), it will show up color coded as either yellow or red, depending on severity.

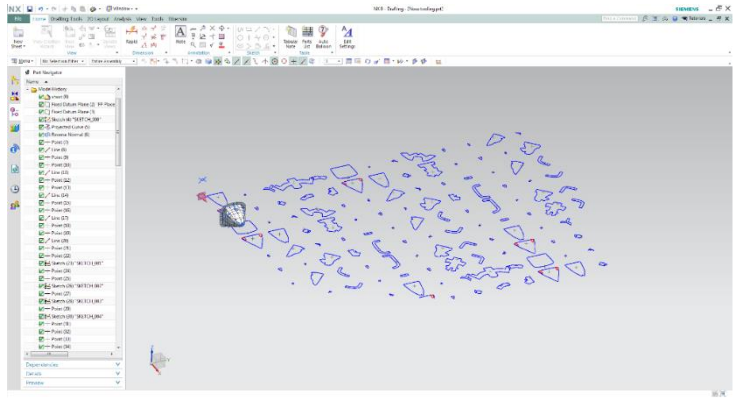


Figure 37 All plies used in the tooling

The difficult part of Fibersim is to not get any split lines of the first three subsequent layers on top of each other. Split lines on top of each other will cause areas with only epoxy, and fail easily because all the strength in that area is from the epoxy alone without the strength of the armament fibers. This means that layer one, two and three need to not have any ply outlines on top of each other, but layer four may share spit lines with layer one, and layer two with layer five etc. This process becomes increasingly more difficult for each layer.

The end product from Fibersim is a so called "plybook". The plybook indicates the direction of the fiber, as well as where on your model the ply is supposed to go. One could say the ply books serves as a recipe for your carbon fiber layup. This year's plybook included several hundred pages of plies, and will therefore not be included in the thesis.

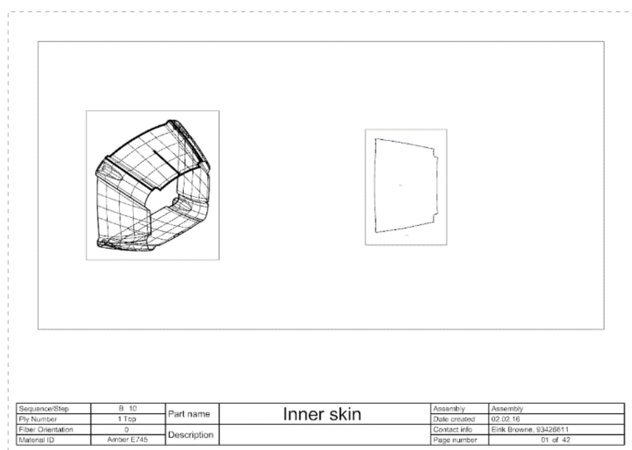


Figure 38 Example of a plybook page

An overview of the different laminate layers can be found in section 13.14 in the appendix.

5.7. Anti-intrusion plate

The layup for the anti-intrusion plate used was $[0/45]_7$. The original thought, as discussed in the Concept chapter was to used $[0/0]_7$, but new information became available during the design phase.

The production crew at Kongsberg Defence and Aerospace (KDA) argued that for penetration tests, using only [0/0] in fiber direction gave better results because you were able to pack the layers closer together. However, the employees at KDA are used to using an autoclave (pressurized oven) with several Bar of pressure, packing the layers very well together. Seeing that the AIP was to be made using only normal vacuum and an oven, this difference was assumed negligible.

The penetration test consists of pressing a mandrel through the panel. When the mandrel moves through a [0/0] layup, shear bands (regions where the fiber fails) will occur in all directions as illustrated by the red arrow on the simplified figure (Figure 39) below. In the [0/0] layup, there is no fiber there to prevent these bands from occurring. On the other hand, a [0/45] layup will be much less susceptible to these shear forces, due to the layup also having fibers in the 45° direction.

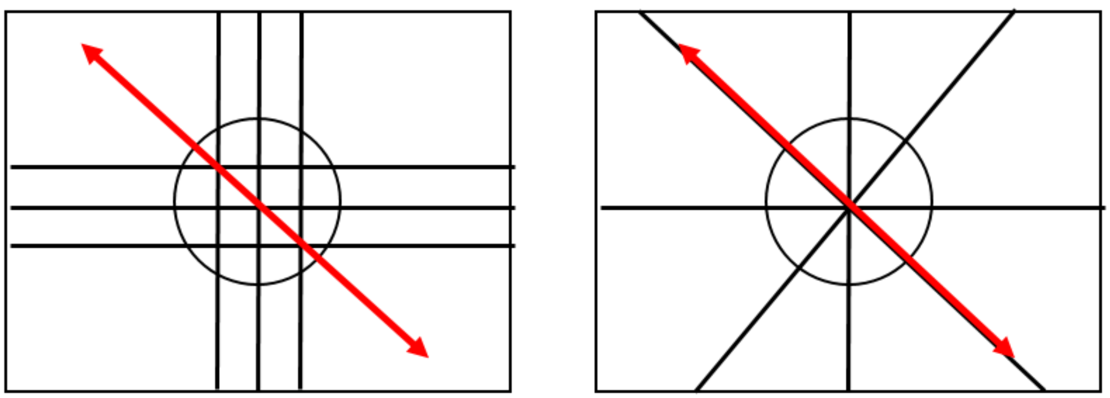


Figure 39 Shear force relative to fiber direction

The optimal situation would have been to have a layup where all the fibers travel in a radial direction from the middle of the hole, but this is of course impossible in practice. However, a [0/45] approach is much closer to this setup than a [0/0].

Figure 40 Finished carbon fiber anti-intrusion plate

6. Production phase

The production phase for the anti-intrusion plate and the crash nose started in the middle of January and lasted until late March. The production of the anti-intrusion plate utilized the composite lab at IPM NTNU for production, while the crash nose itself was produced at the facilities of KDA. It would have been better to produce both the anti-intrusion plate test panels as well as the AIP itself at the facilities of KDA where they had autoclaves, but the team also needed to utilize the testing equipment at NTNU to prove equivalency to steel or aluminum. It would also have been an enormous burden to have to produce and test panels in parallel to producing and crash testing the crash nose.

6.1. Production of test panels and AIP

The original thought was to create the panels using the fiber Tencate E745, but seeing that the crash nose, monocoque and lids as well as all the different test panels for the SES had to be made out of E745 as well, there existed an uncertainty in whether or not there would be enough fiber. A switch to Hexply M18/1 was therefore made, which had material properties within an acceptable range compared to the E745. The fiber was then changed again to Hexply 8552 (see attachment 13.15 for datasheet), because the team members responsible for creating the carbon fiber rims were unsure if they had enough fiber to create their parts. The material properties were comparable, and the switch was made.

The test panels as well as the two anti-intrusion plates, one for the car and one for the crash test, had to be produced. To decide whether to go for a 14 plies or the safer option of 16-plies, the tests with the lowest anticipated safety factor, namely penetration and attachment point tests, were produced and tested first.

As it will be shown later, both the tests passed. At that point, the team had neither time nor carbon fiber enough to produce 16-ply test panels for penetration and attachment point tests, if the 14-ply 3-point bend test failed. Therefore, both the 3-point bend test panel as well as the large panel for water jet cutting the two anti-intrusion plates were produced on a gamble that the 14-ply 3-point bend test would pass as well. This was the test with the highest calculated safety factor, so the risk for failure was low.

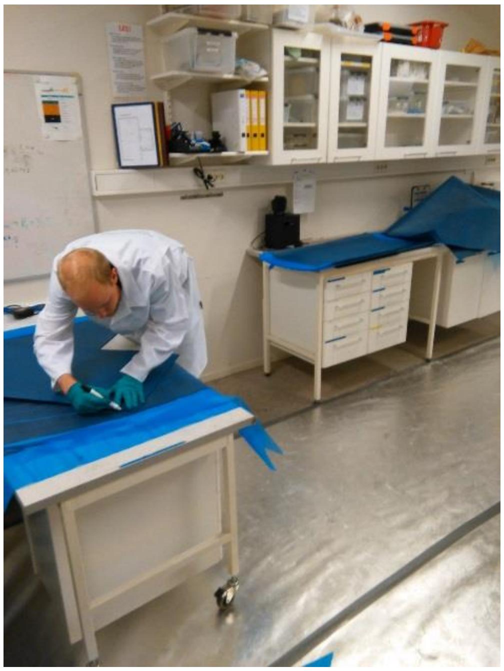


Figure 42 Production at the facilities of IPM, NTNU

Figure 41 Debulking process. Laminate is put under vacuum to pack layers together

6.2. Testing of panels

As previously discussed, equivalency to 1.5 mm steel or 4 mm aluminum had to be proved in order to get the AIP approved for the competition. The weaker of the two, steel, was chosen. This included equivalency in 3-point bend, penetration and attachment point.

6.2.1. 3-point bend

Setup

The tests were carried out at Sør-Trøndelag University Collect, HiST. The test setup provided by the judges required a 25.4 mm deflection for the lowest point on the test panel. Seeing that the test used a 150x150 mm rigid mandrel[6], an Abaqus simulation was performed in order to find the needed test equipment input to achieve the correct maximum deflection on the panel. The simulation result indicated that moving the mandrel down 21 mm would yield a 25.4 mm deflection on the panels.

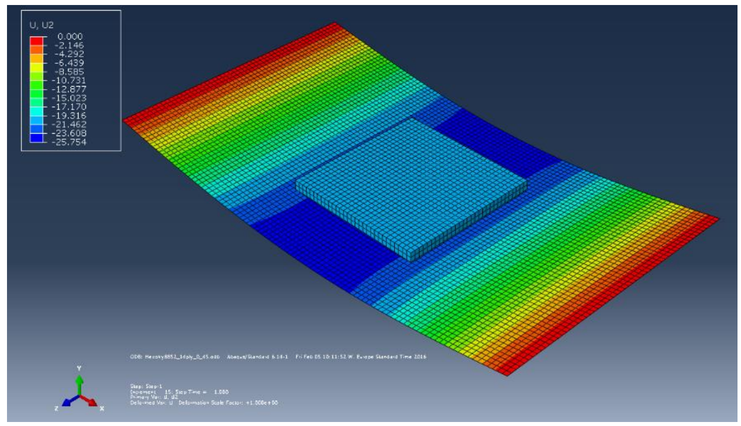


Figure 43 Simulation done to find needed deflection

Figure 45 3-point bend carbon fiber

Figure 44 3-point bend steel

[6] Test setup provided by the judges, see attachment 13.5

6.2.2. Penetration

Setup

The penetration tests were carried out at NTNU. The samples were placed on a plate with a 32 mm in diameter hole aligned co-axially with the 25 mm in diameter mandrel. This setup was specified by the rule set of the competition. The speed chosen was 0.6 mm/minute.

Figure 47 Penetration test carbon fiber

Figure 46 Penetration test steel

6.2.3. Attachment point

Setup

The test was performed using the same machine as the penetration test. Since the rules of the competition did not provide any additional information about how the test was to be performed, the team provided the judges with the suggested test setup, see Figure 48. The test setup was approved and the test could commence. The setup consisted of two metal flanges and the test specimen. The flanges were bolted to the specimen, which were then pulled away from each other until material failure.

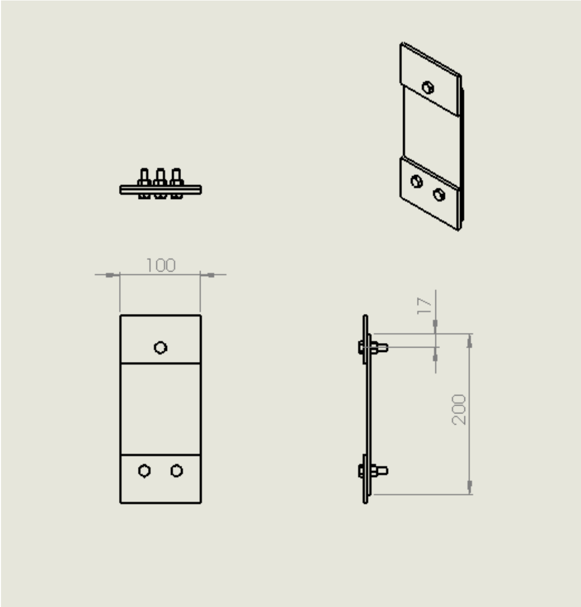


Figure 48 Approved setup

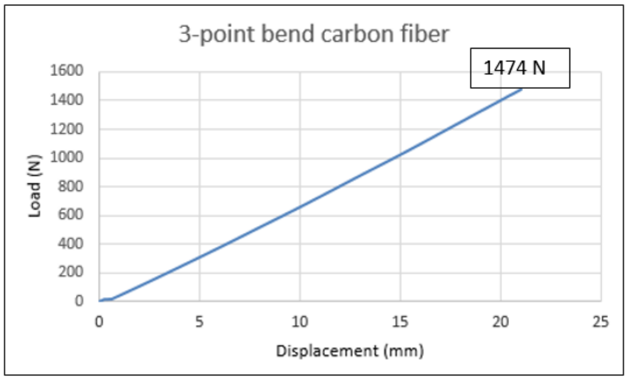
Figure 50 Attachment point test carbon fiber

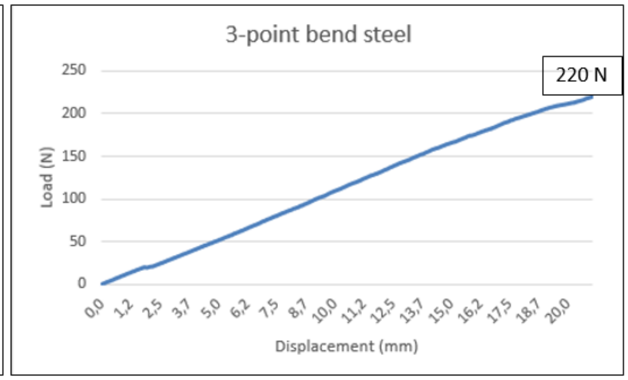
Figure 49 Attachment point test steel

The carbon fiber test specimen proved to be so strong that the head of the bolt was pulled off. Luckily, it had been ensured that the correct bolt classification, 8.8, was used prior to running the test. This meant that even though the test setup proved to be not ideal, the setup was already approved and the correct bolt was used, and as such the judges would have to approve the test. Either way the composite panel, as will be shown in the next chapter, proved to be more than twice as strong as the steel plate before the bolt head was torn off.

6.3. Test results

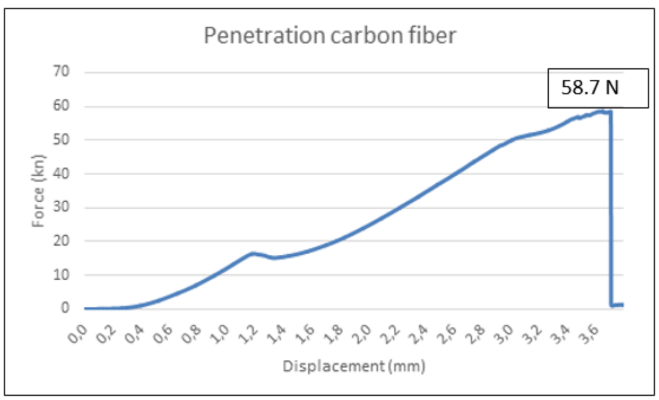
6.3.1. 3-point bend

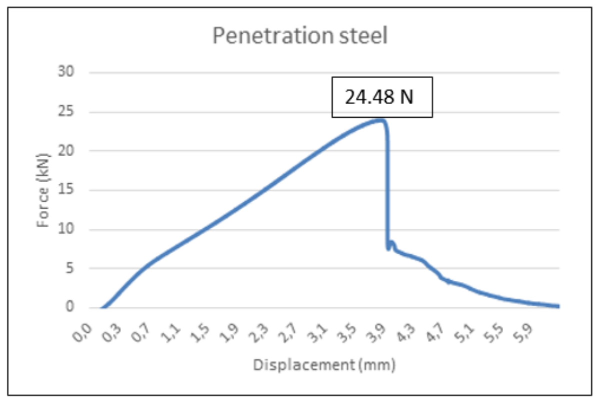




Safety factor: 6.7

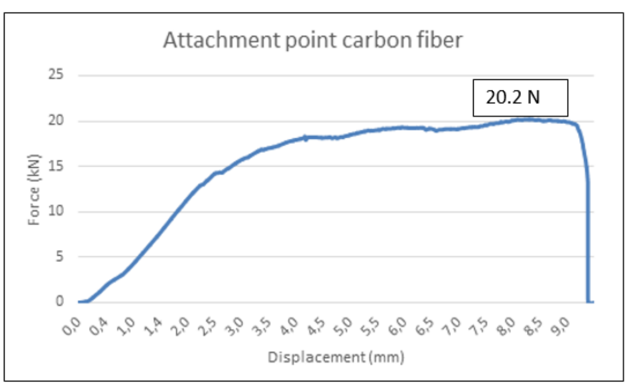
6.3.2. Penetration

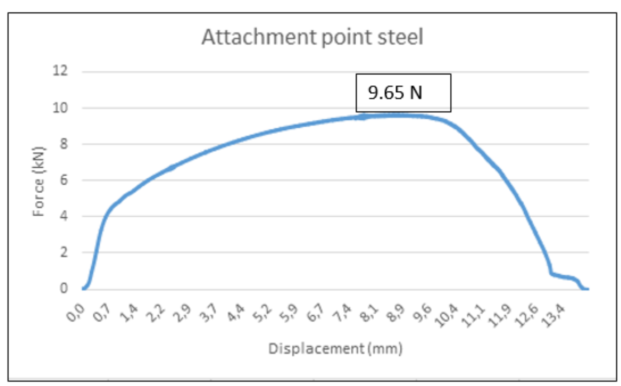




Safety factor: 2.4

6.3.3. Attachment point





Safety factor: 2.1

Both the thickness of the test panels and the safety factor being a lot higher than previously anticipated raised suspicion. It was then discovered that a detail in the carbon fiber data sheet had been overlooked, namely the ply thickness of the carbon fiber. This attributed to several hundred grams of weight, which could have been easily avoided. The error was attributed to the two unplanned fiber changes right before production started.

Even though this year's anti-intrusion plate is probably the strongest in Revolve NTNU's history, it had now been proven stronger than the minimum requirements of steel or aluminum, and it was now approved for the competition. The carbon fiber anti-intrusion plate turned out to weigh 905 grams, paint included. For comparison, if the AIP was to be made out of aluminum it would have weighed around 1600 grams.

6.4. Crash nose production preparations

6.4.1. Core adjustment

This year, the plan was to use a lighter core material than last year, because it was thought to be too strong and it should be an easy weight saving. Unfortunately, due to a lack of communication between Revolve and KDA, a core that was a little bit heavier than last year arrived. At that point, it was too late to order another core, and the one that arrived had to be used instead.

The core material had to be adjusted prior to arriving at the production facilities of Kongsberg Defence and Aerospace (KDA). The core material that the team got from KDA was 1 inch in height, which was too much for use in the crash nose. The honeycomb core material plates, which were about 2 x 4 meters big, were cut into smaller pieces using a band saw. The same band saw was also used to reduce the height of the plates by cutting the small pieces in half in an upright position, which gave a height of about 11 mm.

To get the correct shape on the core material, flat patterns of the core material were made using NX Fibersim. The flat patterns were then printed out on A3 sheets, and the core material was cut using these flat patterns as a guide. The core also had to be chamfered, in order to allow good contact between the inner and outer skin of the carbon fiber. If the core had not been chamfered, one could run the risk of having trapped air between the skins, as illustrated on Figure 51. Any trapped air will fill with epoxy that would otherwise have gone to strengthen the laminate. This makes the fiber in that area very dry, and causes a massive loss of strength. These areas are referred to as dry spots.

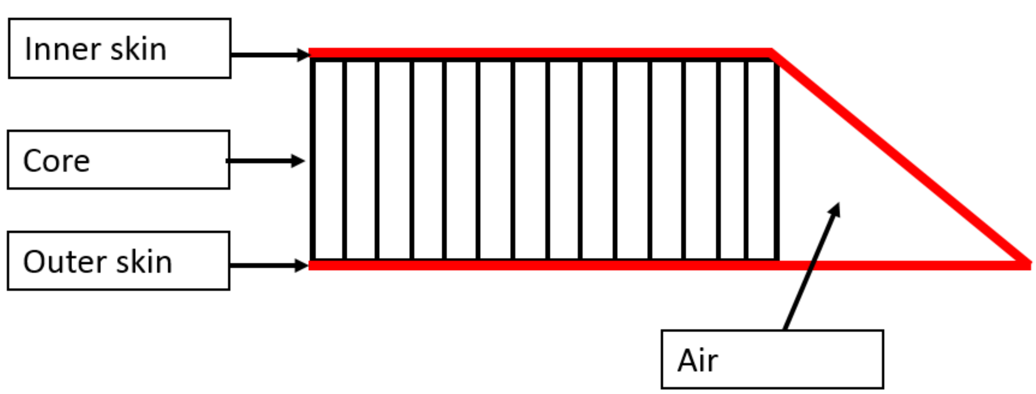


Figure 51 Illustration of trapped air between inner and outer skin at the edge of core material

Chamfering also drastically degreases the chances of core crush during the curing process. As an example, on Figure 52 you can see what happens if you do not chamfer properly. Displayed is one of the penetration test panels used in the SES. When the pressure in the vacuum bag decreases, the bag presses inwards against the core walls and displaces them. The walls of the core material might also buckle and fail if you are unfortunate. Luckily, for the team, all test panels are made larger than needed before they are cut to the correct size, so this did not present too much of an issue.

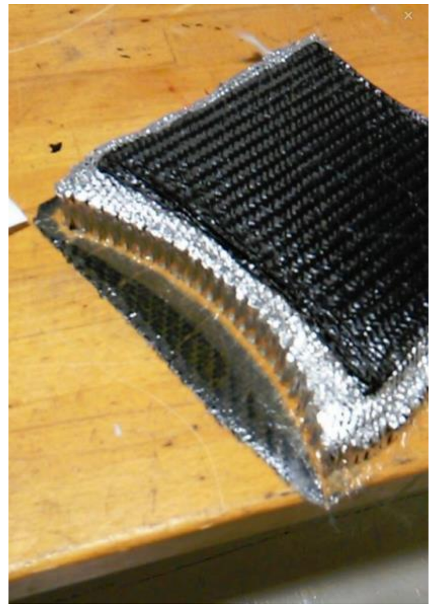


Figure 52 Result of poor core chamfering

6.4.2. Production crash rig

For the crash testing, the nose needed a substrate to which it would be attached during the crash. A crash rig was made using a water jet cut backing plate, four metal tubes and a metal representation of the size of the front bulkhead of the car.

The front bulkhead used in the test setup was produced by water jet cutting a 4 mm steel plate to the same size as the front bulkhead on the car. Originally a smaller front bulkhead was welded on four 150 mm tubes on the crash rig, but the size of the front bulkhead had to be adjusted due to new calculations. Therefore, a bigger 4 mm front bulkhead was placed in front of the old one during the crash testing.

Figure 53 Crash rig

6.4.3. Mold preparation

Before production of the crash nose mold (also called *tooling*) could start, a positive mold of the crash nose was milled in polyurethane (PU) foam. The positive mold was then sanded all the way up to 400 grit sandpaper before it was varnished. Afterwards, it was sanded all the way up to 2000 grit paper, before it was rubbing cleaned and polished. The more thorough you are with the mold preparation, the less supplementary work you have to do post production. It is a lot easier to sand a PU mold than a solid carbon fiber mold.

Figure 54 Mold preparation

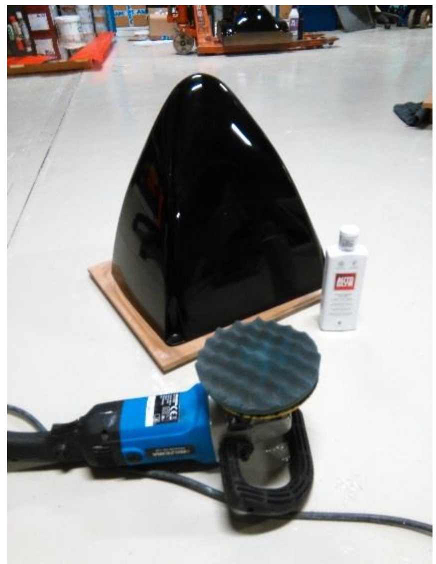


Figure 55 PU-foam mold ready for sealing and releasing

The last step before production of the tooling could begin was to seal and release the PU mold. Sealer is a liquid that as the name suggests seals tiny pores in the material to prepare the surface for the release. The release ensures that the composite cast releases properly after the epoxy has been cured. The sealer was applied 3 times with a 30-minute wait between each layer, and the release was applied 5 times with a 15-minute wait between each layer. This had to be done every time a new crash nose production was to start. The sealer used was called Loctite B-15, and the release was called Loctite Frekote 700-NC.

7. Production

7.1. Tooling production

Upon arriving in Kongsberg 18. February, the first order of business was to sort all the different plies made from the Majestic-files from Fibersim. For the cutting itself, KDA had two CNC cutters that they could program to cut the carbon fiber plies. On Figure 56 you can see the file for the inner and outer skin of the carbon fiber crash nose.

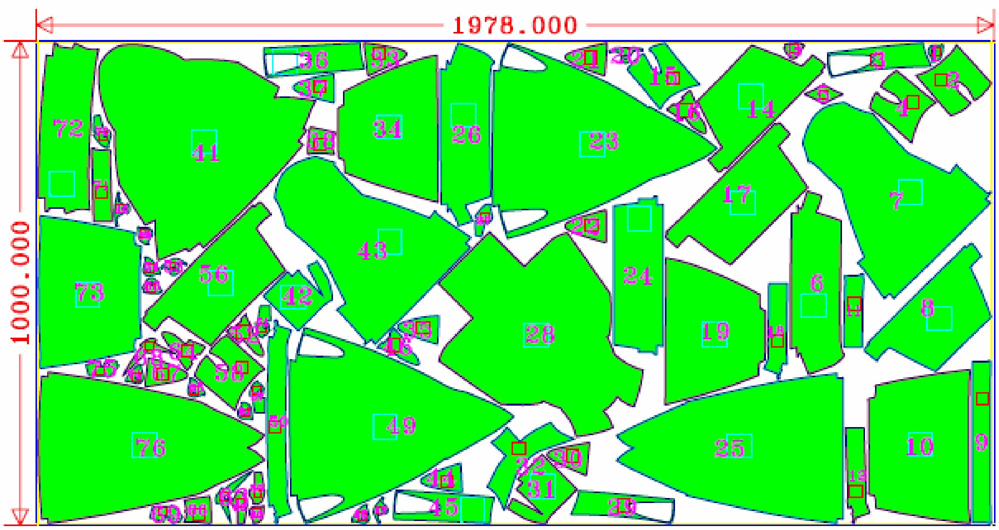


Figure 56 CNC cutting file for inner and outer skin

The cutting file for the tooling was considerably longer than the one for the actual crash nose. The tooling consisted of eight layers that covered the whole nose completely. For comparison, the crash nose only covered itself completely twice, plus several extra layers at the bottom half of the nose where the core was. Luckily, you only need one tooling to produce the crash noses. The reason for creating a tooling is that the fiber used in the crash nose cures at such a high temperature, that a PU-mold would melt or deform heavily.

Figure 57 Tooling production

The tooling fiber used was Tencate Ambertool HX42 3k and 12k. The innermost and the outermost layer were 3k and the layers in-between were 12k. Here 3k and 12k denotes the numbers of filaments (3000 and 12000) per roving in the carbon fiber. These rovings are then woven into carbon fiber fabric. The 3k is very difficult to work with compared to the less formable 12k. One would think that the 3k would be easier to work with than the 12k, but this is in reality not the case. The 3k is very sticky and the plies deform easily, making it a challenge to work with especially for the smaller plies. Often times you would lay a ply wrong or at a slight angle, and need to peel the ply off again. In that case, the 3k plies would deform heavily and need a lot of adjustment before a new attempt to lay the ply could be made.

It proved very rewarding to work on the tooling before moving on the produce the crash nose for the car. Any little mistake you make might prove detrimental to the strength of your composite product, but seeing that the tooling is basically just a very expensive cast, small mistakes are not that detrimental to the end product.

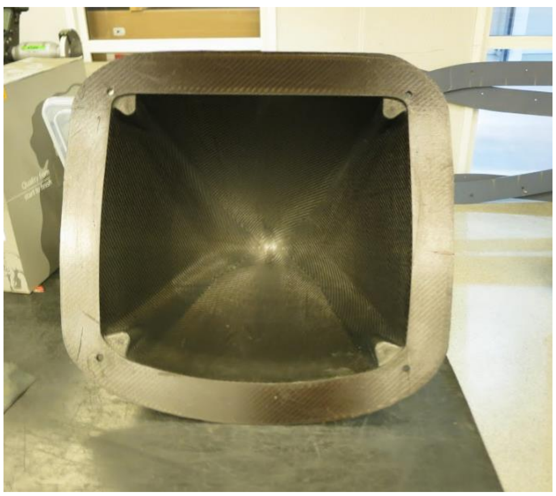


Figure 59 Finished tooling

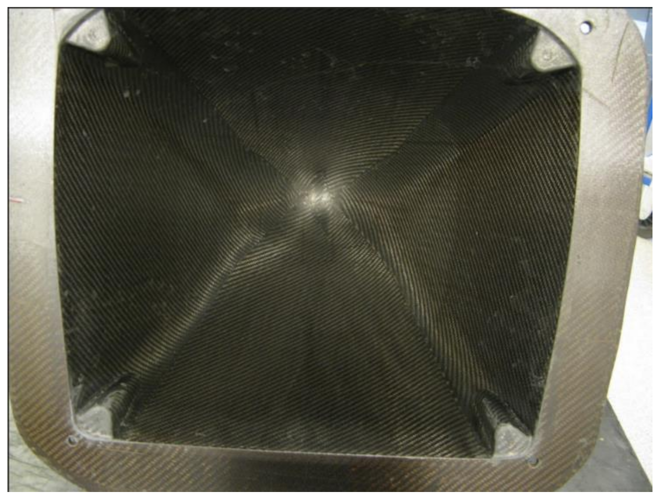


Figure 58 Tooling close-up

The tooling cured for 11 hours at 55°C, and then post-cured for about 8 hours on 190°C, with an 8 hour ramp prior. The post-cure was done to increase the tooling's toughness at elevated temperatures.

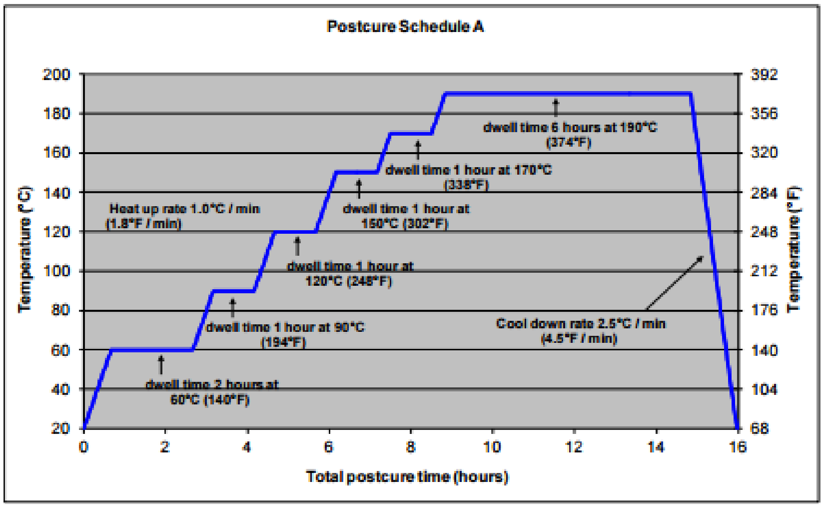


Figure 60 Curing cycle tooling

As you might have noticed on the tooling, there is a carbon fiber flange all around the bottom. This flange is used to fasten the "tooling flange", which was water jet cut from a 4 mm steel plate. This flange serves multiple purposes:

- Reinforcing the tooling so it does not deform during oven cures.
- Limiting the chances of core crush, as the edge at the bottom of the crash nose has not been chamfered.
- Applying mechanical pressure to the carbon fiber against the bottom of the core to avoid air pockets, which may cause dry spots.
- Ensure a flat surface at the bottom of the crash nose.

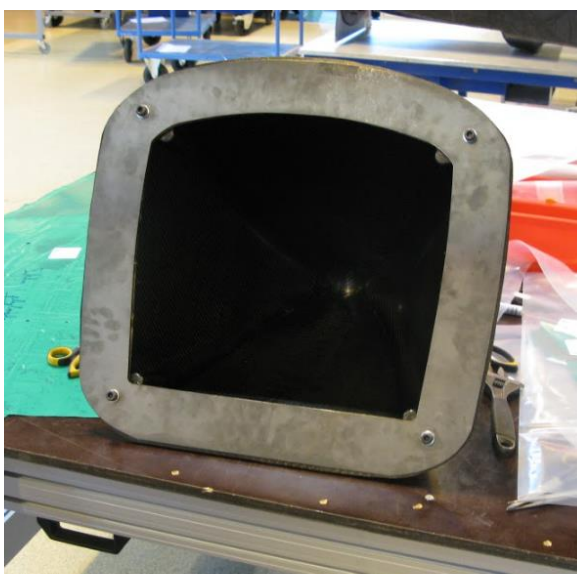


Figure 61 Assembled tooling flange

7.2. Production first nose

After the tooling was complete, the production of the first nose could start. The CNC cut plies were sorted and the plybooks from Fibersim were closely followed in order to make sure that the lay-up was correct. The whole nose was made in one cure, meaning that all plies for both the inner and outer skin was placed before a complete autoclave cure. An alternative would have been to cure the outer skin first, and then use adhesive film to attach the core before placing the inner skin. This would have been a much safer option, seeing that you would have been able to cure the outer skin on a much higher pressure, because you would not have needed to worry about the core being crushed. The elevated pressure would have packed the layers even better together and created a stronger laminate. The whole first nose was cured at 2.5 Bar.

Figure 62 First crash nose in produciton

The process of creating the first crash nose was characterized by a very rushed production due to lack of time. It was very limited when Revolve NTNU could use the autoclaves without halting the normal production of Kongsberg. Therefore the nose had to be made in one day in order to make the autoclave that was set up for the next morning. This was the only time available that day, and the first crash test was scheduled the day after that.

Due to the time constraint, the production was severely lackluster. The plies were not properly packed together, which meant that there were several dry areas in layup after the curing process. There was also a huge problem with there not being enough pressure in the corners, because there was very little space between the elevated area around the bolt holes and the core material on the walls. Therefore, the bag was not able to reach in and apply proper pressure in that area.

The biggest problem however was the edge at the bottom of the crash nose. The plan for wrapping carbon fiber around the bottom edge of the core material was not well planned. Small flaps at the length of the height of the core material (see Figure 63) had been added to the outer skin plies. The thought was that these flaps would wrap around the core material and seal it within the layup. This did not work, as the flaps did not stick to the core material when you tried to wrap it over the bottom of the core. Reinforcement plies were added in order to wrap the flaps properly around the core. This seemed to work to some extent, but the result after the autoclave cure proved otherwise. The core had also moved a little and the combination meant that massive air pockets had formed within the laminate all around the edge. This caused the edge to become very dry and uneven, which meant a huge drop in the strength of the composite crash nose.

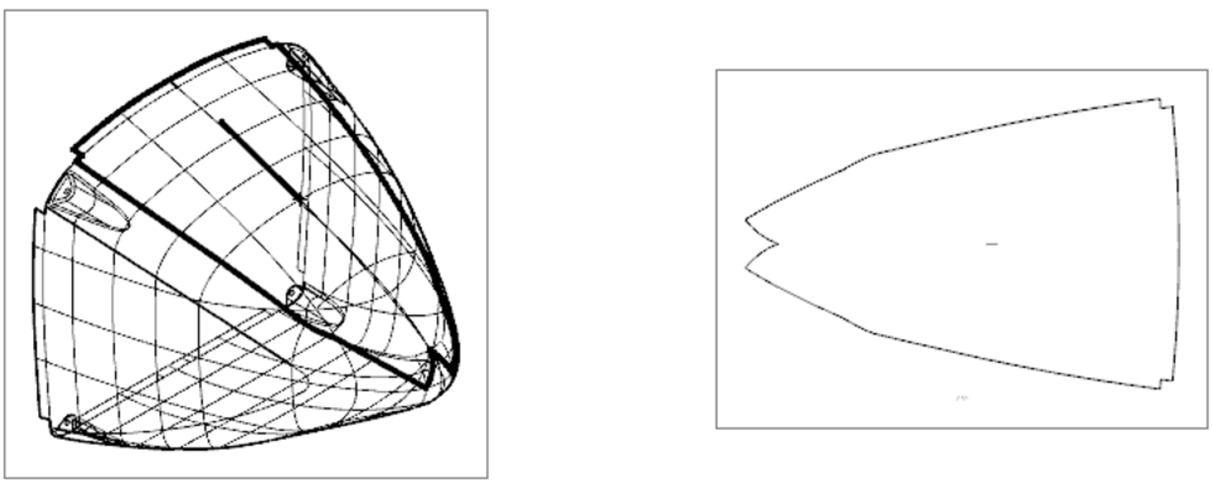


Figure 63 Example of one of the plies in question

The bag was also unable to apply the needed amount of pressure on the area around the bolt holes. As you can see on Figure 64 below, it would be very difficult for the bag to reach down and apply enough pressure across the whole surface. This picture was taken with the tooling and the tooling flange only, meaning that there was even less space there for the bag to fit when there were six layers of carbon fiber there as well. This resulted in the layers not being packed well together, which meant that the fiber in that area became dry during the curing process.

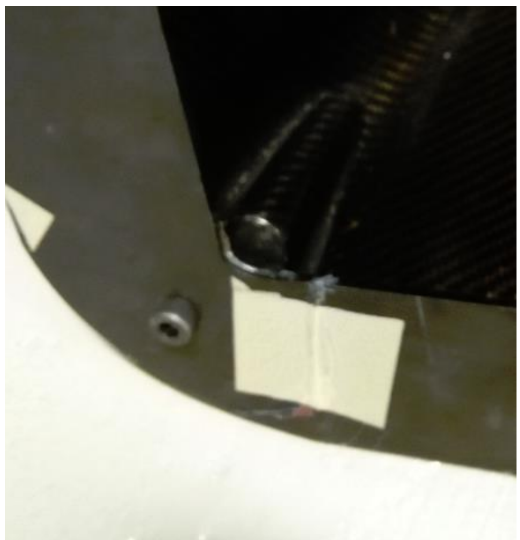


Figure 64 Hard to reach area

The core material used was also poorly chamfered, because it was done using a scalpel. This meant that when you tried to chamfer the bottom edge of the core, the last part would bend away from the knife.

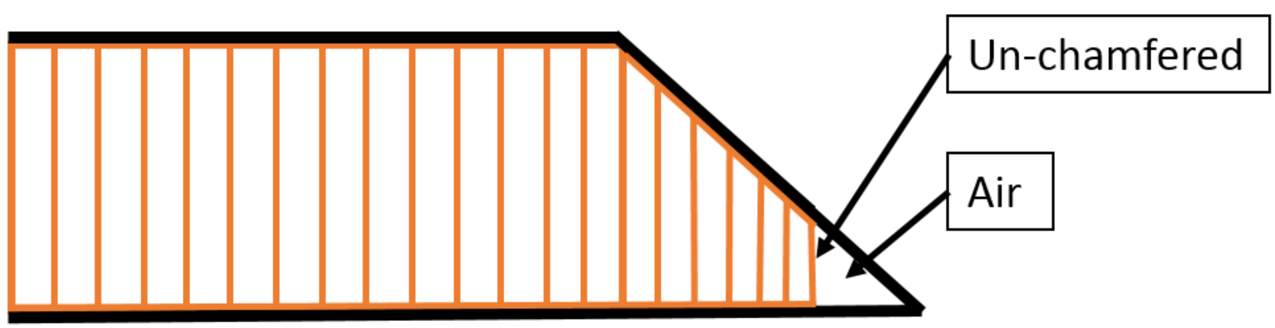


Figure 65 Poor use of tools

This left a small flat part on the end of the chamfer, as illustrated on Figure 65, which caused small air pockets to form between the inner and the outer skin. You can clearly see a silhouette of where the core material is on the crash nose, as the air pockets filled with epoxy and made the carbon fiber in these areas dry.

Figure 66 Dry areas around the core material due to poor core chamfering

The nose weighed in at around 750 grams, which is good seeing that the nose is a lot bigger than last year. The weight was low because there was no need for using adhesive film to apply the core to the outer skin, and there were also very few reinforcement plies in the crash nose.

7.3. First crash test

The crash tests took place at the facilities of Benteler Automotive in Raufoss. Benteler mainly produce aluminum bumpers for the automobile industry. The weight of the sledge was 1017 kg, and the speed was therefore adjusted in order to maintain the correct amount of energy specified by the rule set of 7350 kJ. The needed speed was 3.8 m/s, but to accommodate inaccuracies on the machine the speed was set to 3.9 m/s, or 14 km/t.

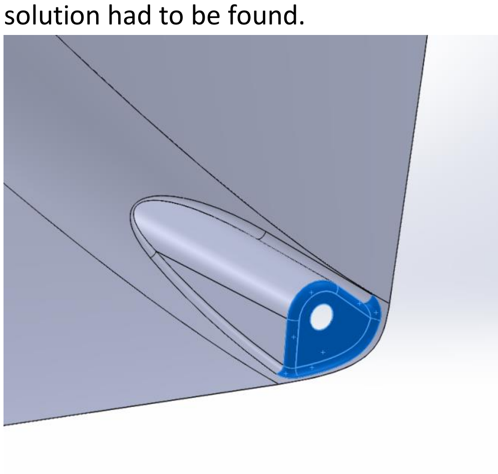
Seeing that the edge of the nose was extremely dry and uneven, as well as having dry spots in the laminate all over, a futile attempt was made to salvage the nose using a considerable amount of epoxy. The result can be seen on Figure 67.

Figure 67 Epoxy used to cover dry araes

The crash went exactly as one might expect; the nose failed completely. The edges of the nose tore diagonally in the corners once it reached the area of the nose with core material (see Figure 68), where most of the energy is supposed to be absorbed. This meant that close to no energy was absorbed during the test, and there was no point in analyzing the data.

Figure 68 Crash nose post-crash

Another area problem that became apparent after the test, was that the flat surface around the bolt holes had torn off completely (see Figure 69). After the crash test, you could see these four surfaces (one for each bolt hole) still sitting left on the crash rig around the bolts, even though the rest of the crash nose lay on the floor. The cause for this was attributed to the fact that this was a very difficult area to Fibersim. Normally, you would want the split lines of two layers of carbon fiber on top of each other to be at least 18 mm apart (10) (KDA even normally operate with 50 mm). This is done so that you do not get weak areas with only epoxy. Unfortunately, due to the extremely difficult curvature in the pits around the bolt holes, it was close to impossible to create flat patterns that did not warp in Fibersim for that area. This was a known problem before the production even started, but it was thought to be manageable because some of the split lines were about 5 mm away from each other. The crash test proved otherwise, and a new solution had to be found.



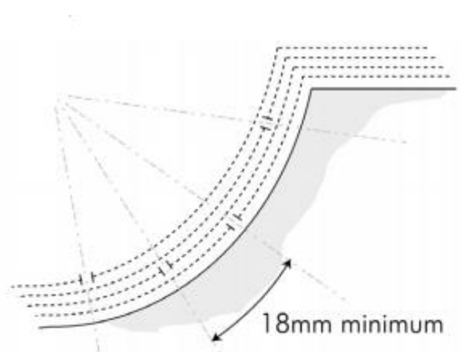


Figure 70 Minimum required overlap

Figure 69 Aforementioned area

7.4. Production second impact attenuator

Even though the first test failed, there was a lot of knowledge generated on how to improve the next crash nose. The root of all the problems was of course the lack of time to produce the crash nose, and thereby lack of time to think through and fix problems that occurred during production. Therefore it fit perfectly that the only time in the nearest future the test facility were able to run another crash test, was one week later. This allowed a much more thorough production process.

This time around, the cure was done in two steps. First, the outer skin of the crash nose was cured at a much higher pressure of 6.2 Bar, compared to the cure on the first crash nose that was cured at 2.5 Bar. This was possible due to there not being any risk for crushing the core material. The high pressure created a strong laminate where the layers were packed very well together, which was especially important in the corners where the previous nose had failed. Due to there not being any core material there, the vacuum bag could apply pressure easily to the whole elevated surface around the bolt holes. The high pressure also provided excellent surface finish on the outside of the crash nose. After the first cure, the core material was attached using adhesive film and the plies for the inner skin were placed. The nose then went back in the autoclave for its final cure on 2.5 Bar.

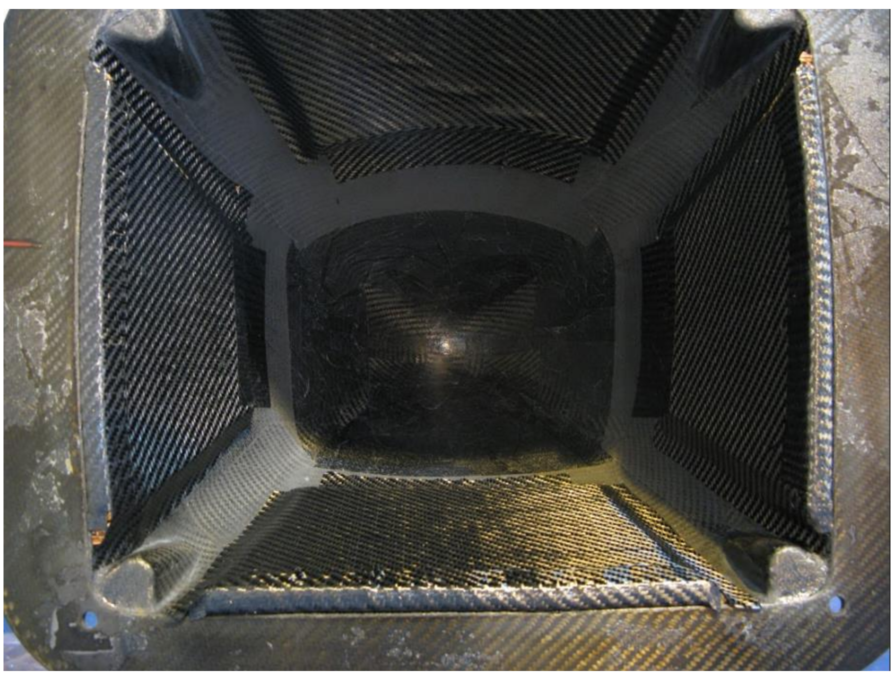


Figure 71 Second crash nose after first cure, with core material firmly in place

To solve the problem of dry spots in the corners of the crash nose, pressure amplifiers made out of bag tape wrapped in Teflon tape were placed in each corner around the bolt holes. This easily deformable package was pressed into the corners to make sure that it filled every nook and cranny. During the cure, the vacuum bag would then press against these amplifiers, which ensured proper pressure even in the hard to reach spots.

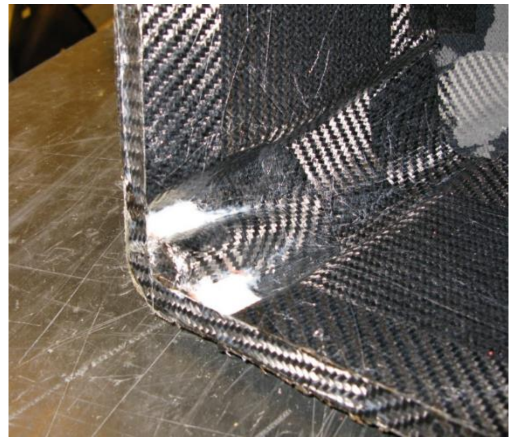


Figure 72 Pressure amplifiers

The plies that were originally meant to cover the flat surface around the bolt holes were also thrown away and replaced with hand cut ones instead, approximately in the shape illustrated below to the left on Figure 73. The bottom part of the ply was placed onto the flat surface, and the “arms” were wrapped around the rest of the elevated surface around the bolt holes. This ensured a much higher contact area than before, which limited the chances of the ply tearing. Plies of the approximate shape of the figure to the right were then placed over the “arms”. This was done interchangeably in between the rest of the crash nose layup, to make sure that the edges of the plies did not land on top of each other.

Figure 73 Plies used around bolt holes

The problem of the bag not reaching the complete area of the flat surface around the bolt holes was also solved by applying several plies of carbon fiber until you reached the level of the rest of the edge on the nose. This way, when the tooling flange was assembled before the oven cure, it would apply mechanical pressure to the surface, and ensure good contact between the carbon fiber plies and therefore limiting the chances of the occurrence of dry spots.

By analyzing the video footage from the first test, you can see that the top of the crash nose goes over the top of the crash rig right before the nose tears completely. Therefore, a carbon fiber flange was also created all around the edge to increase the nose's second moment of area. This flange can be seen more clearly on Figure 75.

Figure 74 Top edge of crash nose going over the crash rig

The time the team had remaining at the production facilities of KDA was coming to an end, because Easter holiday was coming up, meaning that the whole production would shut down. Deadlines for documents concerning the crash nose was also approaching rapidly, and the next nose could not fail. Therefore, several reinforcement plies were added in, causing an increase in weight compared to the first crash nose. All in all, the second crash nose weighed 880 grams. There were no backup alternatives if the second crash nose test failed, other than maybe creating a very heavy aluminum anti-intrusion plate to mount a crash box on. This would have cost the team several kiloes of weight, meaning that it was better to add a couple of hundred grams of extra carbon fiber to be sure that the next crash test did not fail. There was of course no guarantee even with the extra plies, and the tension prior to crash test number two was high.

Figure 75 Finished crash nose during demould

7.5. Second crash test

The second crash test also took place at Benteler Automotive. This time, there was not a single dry spot on the entire nose, and the surface finish was impeccable. The problem with the poor core chamfering had been solved using a circular sander on the edges of the core, allowing perfect chamfering all the way and leaving no flat areas at the end of the core (as describe in Figure 65).

The test was run exactly like last time, at a speed of 14 km/t. As you can see from the pictures below, the test performed well, even leaving about 90 mm of the nose remaining at the bottom. This was also the area with the most fiber, meaning that there was a huge potential for saving weight on the next crash test attempt.

Figure 78 Second crash nose

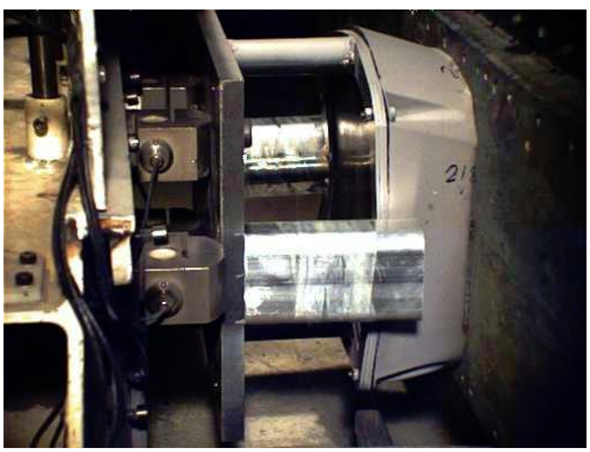


Figure 77 Top edge not going over the edge of crash rig

Figure 76 Second crash nose post-crash

7.6. Second crash test results

The test facility used a trolley with four load sensors. Adding the four load readings gave the total force occurring and the time history for the force is shown in the graphs below. Both the requirement of at least 7350 Joule of absorbed energy and a peak deceleration of 120 kN and average deceleration of 60 kN is satisfied.

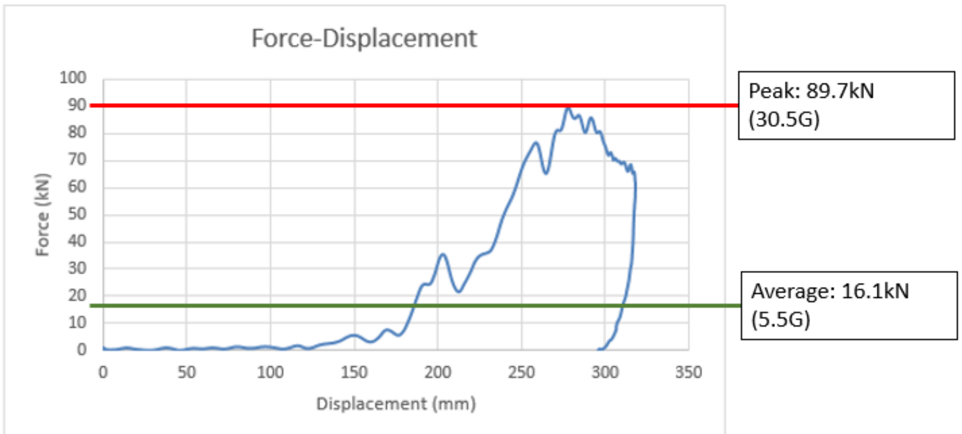


Figure 79 Force-Displacement graph

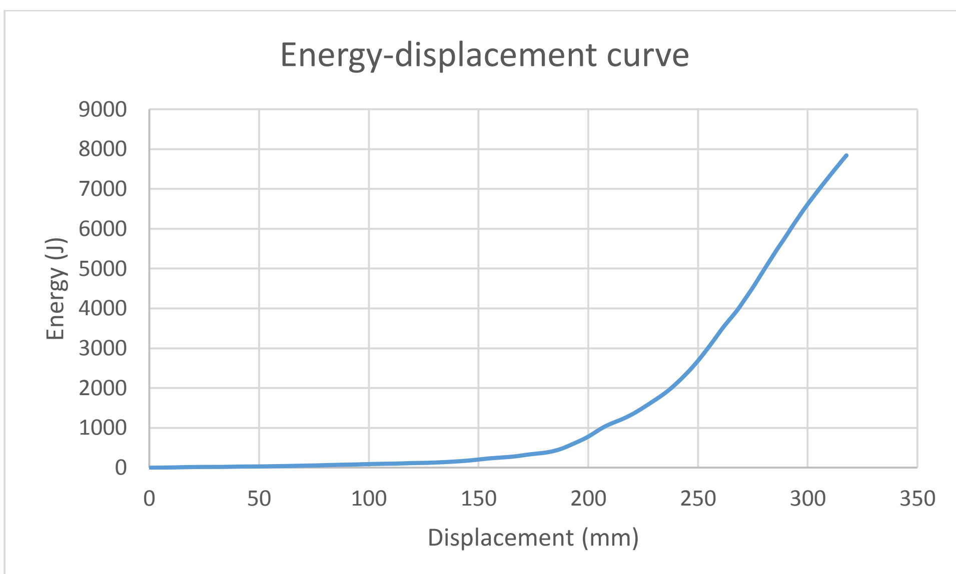


Figure 80 Energy-displacement graph

The deceleration-time graph was calculated as if the sledge weighed 300 kg. This is the weight used as an example in the rules of the competition, which is a fairly good approximation compared to what the car is expected to weigh when it is finished (with the driver included).

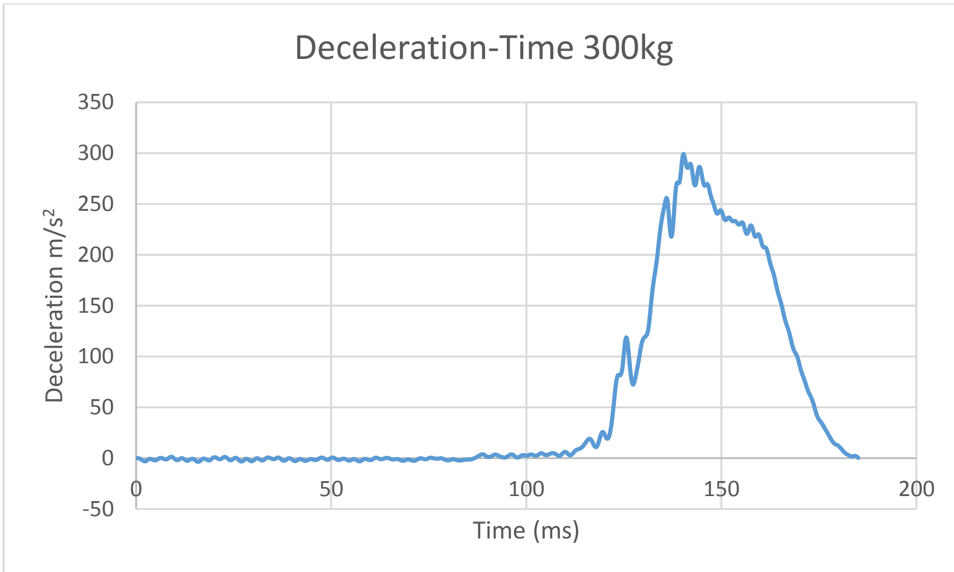


Figure 81 Deceleration-time graph

7.7. Third crash test

After the second crash test, it became clear that neither Benteler Automotive nor NTNU SIMLab (which were the only possible test locations) had room in their busy schedule right before Easter for another test. Therefore, the team had no other choice than to reproduce the nose that passed the test and put that one on the car.

There are however certainly several areas of improvement that could have been done, had the team had the opportunity of another attempt. Seeing that there were about 90 mm left of the nose after the crash, there is definitely room for improvement.

As the forces from the crash presses the bottom of the crash nose outwards, the outer skin is presumably of higher importance than the inner skin. Coupled with the fact that you had such a large part of the nose left after the crash, removing layer 5 and 6 (see Figure 83 and Figure 82) should not present too much of a problem.

Another viable option could be to make the core material smaller. This would both save weight by using less core material, as well as not needing to use as much reinforcement plies to attach the core, because layer 4 would then have covered the whole core. As things were now, you needed reinforcement plies around the whole edge of the core material in order to get the ply to stay down while you were working on the layup.

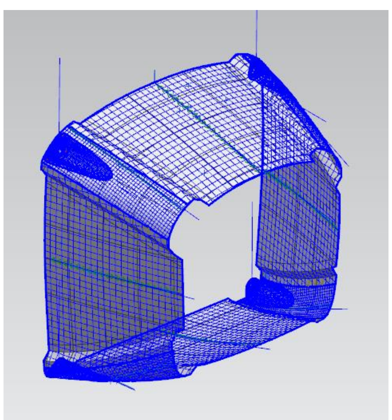


Figure 84 Layer 4

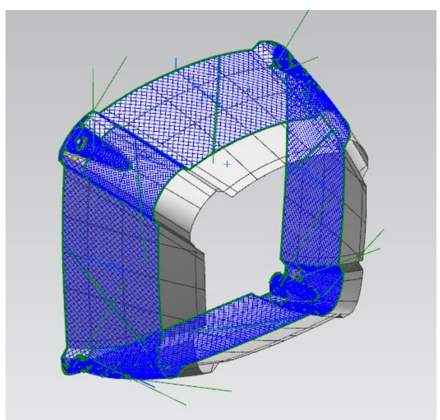


Figure 83 Layer 5

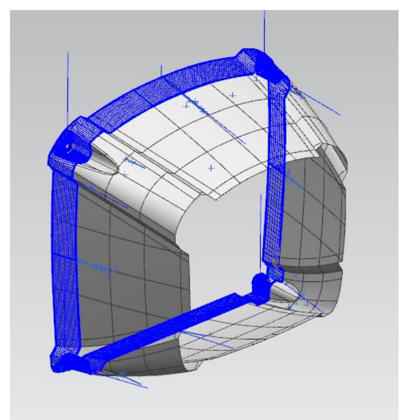


Figure 82 Layer 6

8. Finalizing phase

Unlike many of the other areas of responsibility on the car, the finalizing phase for the crash nose is not a very demanding one. The work mainly consisted of creating holes in the crash nose for the bolts, as well as chamfering the edges of the anti-intrusion plate to fit the curvature between the crash nose and the chassis. The crash nose and the anti-intrusion plate was then sent to the auto-repair shop for painting.

Figure 85 Crash nose before decals were applied

The rather low work load compared to many other system freed up some time, making it possible for the author to help out on other systems that needed attention. In many ways, having the responsibility for the impact attenuator is very diverse, because you need to be done with your project before the Easter holiday to reach the deadlines for the safety reports that need to be handed in to each competition the team participates in. This allows the impact attenuator engineer to work on many different things in the months following the Easter holiday. Among other things, this year that included the accumulator protection, seat, inverter casing, firewall and back wall.

The reports mentioned above are called the Impact Attenuator Datasheet (IAD) reports. The IAD is meant as a document to prove that your solution for impact attenuator is in fact safe enough for use in the competition and that it has been made according to the rules of the competition. The template for what needs to be included varies from competition to competition. The IAD for Formula Student Germany (FSG) has been included in attachment 13.16.

9. Further work

There are several areas that could be improved for the development of the AIP and IA. The problem with crash testing composites, it that it requires an enormous economic investment for each crash test, not only in material cost, but also in manual labor and the use of production and testing facilities. Revolve NTNU was lucky enough to only have to pay for the material cost due to the rest being sponsored, but if one were to further develop the crash nose independently, one would have to pay for these utilities oneself. You could attempt to make small-scale crash noses to test the difference between layups and use for example a drop-tower test, but whether or not these tests are representative compared to a large-scale crash test is unlikely. Investment in both time and money would be needed to find a correlation between small-scale and large-scale tests. However, such knowledge would be very beneficial for future teams.

It should be attempted to use another core material, perhaps aluminum honeycomb or similar. It was supposed to be attempted to use a lighter core this year, but a mix-up in communication resulted in a heavier core as the only option. The core used was therefore more than likely too strong, as core tear did not appear to be a problem on the crash test. It should be an easy task to find a lighter and more suitable core material.

When it comes to the anti-intrusion plate, it is easier to point out areas for improvement. It should be relatively easy to both create test panels and run penetration and attachment point tests, seeing that these test panels are relatively small. This would enable you to rapidly figure out a more optimal layup for the laminate. If nothing else, one should at least be able to save several hundred grams of weight by choosing the correct fiber, and not use a fiber with the wrong thickness as what was used this time.

10. Conclusion

A considerable amount of time has been invested in finding the best solution for an impact attenuator and anti-intrusion plate combination for the Revolve NTNU 2016 racecar. Of the concepts that were investigated, a shell structured crash nosed proved to be the best solution in combination with the anti-intrusion plate by giving best protection of the driver and monocoque, the lightest weight and satisfying all regulatory requirements.

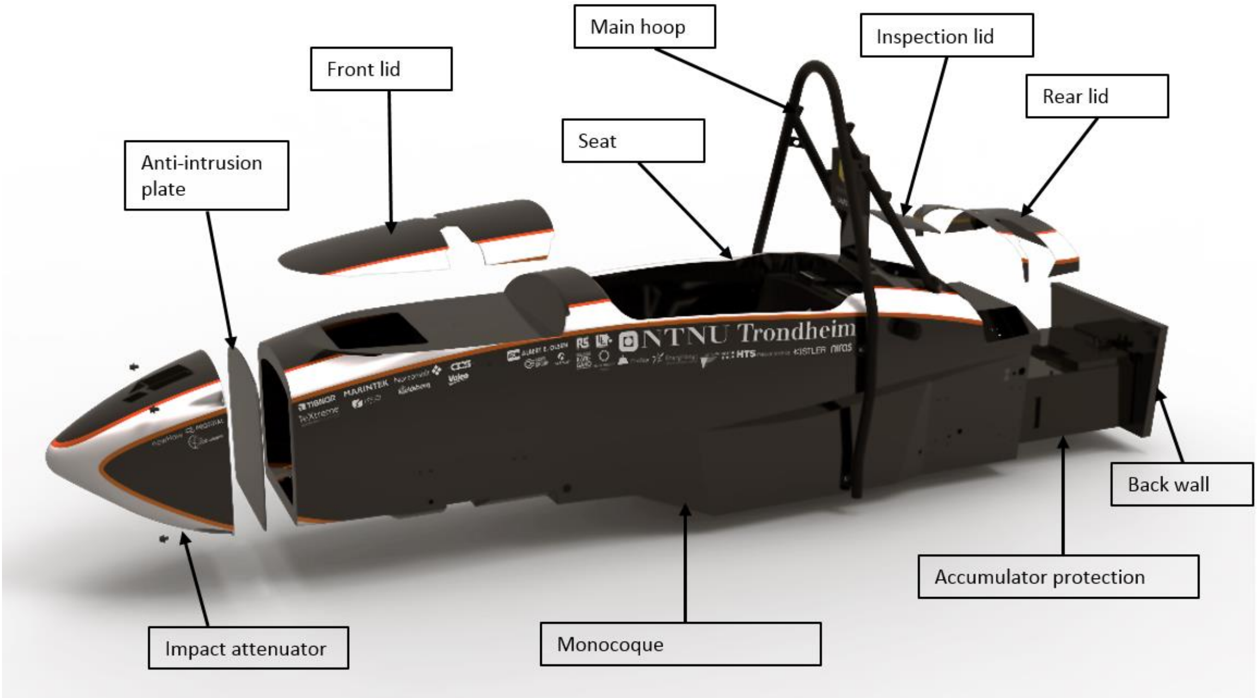
The calculations performed on the lay-up proved vital for moving forward to crash testing. It was estimated that 50 mm would be left of the crash nose after the crash. After running the test, 90 mm was left of the nose, meaning that the calculations were fairly accurate compared to the huge factor of uncertainty in any crash test. The weight of this years enlarged crash nose ended at a weight of 880 grams and was achieved through careful planning and good production methods. This represents an about 10% improvement in weight-to-volume over the 2015 crash nose, but fell short of the very ambitious goal of 700 grams.

The success of the second and final crash nose can be attributed to the failure of the crash test for the first nose. The first crash nose highlighted several areas that needed to be fixed, which allowed the second nose to pass the crash test with excellence. Both the regulatory requirement for energy absorption and deceleration was well within boundaries.

A significant weight reduction has been achieved by choosing to make the anti-intrusion plate from composites. To be allowed to use the composite AI plate in the competition, equivalency to 1.5 mm steel has been proved in 3-point bend, penetration and attachment point tests. This meant the team saved 700 grams on the AIP compared to having to make it in aluminum, as was done in previous years.

A large amount of information has been gathered and documented. This should give a good foundation for future impact attenuator engineers. Although designing a carbon fiber crash nose has been done before, it has at times been difficult to get help from previous IA engineers, as they often had forgotten how they solved specific problems. Hopefully, the work documented in this thesis will serve as a good help for the coming years.

11. Monocoque group areas of responsibility



(Inverter casing and dashboard not shown)

12. Final product

GNIST, REVOLVE NTNU 2016	
LENGTH	2907 mm
WIDTH	1413 mm
HEIGHT	1305 mm
WEIGHT	178.5 kg
ENGINE (ONE IN EACH WHEEL)	AMK / DD5-14-10-POW
HORSEPOWER	190
MAX MOTOR TORQUE (FROM EACH ENGINE)	21 Nm
TOP SPEED	112 kph
ACCELERATION 0-100 KPS	Estimated 2s
DOWNFORCE/DRAG AT 80 KPH	900 N/360 N
GEAR	Hub mounted compound planetary gear

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11. —. Tencate Mold Prep and Primer. [Online] http://www.tencate.com/emea/Images/Chemlease%C2%AE%20MPP%20712%20EZ_en%20(BDO260412)_041312_tcm28-27273.pdf.

13. Attachments

13.1. Collection of impact attenuator rules

T3.8 Composite Materials

T3.8.1 If any composite or other material is used, the team must present documentation of material type, e.g. purchase receipt, shipping document or letter of donation, and of the material properties. Details of the composite lay-up technique as well as the structural material used (cloth type, weight, and resin type, number of layers, core material, and skin material if metal) must also be submitted. The team must submit calculations demonstrating equivalence of their composite structure to one of similar geometry made to the minimum requirements found in Section T3.4.1. Equivalency calculations must be submitted for energy dissipation, yield and ultimate strengths in bending, buckling, and tension. Submit the completed "Structural Equivalency Spreadsheet" per Section T3.9.

T3.20 Impact Attenuator (IA)

T3.20.1 Forward of the Front Bulkhead must be an energy-absorbing Impact Attenuator.

T3.20.2 The Impact Attenuator must be:

a. Installed forward of the Front Bulkhead.

b. At least 200 mm (7.8 in) long, with its length oriented along the fore/aft axis of the Frame.

c. At least 100 mm (3.9 in) high and 200 mm (7.8 in) wide for a minimum distance of 200 mm (7.8 in) forward of the Front Bulkhead.

d. Such that it cannot penetrate the Front Bulkhead in the event of an impact.

e. Attached securely and directly to the Front Bulkhead and not by being part of non-structural bodywork.

T3.20.3 On all cars, a 1.5 mm (0.060 in) solid steel or 4.0 mm (0.157 in) solid aluminum "anti-intrusion plate" must be integrated into the Impact Attenuator. If the Impact Attenuator and Anti-Intrusion Plate (Impact Attenuator Assembly) are bolted to the Front Bulkhead, it must be the same size as the outside dimensions of the Front Bulkhead. If it is welded to the Front Bulkhead, it must extend at least to the centerline of the Front Bulkhead tubing in all directions.

T3.20.4 Alternative designs of the anti-intrusion plate are permissible; equivalency to T3.20.3 must be proven as per T3.38.

T3.20.5 If the Impact Attenuator Assembly is not integral with the frame, i.e. welded, a minimum of four (4) 8 mm Metric Grade 8.8 (5/16 inch SAE Grade 5) bolts must attach the Impact Attenuator Assembly to the Front Bulkhead**.**

T3.20.6 The attachment of the Impact Attenuator Assembly must be constructed to provide an adequate load path for transverse and vertical loads in the event of off-center and off-axis impacts. NOTE: Segmented foam attenuators must have the segments bonded together to prevent sliding or parallelogramming

T3.20.7 The attachment of the Impact Attenuator Assembly to a monocoque structure requires an approved "Structural Equivalency Spreadsheet" per Article T3.9 that shows equivalency to a minimum of four (4) 8 mm Grade 8.8 (5/16 inch Grade 5) bolts.

T3.20.8 If a team uses the "standard" FSAE Impact Attenuator, and the outside edge of the Front Bulkhead extends beyond the Impact Attenuator Assembly by more than 25.4 mm on any side, a diagonal or Xbrace made from 1.00" x 0.049" wall steel tubing, or an approved equivalent per T3.5, must be included in the Front Bulkhead.

T3.20.9 Where the standard IA is used but does not comply with edge distance limits of rule T3.20.8 and does not include a diagonal brace, physical testing must be carried out to prove that the Anti-Intrusion Plate does not permanently deflect more than 25.4mm (1.00 inch).

T3.21 Impact Attenuator Data Requirement

T3.21.1 All teams, whether they are using their own design of IA or the "standard" FSAE Impact Attenuator, must submit an Impact Attenuator Data Report using the Impact Attenuator Data (IAD) Template found at "Downloads" at http://www.fsaeonline.com.

T3.21.2 The team must submit test data to show that their Impact Attenuator Assembly, when mounted on the front of a vehicle with a total mass of 300 kg (661 lbs.) and run into a solid, non-yielding impact barrier with a velocity of impact of 7.0 meters/second (23.0 ft/sec), would give an average deceleration of the vehicle not to exceed 20 g's, with a peak deceleration less than or equal to 40 g's. Total energy absorbed must meet or exceed 7350 Joules.

NOTE 1: These are the attenuator functional requirements not test requirements. Quasi-static testing is allowed.

NOTE 2: The calculations of how the reported absorbed energy, average deceleration, and peak deceleration figures have been derived from the test data MUST be included in the report and appended to the report template.

T3.21.3 Teams using a front wing must prove the combined Impact Attenuator Assembly and front wing do not exceed the peak deceleration of rule T3.21.2. Teams can use the following methods to show the designs does not exceed 300 kg times 40g or 120 kN:

a. Physical testing of the Impact Attenuator Assembly with wing mounts, links, vertical plates, and a structural representation of the aerofoil section to determine the peak force. See fsaeonline.com FAQs for an example of the structure to be included in the test.

b. Combine the peak force from physical testing of the Impact Attenuator Assembly with the wing mount failure load calculated from fastener shear and/or link buckling. c. Combine the Standard Impact Attenuator peak load of 95kN with the wing mount failure load calculated from fastener shear and/or link buckling.

T3.21.4 When using acceleration data, the average deceleration must be calculated based on the raw data. The peak deceleration can be assessed based on the raw data, and if peaks above the 40g limit are apparent in the data, it can then be filtered with a Channel Filter Class (CFC) 60 (100 Hz) filter per SAE Recommended Practice J211 "Instrumentation for Impact Test", or a 100 Hz, 3rd order, low pass Butterworth (-3dB at 100 Hz) filter.

T3.21.5 A schematic of the test method must be supplied along with photos of the attenuator before and after testing.

T3.21.6 The test piece must be presented at technical inspection for comparison to the photographs and the attenuator fitted to the vehicle.

T3.21.7 The test data and calculations must be submitted electronically in Adobe Acrobat ® format (*.pdf file) to the address and by the date provided in the Action Deadlines provided on the relevant competition website. This material must be a single file (text, drawings, data or whatever you are including).

T3.21.8 The Impact Attenuator Data must be named as follows: carnumber_schoolname_competition code_IAD.pdf using the assigned car number, the complete school name and competition code [Example: 087_University of SAE_FSAEM_IAD.pdf] Competition Codes are listed in Rule A.2.6

T3.21.9 Teams that submit their Impact Attenuator Data Report after the due date will be penalized 10 points per day up to a maximum of 50 points, which will be taken off the team's Total Score.

T3.21.10 Impact Attenuator Reports will be evaluated by the organizers and the evaluations will be passed to the Design Event Captain for consideration in that event.

T3.21.11 During the test, the Impact Attenuator must be attached to the Anti-Intrusion plate using the intended vehicle attachment method. The anti-intrusion plate must be spaced at least 50 mm (2 inches) from any rigid surface. No part of the anti-intrusion plate may permanently deflect more than 25.4 mm (1 inch) beyond the position of the anti-intrusion plate before the test. The anti-intrusion plate must be attached to a structurally representative section of the intended chassis that extends a minimum of 50.8mm (2 inches) away from the Front Bulkhead.

NOTE 1: The 25.4 mm (1 inch) spacing represents the front bulkhead support and insures that the plate does not intrude excessively into the cockpit.

NOTE 2: A solid block of material in the shape of the front bulkhead is not "structurally representative". A structurally representative test fixture should have a similar cross sectional moment of inertia as the actual front bulkhead.

T3.21.12 Dynamic testing (sled, pendulum, drop tower, etc.) of the impact attenuator may only be done at a dedicated test facility. The test facility may be part of the University but must be supervised by professional staff or University faculty. Teams are not allowed to construct their own dynamic test apparatus. Quasi-static testing may be performed by teams using their universities facilities/equipment, but teams are advised to exercise due care when performing all tests.

T3.21.13 Standard Attenuator – An officially approved impact attenuator can be found in Appendix T-3. Teams that choose to use the "standard" FSAE Impact Attenuator and the corresponding mounting details need not submit test data with their IAD Report. However, the other requirements of the IAD Report must still be submitted including, but not limited to: a. Use of the standard IA Data Report form. b. Photos of the team's actual attenuator with evidence that it meets the design criteria given in Appendix T-3, e.g., a receipt or packing slip from the supplier. c. The dimensions of their Impact Attenuator anti-intrusion plate. d. Whether or not the team will be using a front wing in which case front wing mount strength calculations are required per rule T3.21.3.

T3.30.3 Primary structure laminate other than side impact – Teams must build representative test panels for each ply schedule used in the regulated regions of the monocoque as a flat panel and perform a 3 point bending test on these panels. The test panels must measure 275mm (10.8") x 500 mm (19.7"). The data from these tests and pictures of the test samples must be included in the SES, the test results will be used to derive strength and stiffness properties used in the SES formula for all laminate panels. The test specimen must be presented at technical inspection.

T3.30.4 The load applicator used to test any panel/tubes as required by T3.30.1, T3.30.2, or T3.30.3 must be metallic and have a radius of 50mm (2 inch). The load applicator shall overhang the test piece to prevent edge loading. It is not acceptable to place any other material between the load applicator and the items on test.

T3.30.5 Perimeter shear tests must be completed by measuring the force required to push or pull a 25mm (1") diameter flat punch through a flat laminate sample. The sample, measuring at least 100mm x 100mm (3.9" x 3.9"), must have core and skin thicknesses identical to those used in the actual monocoque and be manufactured using the same materials and processes. The fixture must support the entire sample, except for a 32mm (1.25") hole aligned co-axially with the punch. The sample must not be clamped to the fixture. The force-displacement data and photos of the test setup must be included in the SES. The first peak in the load-deflection curve must be used to determine the skin shear strength; this may be less than the minimum force required by T3.33.3/T3.34.4. The maximum force recorded must meet the requirements of T3.33.3/T3.34.4. N: The edge of the punch and hole in the fixture may include an optional fillet up-to a maximum radius of 1mm (0.040").

T3.37 Monocoque Impact Attenuator Attachment

The attachment of the Impact Attenuator to a monocoque structure requires an approved "Structural Equivalency Spreadsheet" per Rule T3.9 that shows the equivalency to a minimum of four (4) 8 mm Metric Grade 8.8 (5/16 inch SAE Grade 5) bolts.

T3.38 Monocoque Impact Attenuator Anti-intrusion Plate

T3.38.1 Composite AI plates must not fail in a frontal impact. Strength of the AI plate must be verified by physical testing or a combination of physical testing and analysis. All physical test results and any analysis completed must be included in the SES.

T3.38.2 Strength of composite AI plates may be verified by physical testing under rules T3.21.2 and T3.21.3.

T3.38.3 Strength of composite AI plates may be verified by laminate material testing and calculations of 3 point bending and perimeter shear analysis. Composite laminate materials must be tested under T3.30.3 and T3.30.5. Analysis of the AI plate under 3-point bending must show the AI plate does not fail under a static load of 120 kN distributed over 150mm of length, and perimeter shear analysis must show each attachment can hold 20 kN in any direction.

13.2. Conversation with Ulf Steinfurth

Message Steinfurth, Ulf | 2015-11-16 11:53:41

Exactly these points are required.

Please note that you have to make a advice in your IA report where the reviewer can find the results.

Message Mork, Terje | 2015-11-14 13:10:16

Mr Steinfurth,

In our understanding the following must be achieved in order to prove that a composite AI plate will be approved for the competition:

1. Equivalence in 3-point bending as per your attached drawing "bend_AIP_01" (T3.38.3)
2. Equivalence in perimeter shear analysis (T3.30.5)
3. Composite AI plate must be included into the dynamic crash test of the Impact Attenuator (T3.21), and must not fail.
4. Equivalent strength in each attachment point (T3.38.3)
5. All results must be included in the SES.

Equivalence of the composite AI plate are proved with regards to a steel/aluminium AI plate.

Sincerely,

Terje Mork

Message Steinfurth, Ulf | 2015-11-11 15:43:55

No, the AI plate made of CFRP structure must be included the dynamic test (refer point 2 of my prior answer).

Message Iversen, Roy | 2015-11-11 13:30:09

Mr. Steinfurth.

If we understand correctly based on your answer; if we test an aluminium/steel AIP in the test setup you provided and can prove equivalency or better results with a composite AIP (as long as it also passes shear analysis and the physical testing) this will be accepted in the IAD for FSG?

Best regards

Message Steinfurth, Ulf | 2015-11-09 12:11:32

Dear Team,
for FSG 2016 following rule will be implemented the FS Germany Rules valid for 2016 which will be presented next week:
4.3.3 Anti Intrusion Plate (AIP) Testing (Specific FS Germany change of Formula
SAE® 2016 Rule T3.38)
1. Equivalence of composite AIP to the baseline material (T3.20.3) must be shown by a physical test (T3.38.3). Results must be included in the SES
2. The composite AIP must be included the dynamic test of Impact Attenuator and must not fail.
3. A failure is defined if the IA plate is damaged in any way (e.g. broken) or the attachment points of AIP are destroyed.

Even if your AI plate does not handle that much load as required in T3.38.3 you have to show equivalence by using this test.
For the test set up please have a look to the attached picture.

Uploads

bend_AIP_01.jpg

13.3. Hexply M18/1

HexPly® M18/1

Prepreg Properties – HexPly® M18/1 UD and Woven Carbon Prepregs

Physical Properties

	Units	42% G947 UD	43% G939 Fabric
Fibre Density	g/cm³	1.78	1.78
Filament count/tow		3000	3000
Resin Density	g/cm³	1.22	1.22
Fibre areal weight	g/m²	160	220
Nominal Cured Ply Thickness	mm	0.165	0.227
Nominal Fibre Volume	%	55	55

Mechanical Properties

Test	Standard	Units	Temp (ºC)	Condition UD	42% G947 Fabric	43% G939
0° Tensile Strength	EN2561	MPa	-55	Dry	1750	750
			RT	Dry	1750	800
			135	Wet	1700	800
90° Tensile Strength		MPa	RT	Dry	55	800
0° Tensile Modulus	EN2561	GPa	-55	Dry	127	67
			RT	Dry	128	65
			135	Wet	133	67
90° Tensile Modulus		GPa	RT	Dry	9.3	67
0° Compression Strength	EN2850 Type A	MPa	-55	Dry	1500	850
			RT	Dry	1200	800
			135	Wet	750	500
90° Compression Strength		MPa	RT	Dry	220	800
0° Compression Modulus	EN2850 Type A	GPa	-55	Dry	121	62
			RT	Dry	121	64
			135	Wet	121	63
90° Compression Modulus		GPa	RT	Dry	10.2	62
0° ILSS (Short beam shear)	EN2563	MPa	RT	Dry	95	70
			75	Wet	65	56
			135	Wet	50	40
In-plane Shear Strength	EN6031	MPa	RT	Dry	95	100
			75	Wet	90	85
			135	Wet	70	65

Wet : 1 week at 70°C 95% relative humidity (RH) and 3 weeks at 70°C 85% RH

These are values obtained on a 55% fibre volume content laminate (i.e. a cured ply thickness of approx. 0.165mm with G947 and 0.227 mm with G939).

HEXCEL

13.4. Abaqus inputs

Abbreviation	Explanation
E1, E2	Young's moduli X- and Y-direction
V12	Poisson's ratio
G12, G13, G23	Shear moduli XY-, XZ- and YZ-plane
S1T	Tensile stress limit in the fiber direction
S1C	Compressive stress limit in the fiber direction
S2T	Tensile stress limit in the transverse direction
S2C	Compressive stress limit in the transverse direction
Shear	Shear strength in X-Y plane

13.5. Rule clarification

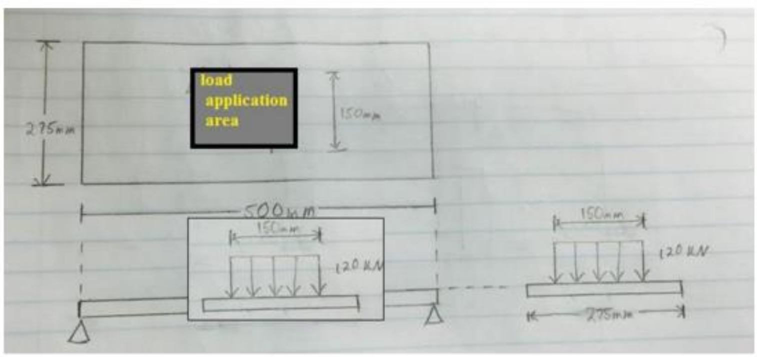
Dear Team,

for FSG 2016 following rule will be implemented the FS Germany Rules valid for 2016 which will be presented next week:
4.3.3 Anti Intrusion Plate (AIP) Testing (Specific FS Germany change of Formula
SAE® 2016 Rule T3.38)

1. Equivalence of composite AIP to the baseline material (T3.20.3) must be shown by a physical test (T3.38.3). Results must be included in the SES
2. The composite AIP must be included the dynamic test of Impact Attenuator and must not fail.
3. A failure is defined if the IA plate is damaged in any way (e.g. broken) or the attachment points of AIP are destroyed.

Even if your AI plate does not handle that much load as required in T3.38.3 you have to show equivalence by using this test.

For the test set up please have a look to the attached picture.



13.6. SES Material input

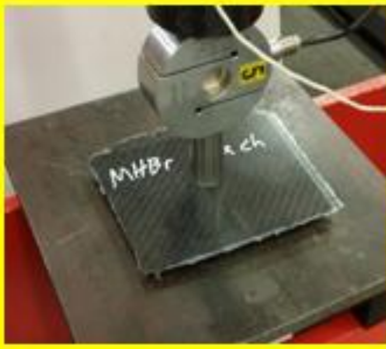
Material Data Sheet

Material Spreadsheet Code	Steel	Aluminium 1
Material name	Steel	Aluminium 1
Youngs Modulus, E	2,00E+11	7,00E+10
Yield strength, Pa	3,05E+08	2,50E+08
UTS, Pa	3,65E+08	3,50E+08
Yield strength, welded, Pa	1,80E+08	1,25E+08
UTS welded, Pa	3,00E+08	1,75E+08
UTS shear, Pa	2,19E+08	2,02E+08

13.7. 10 ply penetration test

2015 FSAE™ SES - OTHER MATERIAL "X" SHEAR TEST RESULTS

University Name rwegian University of Science and Technol Car No.(s) & Event(s) 08 at FSUK & E08 at FSA



mages of test setup here

specimens must be present

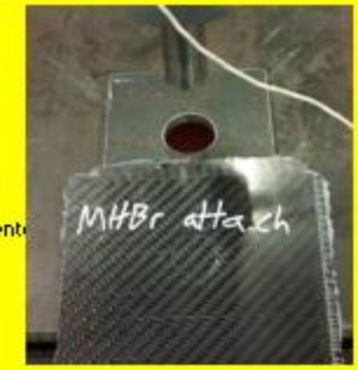


Figure 1: Test setup

Figure 2: Load Deflection Curve

Enter values for force at first and second peak (see monocoque guidance tab)

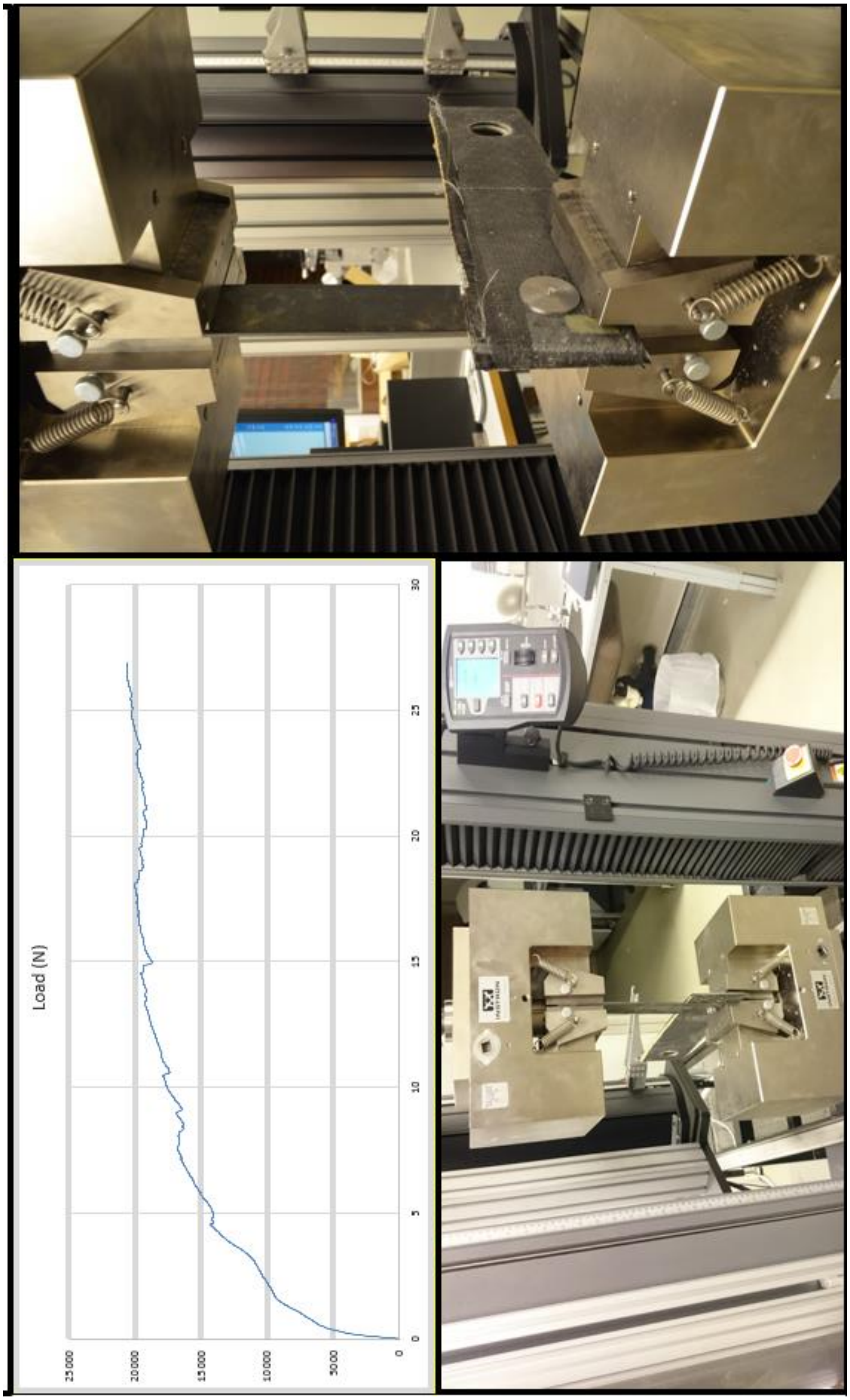
y_{max} (N) 33140

Enter details of skin thickness

t (mm) 2,00

σ_{shear} (Mpa) 211,0 Shear strength of skin, used for attachment calcs where appropriate

13.8. ION Racing Attachment point test



13.9. Tencate E745

TECHNICAL DATA

TENCATE

TENCATE ADVANCED COMPOSITES

TenCate E745

Mid temperature curing toughened epoxy component prepreg

PRODUCT TYPE

275°F (135°C) cure

Mid temperature curing toughened epoxy component prepreg

TYPICAL APPLICATIONS

- Side impact structures
- F1 nose boxes
- Mechanically demanding structural applications

SHELF LIFE

Out life
60 days at @ 20°C (68°F)

Storage life
12 months @ -18°C (0°F)

Out life is the maximum time allowed at room temperature before cure.

To avoid moisture condensation:
Following removal from cold storage, allow the prepreg to reach room temperature before opening the polythene bag. Typically the thaw time for a full roll of material will be 4 to 6 hours.

PRODUCT DESCRIPTION

TenCate E745 is a toughened epoxy resin system developed for impact structures and other mechanically demanding structural applications. The resin system cures at 135°C (275°F) and can be impregnated into a range of fibre and fabric types.

TENCATE E745 PREPREG BENEFITS/FEATURES

- Excellent tack and drape
- 1 hour at 135°C (275°F) cure
- High toughness and impact properties
- 60 days shelf life at ambient temperature
- Excellent surface finish
- Low volatile content - no solvents used during processing

TYPICAL NEAT RESIN PROPERTIES

Density .... 1.24 g/cm³ (77.4 lbs/ft³) at 23°C (73°F)

Tg (DMTA) after 1 hr at 135°C (275°F) .... Onset: 118°C (244.4°F); Peak tan δ: 131°C (267.8°F)

TYPICAL LAMINATE PROPERTIES

GIC (J/m²) .... 1,137 J/m²

SEA (Dynamic crush test)(J/g) .... 84.0 J/g

IM0223 - CARBON 200 GSM 2x2 TWILL IM7 GP 6K 42% R.W. CURED 1 HR AT 135°C (275°F)

Property	Condition	Method	Results	
Tensile Strength (Warp)*	RTD	ISO 527-4	1072 MPa	156 ksi
Tensile Modulus (Warp)*	RTD	ISO 527-4	75.9 GPa	11.0 Msi
Poisson's Ratio	RTD	ISO 527-4	0.04	
Tensile Strength (Weft)*	RTD	ISO 527-4	1130 MPa	164 ksi
Tensile Modulus (Weft)*	RTD	ISO 527-4	78.9 GPa	11.4 Msi
Poisson's Ratio	RTD	ISO 527-4	0.81	
Compression Strength (Warp)*	RTD	EN2580	717 MPa	104 ksi
Compression Modulus (Warp)*	RTD	EN2580	70.6 GPa	10.2 Msi
Compression Strength (Warp)*	RTD	EN2580	707 MPa	103 ksi
Compression Modulus (Weft)*	RTD	EN2580	71.4 GPa	10.4 Msi
In-Plane Shear Strength	RTD	ISO 14129	124 MPa	18 ksi
In-Plane Shear Modulus	RTD	ISO 14129	3.9 GPa	0.6 Msi
ILSS Warp	RTD	ISO 14130	70 MPa	10 ksi
ILSS Weft	RTD	ISO 14130	69 MPa	10 ksi

*Results normalized to 55% Vf, otherwise results are at actual 49.3% Vf

13.10. Suggested crash nose (shell) layup

Crash nose Revolve NTNU 2016

Material properties:		**Parameters:**	u	m	Requirement (J):	7350		
GIC (J/mm^2)	0,00113	Crush factor:	5 %	55 %	Energy in the system:	8026,92576	Total area (m^2):	0,4069981
SEA (J/g)	84	Fracture every (mm):	10				Length nose (mm):	403
Density (g/mm^3):	1,51E-03	Speed (m/s):	6,31		Total energy absorbation (J):	14285,18	Crushed length (mm):	310
Core weight:	125	Mass (kg):	403,2		Total weight (g):	433,65		
		1G:	9,80665		Average G:	0,45014201		
					Crash time:	0,08237		

Lende nese(mm):	Perimeter (mm):	Number of layers:	Thickness (mm):	Area (mm^2):	Volume (mm^3)	Weight (g)	Energy absorption (J):	Energy absorbation in nose (J)	Energy reduction:	Speed	Δv	Δt	Acceleration (m/s^2):	G-force:	Force (kN)
0	0,00	2	0,4	0,00	0,00	0,00	0,00	0,00	8026,93	6,310	0,000	0,00079	0,00000	0,00000	0,00000
5	121,74	2	0,4	48,70	243,48	0,37	1,54	1,54	8025,38	6,309	0,001	0,00079	0,76595	0,07810	0,30883
10	180,98	2	0,4	72,39	361,96	0,55	2,30	3,84	8023,09	6,308	0,001	0,00079	1,13867	0,11611	0,45911
15	223,93	2	0,4	89,57	447,86	0,68	2,84	6,68	8020,25	6,307	0,001	0,00079	1,40889	0,14367	0,56807
20	257,73	2	0,4	103,09	515,46	0,78	3,27	9,95	8016,98	6,306	0,001	0,00079	1,62155	0,16535	0,65381
25	286,52	2	0,4	114,61	573,04	0,87	3,63	13,58	8013,34	6,305	0,001	0,00079	1,80269	0,18382	0,72684
30	312,91	2	0,4	125,16	625,82	0,94	3,97	17,55	8009,37	6,303	0,002	0,00079	1,96873	0,20075	0,79379
35	337,89	2	0,4	135,16	675,78	1,02	4,29	21,84	8005,09	6,301	0,002	0,00079	2,12589	0,21678	0,85716
40	361,93	2	0,4	144,77	723,86	1,09	4,59	26,43	8000,50	6,300	0,002	0,00079	2,27714	0,23220	0,91814
45	385,30	2	0,4	154,12	770,60	1,16	4,89	31,32	7995,61	6,298	0,002	0,00079	2,42418	0,24720	0,97743
50	408,16	2	0,4	163,26	816,32	1,23	5,18	36,49	7990,43	6,296	0,002	0,00079	2,56801	0,26186	1,03542
55	430,61	2	0,4	172,24	861,22	1,30	5,46	41,95	7984,97	6,293	0,002	0,00079	2,70925	0,27627	1,09237
60	452,72	2	0,4	181,09	905,44	1,37	5,74	47,70	7979,23	6,291	0,002	0,00079	2,84836	0,29045	1,14846
65	474,56	2	0,4	189,82	949,12	1,43	6,02	53,72	7973,21	6,289	0,002	0,00079	2,98577	0,30446	1,20386
70	496,16	2	0,4	198,46	992,32	1,50	6,29	60,01	7966,92	6,286	0,002	0,00080	3,12167	0,31832	1,25866
75	517,53	2	0,4	207,01	1035,06	1,56	6,56	66,57	7960,35	6,284	0,003	0,00080	3,25613	0,33203	1,31287
80	538,71	2	0,4	215,48	1077,42	1,63	6,83	73,41	7953,52	6,281	0,003	0,00080	3,38938	0,34562	1,36660
85	559,67	2	0,4	223,87	1119,34	1,69	7,10	80,51	7946,42	6,278	0,003	0,00080	3,52126	0,35907	1,41977
90	580,44	2	0,4	232,18	1160,88	1,75	7,36	87,87	7939,06	6,275	0,003	0,00080	3,65194	0,37239	1,47246
95	600,99	2	0,4	240,40	1201,98	1,81	7,62	95,49	7931,43	6,272	0,003	0,00080	3,78123	0,38558	1,52459
100	621,33	2	0,4	248,53	1242,66	1,88	7,88	103,37	7923,55	6,269	0,003	0,00080	3,90920	0,39863	1,57619
105	641,45	2	0,4	256,58	1282,90	1,94	8,14	111,51	7915,42	6,266	0,003	0,00080	4,03579	0,41154	1,62723
110	661,25	2	0,4	264,50	1322,50	2,00	8,39	119,90	7907,03	6,263	0,003	0,00080	4,16036	0,42424	1,67746
115	680,74	2	0,4	272,30	1361,48	2,06	8,63	128,53	7898,40	6,259	0,003	0,00080	4,28299	0,43674	1,72690
120	699,92	2	0,4	279,97	1399,84	2,11	8,88	137,41	7889,52	6,256	0,004	0,00080	4,40366	0,44905	1,77556
125	719,23	2	0,4	287,69	1438,46	2,17	9,12	146,53	7880,40	6,252	0,004	0,00080	4,52516	0,46144	1,82454
130	738,38	2	0,4	295,35	1476,76	2,23	9,37	155,90	7871,03	6,248	0,004	0,00080	4,64564	0,47372	1,87312
135	757,12	2	0,4	302,85	1514,24	2,29	9,60	165,50	7861,43	6,245	0,004	0,00080	4,76355	0,48575	1,92066
140	775,50	2	0,4	310,20	1551,00	2,34	9,84	175,34	7851,59	6,241	0,004	0,00080	4,87919	0,49754	1,96729
145	793,64	2	0,4	317,46	1587,28	2,40	10,07	185,40	7841,52	6,237	0,004	0,00080	4,99332	0,50918	2,01331
150	811,54	2	0,4	324,62	1623,08	2,45	10,29	195,70	7831,23	6,233	0,004	0,00080	5,10594	0,52066	2,05871
155	829,13	2	0,4	331,65	1658,26	2,50	10,52	206,21	7820,71	6,228	0,004	0,00080	5,21661	0,53195	2,10334
160	846,42	2	0,4	338,57	1692,84	2,56	10,74	216,95	7809,98	6,224	0,004	0,00080	5,32539	0,54304	2,14720
165	863,42	2	0,4	345,37	1726,84	2,61	10,95	227,90	7799,03	6,220	0,004	0,00080	5,43235	0,55395	2,19032
170	880,12	2	0,4	352,05	1760,24	2,66	11,16	239,06	7787,86	6,215	0,004	0,00080	5,53742	0,56466	2,23269
175	896,55	2	0,4	358,62	1793,10	2,71	11,37	250,44	7776,49	6,211	0,005	0,00080	5,64079	0,57520	2,27437
180	912,73	2	0,4	365,09	1825,46	2,76	11,58	262,01	7764,91	6,206	0,005	0,00081	5,74259	0,58558	2,31541
185	928,65	2	0,4	371,46	1857,30	2,80	11,78	273,79	7753,13	6,201	0,005	0,00081	5,84276	0,59580	2,35580
190	944,37	2	0,4	377,75	1888,74	2,85	11,98	285,77	7741,16	6,197	0,005	0,00081	5,94166	0,60588	2,39568
195	959,84	2	0,4	383,94	1919,68	2,90	12,17	297,94	7728,98	6,192	0,005	0,00081	6,03899	0,61581	2,43492
200	975,15	2	0,4	390,06	1950,30	2,94	12,37	310,31	7716,61	6,187	0,005	0,00081	6,13532	0,62563	2,47376
205	990,15	2	0,4	396,06	1980,30	2,99	12,56	322,87	7704,05	6,182	0,005	0,00081	6,22969	0,63525	2,51181

210	1004,82	2	0,4	401,93	2009,64	3,03	12,75	335,62	7691,31	6,177	0,005	0,00081	6,32199	0,64466	2,54903
215	1019,14	2	0,4	407,66	2038,28	3,08	12,93	348,54	7678,38	6,171	0,005	0,00081	6,41209	0,65385	2,58535
220	1033,16	3	0,6	619,90	3099,48	4,68	216,23	564,77	7462,16	6,084	0,088	0,00082	107,25492	10,93696	43,24518
225	1047,09	3	0,6	628,25	3141,27	4,74	219,14	783,91	7243,01	5,994	0,090	0,00083	108,70103	11,08442	43,82826
230	1060,93	3	0,6	636,56	3182,79	4,81	222,04	1005,95	7020,98	5,901	0,093	0,00084	110,13780	11,23093	44,40756
235	1074,60	3	0,6	644,76	3223,80	4,87	224,90	1230,85	6796,08	5,806	0,095	0,00085	111,55691	11,37564	44,97975
240	1088,09	3	0,6	652,85	3264,27	4,93	227,72	1458,57	6568,36	5,708	0,098	0,00087	112,95734	11,51844	45,54440
245	1101,36	3	0,6	660,82	3304,08	4,99	230,50	1689,07	6337,86	5,607	0,101	0,00088	114,33494	11,65892	46,09985
250	1114,41	3	0,6	668,65	3343,23	5,05	233,23	1922,30	6104,63	5,503	0,104	0,00090	115,68969	11,79707	46,64608
255	1127,25	3	0,6	676,35	3381,75	5,11	235,92	2158,22	5868,71	5,395	0,107	0,00092	117,02264	11,93299	47,18353
260	1139,91	3	0,6	683,95	3419,73	5,16	238,57	2396,78	5630,14	5,285	0,111	0,00094	118,33691	12,06701	47,71344
265	1152,38	3	0,6	691,43	3457,14	5,22	241,18	2637,96	5388,96	5,170	0,114	0,00096	119,63145	12,19901	48,23540
270	1164,69	3	0,6	698,81	3494,07	5,28	243,75	2881,72	5145,21	5,052	0,118	0,00098	120,90938	12,32933	48,75066
275	1176,79	3	0,6	706,07	3530,37	5,33	246,29	3128,00	4898,93	4,930	0,122	0,00100	122,16551	12,45742	49,25713
280	1188,75	4	0,8	951,00	4755,00	7,18	331,72	3459,72	4567,21	4,760	0,170	0,00103	164,54281	16,77870	66,34366
285	1200,58	4	0,8	960,46	4802,32	7,25	335,02	3794,74	4232,19	4,582	0,178	0,00107	166,18028	16,94567	67,00389
290	1212,18	4	0,8	969,74	4848,72	7,32	338,26	4132,99	3893,93	4,395	0,187	0,00111	167,78592	17,10940	67,65128
295	1223,66	4	0,8	978,93	4894,64	7,39	341,46	4474,45	3552,47	4,198	0,197	0,00116	169,37494	17,27144	68,29198
300	1234,99	4	0,8	987,99	4939,96	7,46	344,62	4819,08	3207,85	3,989	0,209	0,00122	170,94320	17,43136	68,92430
305	1246,16	4	0,8	996,93	4984,64	7,53	347,74	5166,81	2860,11	3,767	0,222	0,00129	172,48931	17,58901	69,54769
310	1257,18	4	0,8	1005,74	5028,72	7,59	350,81	5517,63	2509,30	3,528	0,239	0,00137	174,01467	17,74456	70,16271
315	1252,77	4	0,8	1002,22	5011,08	7,57	349,58	5867,21	2159,71	3,273	0,255	0,00147	173,40425	17,68231	69,91659
320	1263,03	4	0,8	1010,42	5052,12	7,63	352,45	6219,66	1807,27	2,994	0,279	0,00160	174,82440	17,82713	70,48920
325	1272,62	4	0,8	1018,10	5090,48	7,69	355,12	6574,78	1452,15	2,684	0,310	0,00176	176,15182	17,96249	71,02441
330	1283,31	5	1,0	1283,31	6416,55	9,69	447,63	7022,41	1004,52	2,232	0,452	0,00203	222,03937	22,64171	89,52627
335	1295,36	5	1,0	1295,36	6476,80	9,78	451,83	7474,25	552,68	1,656	0,576	0,00257	224,12427	22,85431	90,36690
340	1308,58	5	1,0	1308,58	6542,90	9,88	456,45	7930,69	96,23	0,691	0,965	0,00426	226,41160	23,08756	91,28916
345	1322,58	5	1,0	1322,58	6612,90	9,99	461,33	8392,02	0,00	0,000	0,691	0,01447	47,73551	4,86767	19,24696
350	1336,85	5	1,0	1336,85	6684,25	10,09	466,31	8858,33	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
355	1351,23	5	1,0	1351,23	6756,15	10,20	471,32	9329,65	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
360	1366,03	5	1,0	1366,03	6830,15	10,31	476,48	9806,13	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
365	1380,47	5	1,0	1380,47	6902,35	10,42	481,52	10287,66	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
370	1394,54	5	1,0	1394,54	6972,70	10,53	486,43	10774,09	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
375	1408,25	5	1,0	1408,25	7041,25	10,63	491,21	11243,46	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
380	1421,60	5	1,0	1421,60	7108,00	10,73	495,87	11739,33	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
385	1434,59	5	1,0	1434,59	7172,95	10,83	500,40	12239,73	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
390	1447,23	5	1,0	1447,23	7236,15	10,93	504,81	12744,54	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
395	1459,49	5	1,0	1459,49	7297,45	11,02	509,08	13253,62	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
400	1460,96	5	1,0	1460,96	7304,80	11,03	509,60	13763,22	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000
405	1433,80	5	1,0	1433,80	7169,00	10,83	500,12	14263,34	0,00	0,000	0,000	0,00000	0,00000	0,00000	0,00000

13.11. Suggested carbon fiber crash cone layup

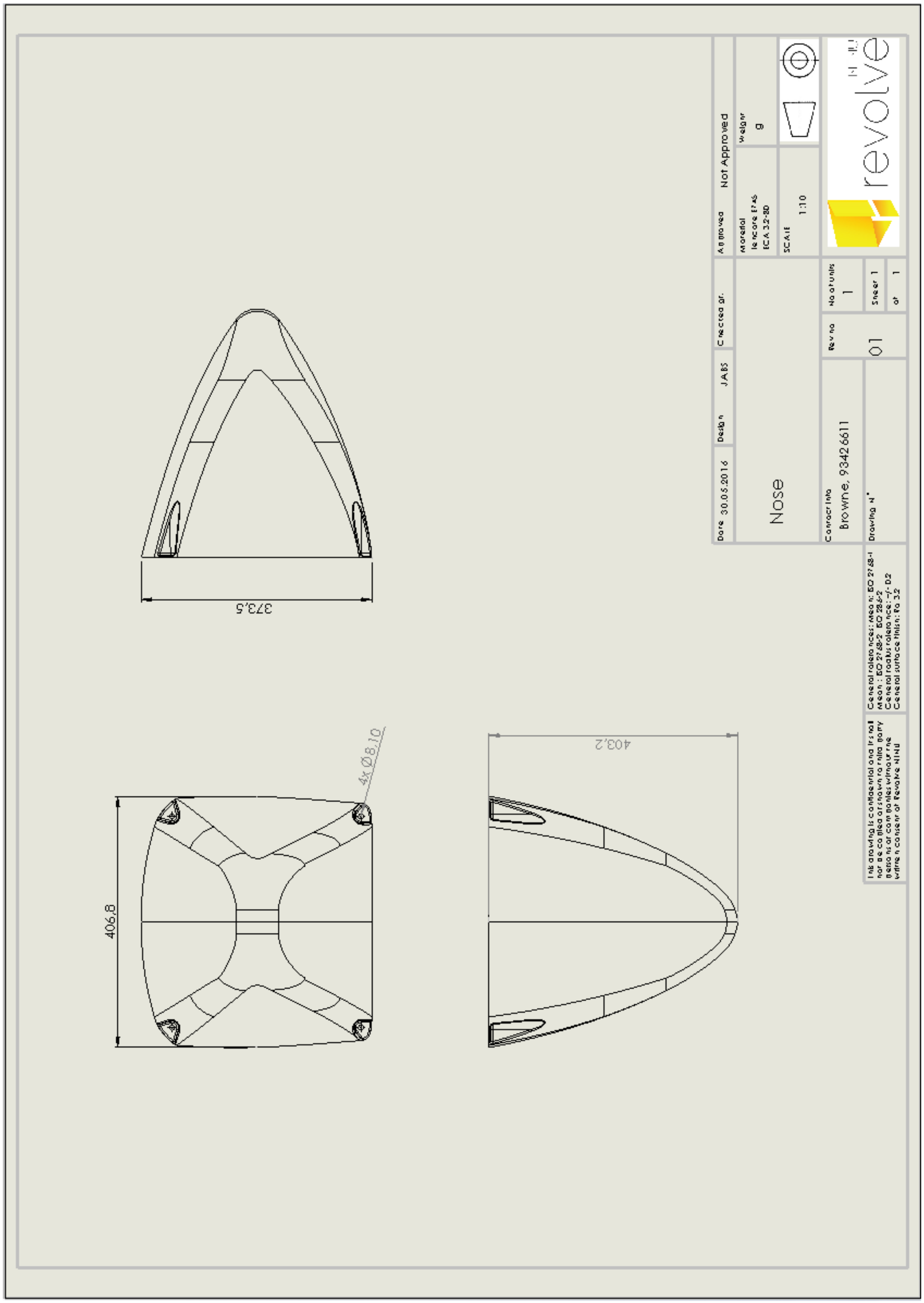
Crash box, Revolve NTNU 2016

Material properties:		Parameters:		u	m					
GIC (J/mm^2)	0,00113	Crush factor:		55 %	5 %	Requirement (J):	7350			
SEA (J/g)	84	Fracture every (mm):		10		Energy in the system:	8026,92576			
Density (g/mm^3):	1,24E-03	Speed (m/s):		6,31				Total area (m^2):	0,2237	
Core weight:	43	Mass (kg):		403,2		Total energy absorbation (J):	12964,39	Length nose (mm):	350	
		1G:		9,80665		Total weight (g):	327,06	Cruched length (mı	270	
						Average G:	6,548568179			
						Crash time:	0,07242			

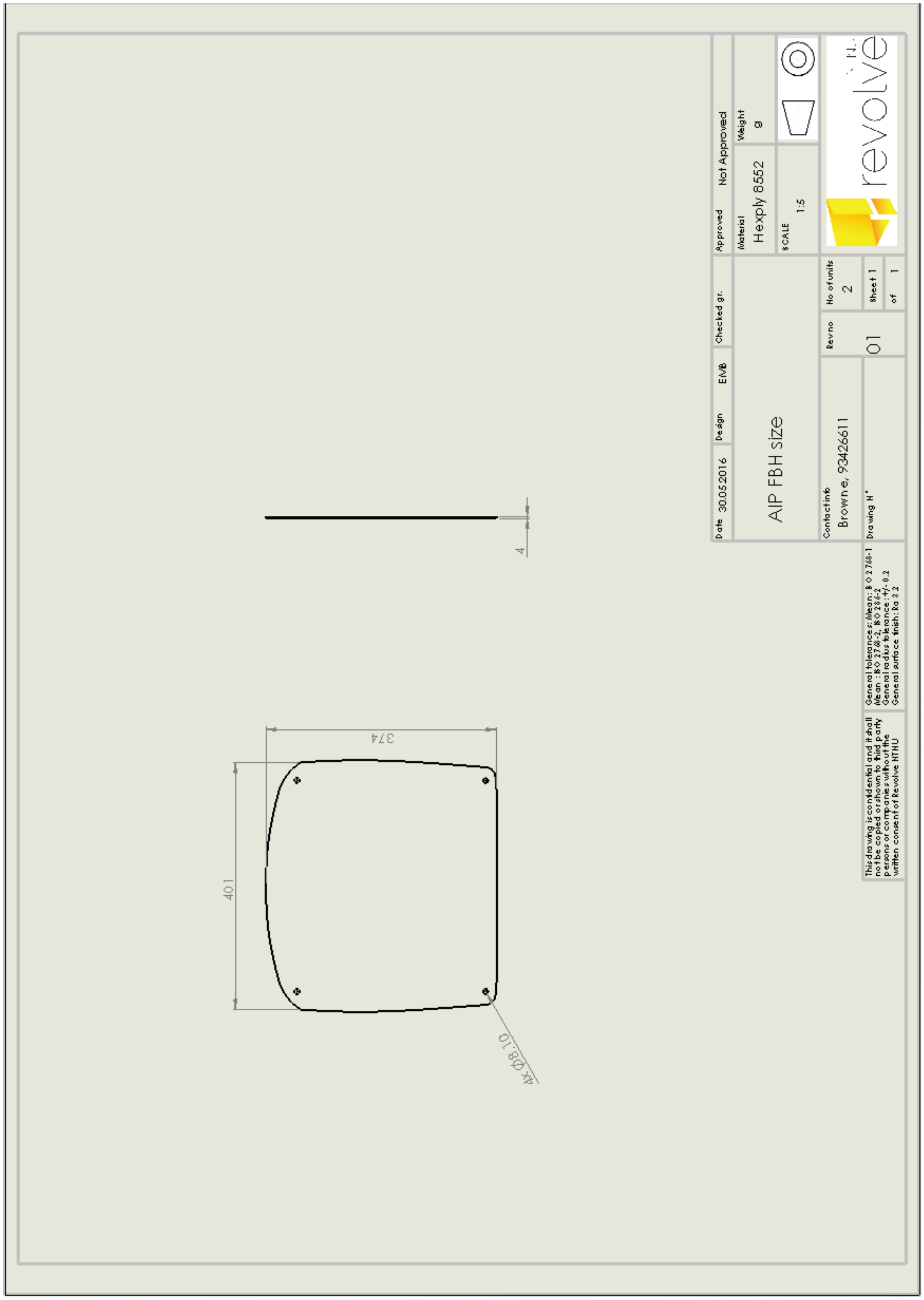
Lende nese(mm):	Perimeter (mm):	Number of layers:	Thickness (mm):	Area (mm^2):	Volume (mm^3)	Weight (g)	Energy absorption (J):	Energy absorbation in nose (J)	Energy reduction:	Speed	Δv	Δt	Acceleration (m/s^2):	G-force:	Force (kN)
0	0	2	0,4	0,00	0,00	0,00	0,00	0,00	8026,93	6,310	0,000	0,00079	0	0	0
5	38,22	2	0,4	15,29	76,44	0,09	0,40	0,40	8026,53	6,310	0,000	0,00079	0,19747	0,020136336	0,079619904
10	63,66	2	0,4	25,46	127,32	0,16	0,66	1,06	8025,86	6,310	0,000	0,00079	0,32891	0,033539486	0,132616512
15	89,10	2	0,4	35,64	178,20	0,22	0,93	1,99	8024,94	6,309	0,000	0,00079	0,46035	0,046942636	0,18561312
20	114,54	2	0,4	45,82	229,08	0,28	1,19	3,18	8023,74	6,309	0,000	0,00079	0,59179	0,060345786	0,238609728
25	139,98	2	0,4	55,99	279,96	0,35	1,46	4,64	8022,29	6,308	0,001	0,00079	0,72323	0,073748936	0,291606336
30	165,42	2	0,4	66,17	330,84	0,41	1,72	6,36	8020,56	6,307	0,001	0,00079	0,85467	0,087152086	0,344602944
35	190,86	2	0,4	76,34	381,72	0,47	1,99	8,35	8018,57	6,307	0,001	0,00079	0,98611	0,100555235	0,397599552
40	216,30	2	0,4	86,52	432,60	0,54	2,25	10,60	8016,32	6,306	0,001	0,00079	1,11755	0,113958385	0,45059616
45	241,74	2	0,4	96,70	483,48	0,60	2,52	13,12	8013,80	6,305	0,001	0,00079	1,24899	0,127361535	0,503592768
50	267,18	2	0,4	106,87	534,36	0,66	2,78	15,91	8011,02	6,304	0,001	0,00079	1,38043	0,140764685	0,556589376
55	292,62	2	0,4	117,05	585,24	0,73	33,53	49,43	7977,49	6,291	0,013	0,00079	16,63057	1,695846186	6,705445824
60	318,06	2	0,4	127,22	636,12	0,79	36,44	85,87	7941,05	6,276	0,014	0,00080	18,07641	1,843280835	7,288408512
65	343,50	2	0,4	137,40	687,00	0,85	39,36	125,23	7901,69	6,261	0,016	0,00080	19,52225	1,990715484	7,8713712
70	368,94	2	0,4	147,58	737,88	0,91	42,27	167,50	7859,42	6,244	0,017	0,00080	20,96809	2,138150133	8,454333888
75	394,38	2	0,4	157,75	788,76	0,98	45,19	212,69	7814,24	6,226	0,018	0,00080	22,41393	2,285584782	9,037296576
80	419,82	2	0,4	167,93	839,64	1,04	48,10	260,79	7766,13	6,207	0,019	0,00080	23,85977	2,433019431	9,620259264
85	445,26	2	0,4	178,10	890,52	1,10	51,02	311,81	7715,12	6,186	0,020	0,00081	25,30561	2,58045408	10,20322195
90	470,70	2	0,4	188,28	941,40	1,17	53,93	365,74	7661,19	6,165	0,022	0,00081	26,75145	2,727888729	10,78618464
95	496,14	2	0,4	198,46	992,28	1,23	56,85	422,58	7604,34	6,142	0,023	0,00081	28,19729	2,875323378	11,36914733
100	521,58	4	0,8	417,26	2086,32	2,59	119,52	542,10	7484,82	6,093	0,048	0,00082	59,28626	6,045516053	23,90422003
105	531,00	4	0,8	424,80	2124,00	2,63	121,68	663,78	7363,14	6,043	0,050	0,00082	60,357	6,154701147	24,3359424
110	539,41	4	0,8	431,53	2157,64	2,68	123,61	787,39	7239,53	5,993	0,051	0,00083	61,31293667	6,252179558	24,72137606
115	547,83	4	0,8	438,26	2191,32	2,72	125,54	912,93	7114,00	5,940	0,052	0,00084	62,27001	6,349773878	25,10726803
120	556,25	4	0,8	445,00	2225,00	2,76	127,47	1040,39	6986,53	5,887	0,053	0,00085	63,22708333	6,447368197	25,49316
125	564,67	4	0,8	451,74	2258,68	2,80	129,40	1169,79	6857,14	5,832	0,055	0,00085	64,18415667	6,544962517	25,87905197
130	573,08	5	1,0	573,08	2865,40	3,55	164,15	1333,94	6692,98	5,762	0,070	0,00086	81,42511667	8,303051161	32,83060704
135	581,50	5	1,0	581,50	2907,50	3,61	166,56	1500,51	6526,42	5,690	0,072	0,00087	82,62145833	8,42504406	33,312972
140	589,92	5	1,0	589,92	2949,59	3,66	168,98	1669,48	6357,44	5,616	0,074	0,00088	83,81739405	8,546995564	33,79517328
145	598,33	5	1,0	598,33	2991,67	3,71	171,39	1840,87	6186,06	5,539	0,076	0,00090	85,01332976	8,668947068	34,27737456
150	606,75	5	1,0	606,75	3033,76	3,76	173,80	2014,67	6012,26	5,461	0,078	0,00091	86,20926548	8,790898571	34,75957584
155	615,17	5	1,0	615,17	3075,84	3,81	176,21	2174,97	5836,05	5,380	0,081	0,00092	87,40520119	8,912850075	35,24177712
160	623,59	6	1,2	748,30	3741,51	4,64	214,34	2389,31	5621,71	5,281	0,100	0,00094	106,3213643	10,84176189	42,86877408
165	632,00	6	1,2	758,40	3792,02	4,70	217,24	2606,55	5404,47	5,178	0,103	0,00096	107,7564871	10,9881037	43,44741562
170	640,42	6	1,2	768,50	3842,52	4,76	220,13	2826,68	5184,34	5,071	0,107	0,00098	109,19161	11,1344455	44,02605715
175	648,84	6	1,2	778,60	3893,02	4,83	223,02	3049,71	4961,31	4,961	0,110	0,00100	110,6267329	11,28078731	44,60469869
180	657,25	6	1,2	788,71	3943,53	4,89	225,92	3275,62	4735,40	4,847	0,114	0,00102	112,0618557	11,42712911	45,18334022
185	665,67	6	1,2	798,81	3994,03	4,95	228,81	3504,43	4506,59	4,728	0,119	0,00104	113,4969786	11,57347092	45,76198176

190	674,09	6	1,2	808,91	4044,53	5,02	231,70	3736,14	4274,89	4,605	0,123	0,00107	114,9321014	11,71981272	46,3406233
195	682,51	6	1,2	819,01	4095,03	5,08	234,60	3970,73	4040,29	4,477	0,128	0,00110	116,3672243	11,86615453	46,91926483
200	690,92	6	1,2	829,11	4145,54	5,14	237,49	4208,22	3802,80	4,343	0,134	0,00113	117,8023471	12,01249633	47,49790637
205	699,34	6	1,2	839,21	4196,04	5,20	240,38	4448,60	3562,42	4,204	0,140	0,00117	119,23747	12,15883814	48,0765479
210	707,76	6	1,2	849,31	4246,54	5,27	243,28	4044,00	3319,14	4,058	0,146	0,00121	120,6725929	12,30517994	48,65518944
215	716,17	6	1,2	859,41	4297,05	5,33	246,17	4290,17	3072,97	3,904	0,153	0,00126	122,1077157	12,45152174	49,23383098
220	724,59	6	1,2	869,51	4347,55	5,39	249,06	4539,23	2823,91	3,743	0,162	0,00131	123,5428386	12,59786355	49,81247251
225	733,01	6	1,2	879,61	4398,05	5,45	251,96	4791,19	2571,95	3,572	0,171	0,00137	124,9779614	12,74420535	50,39111405
230	741,43	6	1,2	889,71	4448,55	5,52	254,85	5046,04	2317,10	3,390	0,182	0,00144	126,4130843	12,89054716	50,96975558
235	749,84	6	1,2	899,81	4499,06	5,58	257,74	5303,78	2059,36	3,196	0,194	0,00152	127,8482071	13,03688896	51,54839712
240	758,26	6	1,2	909,91	4549,56	5,64	260,64	5564,41	1798,73	2,987	0,209	0,00162	129,28333	13,18323077	52,12703866
245	766,68	6	1,2	920,01	4600,06	5,70	263,53	5827,94	1535,20	2,760	0,227	0,00174	130,7184529	13,32957257	52,70568019
250	775,09	6	1,2	930,11	4650,57	5,77	266,42	6094,36	1268,78	2,509	0,251	0,00190	132,1535757	13,47591438	53,28432173
255	783,51	6	1,2	940,21	4701,07	5,83	269,31	6363,68	999,46	2,227	0,282	0,00211	133,5886986	13,62225618	53,86296326
260	791,93	6	1,2	950,31	4751,57	5,89	272,21	6635,89	727,25	1,899	0,327	0,00242	135,0238214	13,76859798	54,4416048
265	800,35	6	1,2	960,41	4802,07	5,95	275,10	5169,55	452,15	1,498	0,402	0,00294	136,4589443	13,91493979	55,02024634
270	808,76	6	1,2	970,52	4852,58	6,02	277,99	5447,55	174,16	0,929	0,568	0,00412	137,8940671	14,06128159	55,59888787
275	817,18	5	1,0	817,18	4085,90	5,07	234,07	5681,62	0,00	0,000	0,929	0,01076	86,38845643	8,809170963	34,83182563
280	825,60	6	1,2	990,72	4953,58	6,14	283,78	5965,40	0,00	0,000	0,000	0,00000	0	0	0
285	834,01	6	1,2	1000,82	5004,09	6,21	286,67	6252,07	0,00	0,000	0,000	0,00000	0	0	0
290	842,43	6	1,2	1010,92	5054,59	6,27	289,57	6541,64	0,00	0,000	0,000	0,00000	0	0	0
295	850,85	6	1,2	1021,02	5105,09	6,33	292,46	6834,10	0,00	0,000	0,000	0,00000	0	0	0
300	859,27	6	1,2	1031,12	5155,59	6,39	295,35	7129,46	0,00	0,000	0,000	0,00000	0	0	0
305	867,68	6	1,2	1041,22	5206,10	6,46	298,25	7427,70	0,00	0,000	0,000	0,00000	0	0	0
310	876,10	6	1,2	1051,32	5256,60	6,52	301,14	7728,84	0,00	0,000	0,000	0,00000	0	0	0
315	884,52	6	1,2	1061,42	5307,10	6,58	304,03	8032,88	0,00	0,000	0,000	0,00000	0	0	0
320	892,93	6	1,2	1071,52	5357,61	6,64	306,93	5791,07	0,00	0,000	0,000	0,00000	0	0	0
325	901,35	7	1,4	1261,89	6309,46	7,82	361,46	6152,52	0,00	0,000	0,000	0,00000	0	0	0
330	909,77	7	1,4	1273,68	6368,38	7,90	364,83	6517,36	0,00	0,000	0,000	0,00000	0	0	0
335	918,19	7	1,4	1285,46	6427,30	7,97	368,21	6885,56	0,00	0,000	0,000	0,00000	0	0	0
340	926,60	7	1,4	1297,24	6486,22	8,04	371,58	7257,15	0,00	0,000	0,000	0,00000	0	0	0
345	935,02	7	1,4	1309,03	6545,14	8,12	374,96	7632,10	0,00	0,000	0,000	0,00000	0	0	0
350	943,44	7	1,4	1320,81	6604,06	8,19	378,33	8010,44	0,00	0,000	0,000	0,00000	0	0	0

13.12. Work drawing crash nose

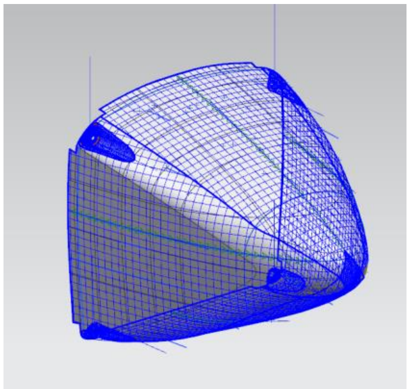
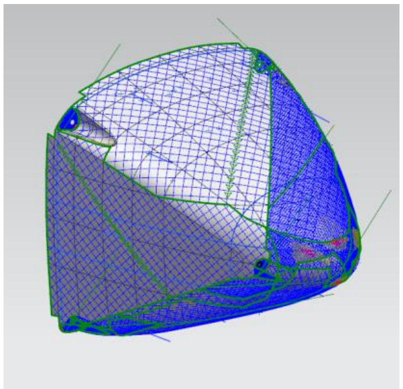
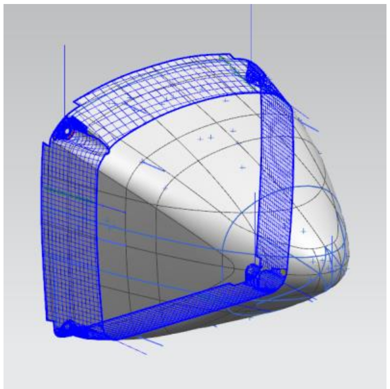


13.13. Work drawing anti-intrusion plate



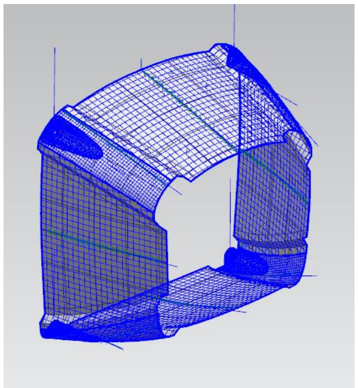
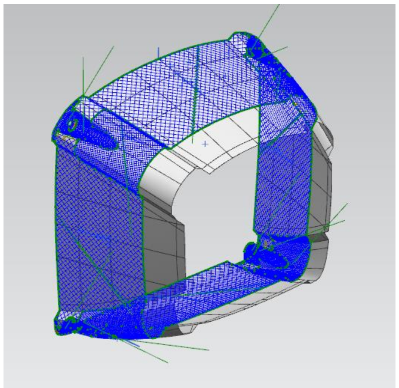
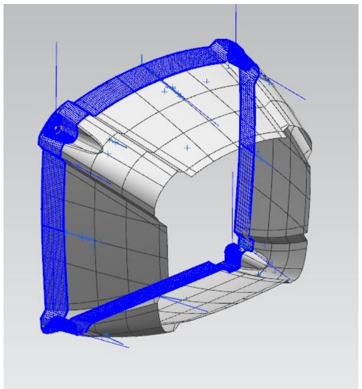
13.14. Fibersim

13.14.1. Outer skin

Layer 1, 2 and 3

13.14.2. Inner skin

Layer 4, 5 and 6

13.15. Hexcel Hexply 8552

HexPly® 8552

Prepreg Properties - HexPly® 8552 Woven Carbon Prepregs (IM7 Fibre)

Physical Properties

	Units	SPG 196-P	SPG 370-8H
Fibre Type Fibre density Weave Mass Weight Ratio, Warp : Fill	- g/cm³ *(lb/in³)* - g/m² *(oz/yd²)*	IM7 6K 1.77 *(0.064)* Plain 196 *(5.78)* 50 :50	IM7 6K 1.77 *(0.064)* 8HS 374 *(11.03)* 49 :51
Nominal cured ply thickness @ 37% resin content	mm *(inch)*	0.199 *(0.0078)*	0.380 *(0.0150)*
Nominal Fibre Volume	%	55.57	55.57
Nominal Laminate Density	g/cm³ *(lb/in³)*	1.56 *(0.056)*	1.56 *(0.056)*

Mechanical Properties

Test	Units	Temp°C (°F)	Condition	SPG 196-PW	SPG 370-8H
0°Tensile Strength	MPa *(ksi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	979 *(142)* 1090 *(158)* -	965 *(140)* 1014 *(147)* -
90°Tensile Strength	MPa *(ksi)*	-55*(-67)* 25*(77)* 93*(200)*	Dry Dry Dry	862 *(125)* 945 *(137)* **979 *(142)******	903 *(131)* 959 *(139)* **879 *(130)****
0°Tensile Modulus	GPa *(msi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	85 *(12.3)* 85 *(12.3)* -	86 *(12.5)* 86 *(12.4)* -
90°Tensile Modulus	GPa *(msi)*	-55*(-67)* 25*(77)* 93*(200)*	Dry Dry Dry	80 *(11.6)* 80 *(11.6)* **79 *(11.5)****	81 *(11.7)* 81 *(11.7)* **79 *(11.5)****
0° ILSS (Shortbeam shear)	MPa *(ksi)*	-55*(-67)* 25*(77)* 91*(195)*	Dry Dry Dry	- 88 *(12.7)* **69 *(10)****	- 90 *(13)* **74 *(10.8)****
		25*(77)* 71*(160)* 91*(195)*	Wet Wet Wet	80 *(11.6)* **61 *(8.8)***** -	83 *(12.1)* **63 *(9.1)***** -

Bold 93°C *(200°F)* **Bold* 104°C *(220°F)*** **Bold** 82°C *(180°F)***

Typical Neat Resin Data

Colour	Yellow	
Density	1.301 g/cc	*(0.0470 lb/in³)*
Glass Transition Temperature, Tg dry	200°C	*(392°F)*
Glass Transistion Temperature, Tg wet	154°C	*(309°F)*
Tensile Strength	121 MPa	*(17.5 ksi)*
Tensile Modulus	4670 MPa	*(0.677 msi)*

13.16. IAD FSG

APPENDIX T-2
2016 FSAE® IMPACT ATTENTUATOR DATA REPORT

FORMULA STUDENT GERMANY
Impact Attenuator Data Form - **Team's Own IA Design**

This form must be completed and uploaded to the "My Team" area on the FSG website **no later than the date specified** in the Action Deadlines. The FSG Technical Committee will review all submissions which deviate from the FSAE® and FSG rules for the Impact Attenuator. A printed copy of this form must be presented together with the vehicle at Technical Inspection.

The Impact Attenuator Data (IAD) and supporting calculations must be submitted electronically in Adobe Acrobat format (*.pdf). Late submissions will be penalized with -10 (minus ten) points per each commenced day, up to a maximum of -70 points, which will be deducted from the team's Total Score. Teams, which miss the IAD deadline by more than 7 days will be removed from the list of registered teams for the FSG competition.

In the event that the FSG Technical Committee requests additional information or calculations, teams have **7 days** from the date of the request to submit the requested information. Late submissions will be penalized with -5 (minus five) points per each commenced day, up to a maximum of -35 points, which will be deducted from the team's Total Score.

Contact Details

Car Number	E063
University Name	Norwegian University of Science and Technology
Team Contact Person	
Last Name, First Name	Browne, Eirik Monteagle
Telephone Number	0047 9342 6611
E-mail Address	eirik.browne@revolve.no

Attach Proof of Impact Attenuator

If the IA (Impact Attenuator) is a "Team's Own IA Design", the following points must be included:

1. The first page must always be this FSG_Impact_Attenuator_Data_Form
2. The report must be written in „engineering style" (e.g. contents, captions, symbols and abbreviations, page numbers, experimental setup, evaluation)
3. FS Germany accepts only dynamic impact attenuator tests (e.g. sledge test or drop down) with real test data (shown in T 3.22), including impact attenuator, anti intrusion plate (AIP) and front bulkhead (please note T3.22.11)
4. Design of IA and positioning on the AIP (dimensions in mm)
5. Method for attachment of the IA to the AIP (including data sheets e.g. if it bonded together)
6. Dimensions of the front bulkhead (dimensions in mm)
7. Design of the AIP (material, thickness and dimension in mm) and method for attachment to the front bulkhead
8. Description of the test set up (including sensor, data acquisition system)
9. If the test is accomplished at a company or research center, a letter of conformity must be attached to the report.
10. If the test is accomplished at the university, an official of the university (with contact details) must sign a letter of conformity (must be attached to the report).
11. Table of measured results of the dynamic impact attenuator test: test speed, absorbed energy, graph of average deceleration and peak deceleration over an interval of time (a=f(t)), permanent deflection of the AIP
12. Receipt of the material, a packing slip or letter of donation of the IA
13. Pictures before / after the dynamic impact attenuator test
14. Please comply with the particular FSAE rules for front wings, if applicable

steinfurth@formulastudent.de 1 / 1 18.02.2015

APPENDIX T-2
2016 FSAE® IMPACT ATTENTUATOR DATA REPORT

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Team Contact: Eirik M. Browne E-mail Address: eirik.browne@revolve.no
Faculty Advisor: Øyvind Andersen E-mail Address: oyvind.andersen@ntnu.no

Material(s) Used	Carbon fibre (Tencate E745), Kevlar honeycomb (ECA 3.2-80)
Description of form/shape	Pyramid shaped
IA to Anti-Intrusion Plate mounting method	Four M8 bolts.
Anti-Intrusion Plate to Front Bulkhead mounting method	Four M8 bolts
Peak deceleration (<= 40 g's)	30.5G
Average deceleration (<= 20 g's)	5.5G

Confirm that the attenuator contains the minimum volume 200mm wide x 100mm high x 200mm long [x]

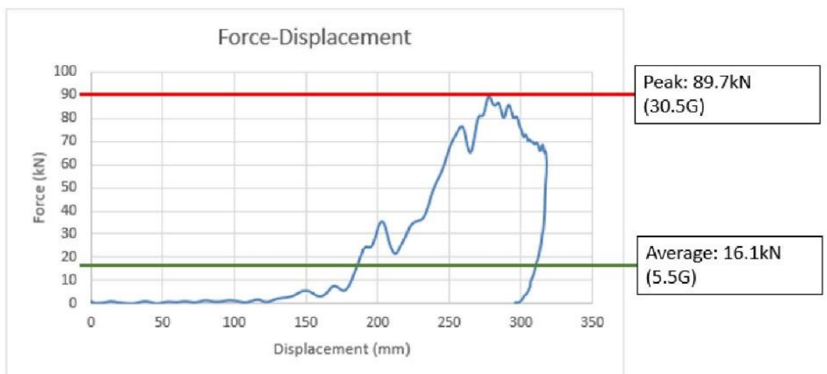


Figure 1: Force-Displacement Curve (dynamic tests must show displacement during collision and after the point v=0 and until force becomes = 0)

ATTACH PROOF OF EQUIVALENCY
TECHNICAL COMMITTEE DECISION/COMMENTS
____
Approved by____ Date_____________

NOTE: THIS FORM AND THE APPROVED COPY OF THE SUBMISSION MUST BE PRESENTED AT TECHNICAL INSPECTION AT EVERY FORMULA SAE EVENT ENTERED

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

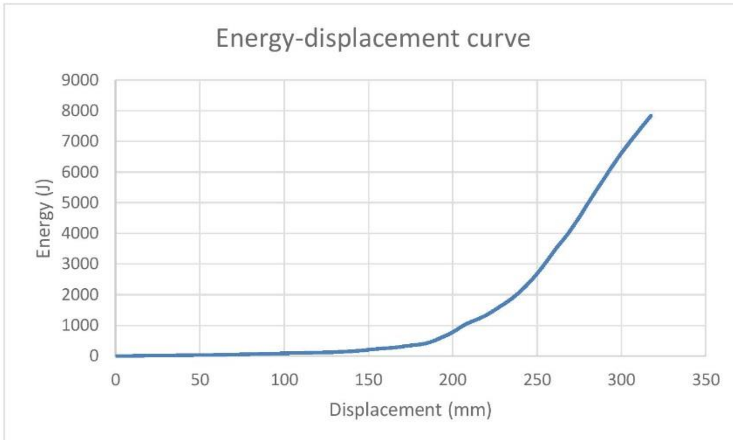


Figure 2: Energy-Displacement Curve (dynamic tests must show displacement during collision and after v=0)

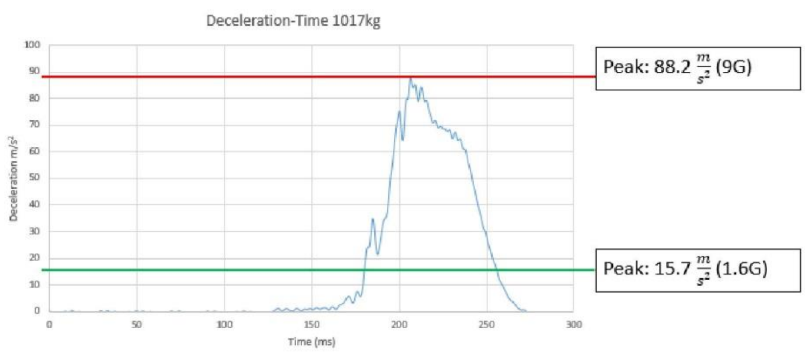


Figure 3: Deceleration-Time Curve. Note that the trolley weight was 1017 kg, and that the acceleration to force ratio was therefore somewhat decreased compared to the standard 300 kg trolley.

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Figure 3: Attenuator as Constructed

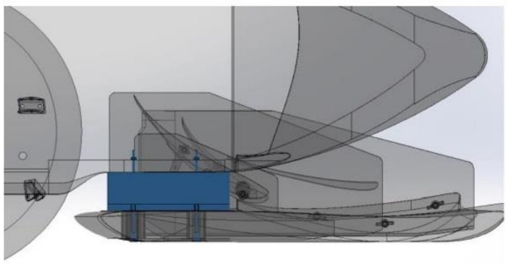
Figure 4: Attenuator after Impact

Energy Absorbed (J): Must be >= 7350 J	7839	Vehicle includes front wing in front of front bulkhead?	Yes
IA Max. Crushed Displacement (mm):	318	Wing structure included in test?	No
IA Post Crush Displacement - demonstrating any return (mm):	254	Test Type: (e.g. barrier test, drop test, quasi-static crush)	Trolley test
Anti-Intrusion Plate Deformation (mm):	0	Test Site: (must be from approved test site list on website for dynamic tests)	Benteler Automotive Raufoss
Test speed (m/s):	3.9	Trolley weight (kg):	1017

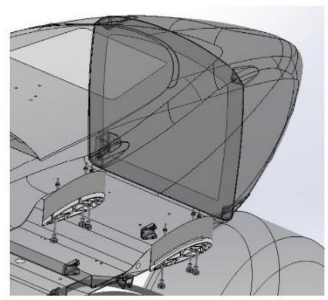
University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Front Wing Attachment Shear Calculations

The front wing is attached to the front bulkhead support structure with six M3 Metric grade 8.8 steel bolts as seen in picture (1) and (2). Underneath follows the equations according to rule T3.21.3b. UTS for these bolts are 800 MPa.



Picture 1 Front wing attachment seen from the side



Picture 2 Front wing attachment seen from the low front

Calculations T3.21.3b

Expression for shear stress on a single bolt: $\tau_{max} = \frac{F_{max}}{A} = \frac{F_{max}}{\frac{\pi}{4}D^2}$ (eq. 1)

Von Mises criteria for pure shear: $\tau_{max} = \frac{\sigma_{UTS}}{\sqrt{3}}$ (eq. 2)

Combining eq. 1 and eq. 2: $F_{max} = \frac{\pi}{4\sqrt{3}}\sigma_{UTS}D^2$

Where: $\sigma_{UTS} = 800\ MPa$ and $D_{min} = 2.387\ mm$

This will in turn give: $F_{max} = \frac{\pi}{4\sqrt{3}}800(2.387)^2 = 2067\ N$

This means that six bolts will give: $F_{max_6} = 12401N$

Which gives a total maximum deceleration of:

$$a_{max} = \frac{12401}{300 \times 9.81}G + \frac{89709}{300 \times 9.81}G = 4.21G + 30.5G = 34.7G$$

The calculations for T3.21.2 Note 2 can be found in attachment 2.

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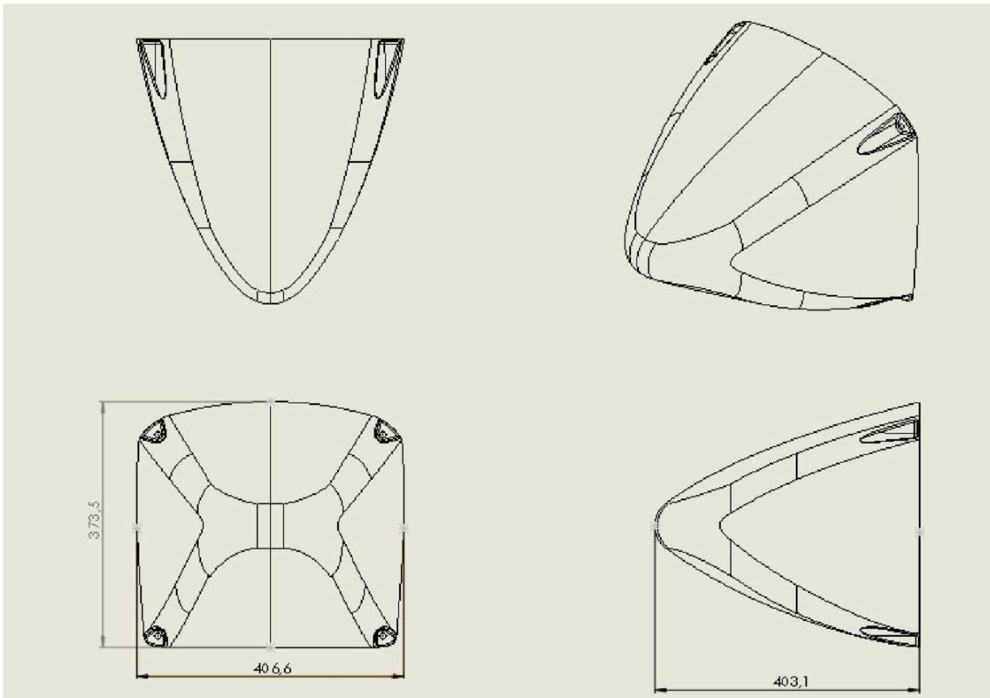

Picture 3 Impact attenuator measurements

Length (fore/aft direction): 403.1 mm (>=200mm)
Width (lateral direction): 406.6 mm (>=200mm)
Height (vertical direction): 373.5 mm (>=100mm)
Attenuator is at least 200mm wide by 100mm high for at least 200mm: Yes
Attach additional information below this point and/or on additional sheets

Test schematic, photos of test, design report including reasons for selection and advantages/disadvantages, etc. Additional information shall be kept concise and relevant.

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Test setup

Mass and speed of choice

For our dynamic test, we used a trolley machine located at Benteler Automotive in Raufoss, Norway. The test sample is fixed to the trolley and the trolley is accelerated to the desired speed. The trolley at Benteler Automotive weights 1017 kg. To ensure that the test was completed correctly in accordance to rule T3.21.2, the speed was adjusted to compensate for the additional mass.

Picture 4 Impact attenuator on crash rig

Picture 5 Impact attenuator post crash

Picture 6 Impact attenuator frontal view

Speed adjustment:

$$E_{min} = 7350\,J \rightarrow v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2 * 7350}{1017}} = 3{,}8\ \frac{m}{s}$$

Due to inaccuracies in the machine the speed was set to 3.9 m/s.

University Name: Norwegian University of Science and Technology
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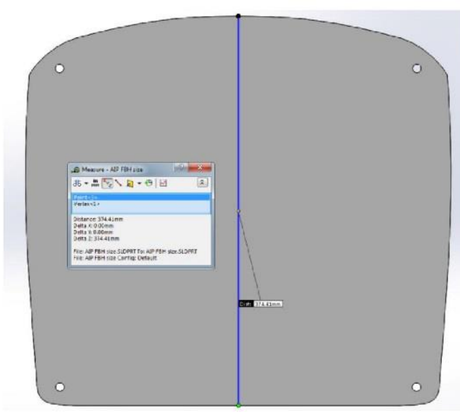
Design of anti-intrusion plate

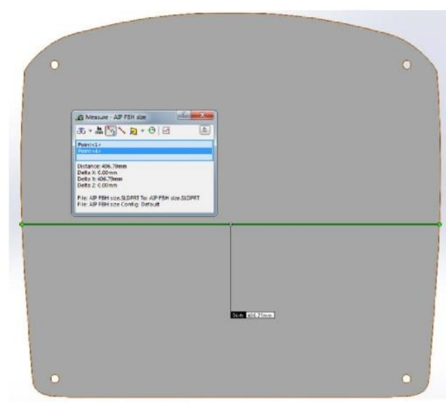
The anti-intrusion plate (AIP) is made out of 14 plies of Hexply 8552, making it about 4 mm thick. The orientation of the fibers are [0/45]x7. The two anti-intrusion plates were water jet cut from one large carbon fiber plate. The outer measurements can be seen in picture 9 and 10. The AIP is fixed to the front bulkhead of the car using four M8 bolts.

Picture 7 Carbon fiber label

Picture 8 Panel production



Picture 9 AIP hight

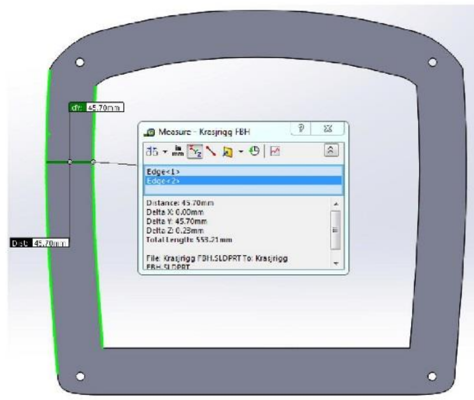


Picture 10 AIP width

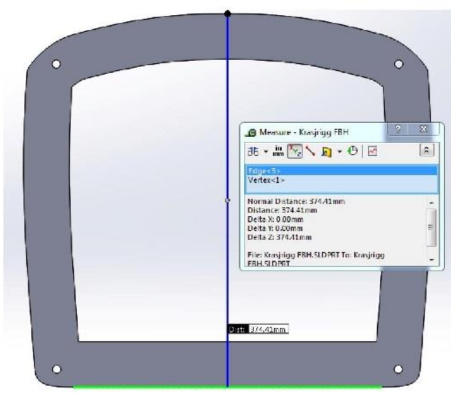
University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Front bulkhead

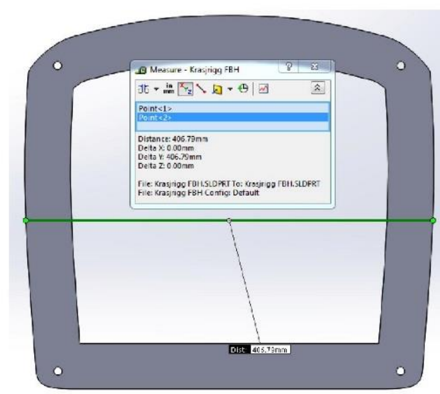
The thickness of the front bulkhead (FBH) is the same all the way around the edge (45.7 mm). The outer measurements of the front bulkhead are the same as for the anti-intrusion plate.



Picture 11 FBH brim width



Picture 12 FBH height



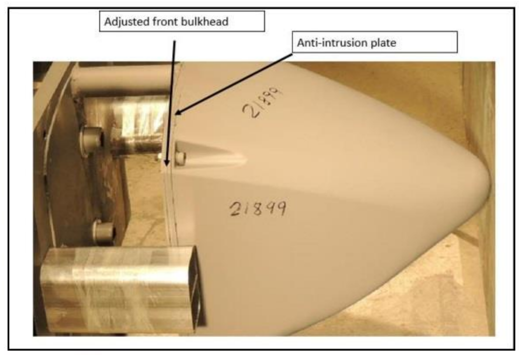
Picture 13 FBH width

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Rig setup

The front bulkhead used in the test setup was produced by water jet cutting a 4 mm steel plate to the same size as the front bulkhead on the car. Originally a smaller front bulkhead was welded on four 150 mm tubes on the crash rig, but the size of the front bulkhead had to be adjusted due to new calculations. As such, the correctly sized front bulkhead is mounted in front of the other, between the crash rig and the anti-intrusion plate. The composite anti-intrusion plate is about 4 mm thick and fills the outer perimeter of the front bulkhead. It is placed between the front bulkhead and the nose. The whole setup is fixed together using four M8 Metric grade 12.9 bolts.

Picture 14 Impact attenuator as mounted on crash rig



Picture 15 Crash rig setup

Two aluminum profiles were placed on either side of the crash rig to absorb energy in the event of a catastrophic impact attenuator failure to limit damage on the load cells. These can be seen in picture 15.

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Letter of conformity

Crash test:

Speed of 3.9 m/s

Mass of 1017 kg

Front bulkhead, impact attenuator and anti-intrusion plate as shown on picture 4, 5 and 6.

Calculations:

Peak deceleration

Average deceleration

Energy absorbed

Impact attenuator and anti-intrusion plate displacement

Graphs:

Force-Displacement curve, figure 1

Energy-Displacement curve, figure 2

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(Raufoss) AS

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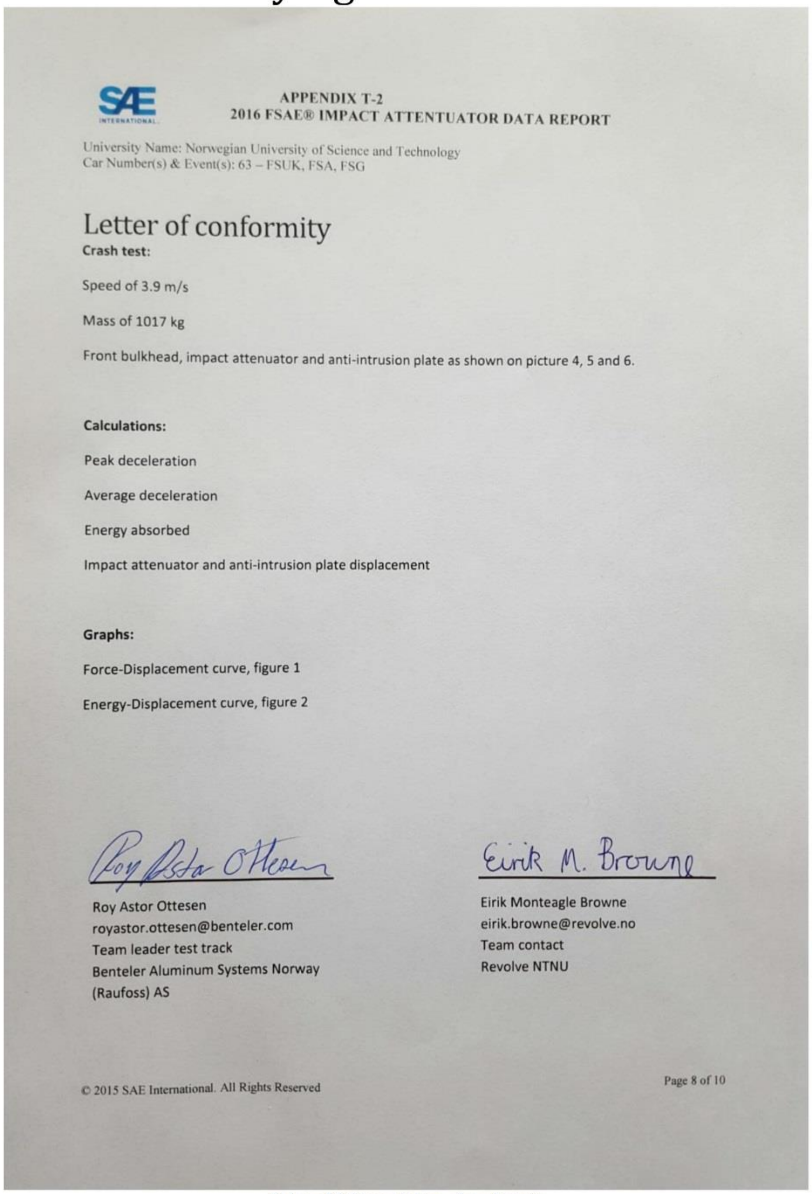
Team contact
Revolve NTNU

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Letter of conformity signed



APPENDIX T-2
2016 FSAE® IMPACT ATTENTUATOR DATA REPORT

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Letter of conformity

Crash test:

Speed of 3.9 m/s

Mass of 1017 kg

Front bulkhead, impact attenuator and anti-intrusion plate as shown on picture 4, 5 and 6.

Calculations:

Peak deceleration

Average deceleration

Energy absorbed

Impact attenuator and anti-intrusion plate displacement

Graphs:

Force-Displacement curve, figure 1

Energy-Displacement curve, figure 2

Roy Astor Ottesen

Roy Astor Ottesen
royastor.ottesen@benteler.com
Team leader test track
Benteler Aluminum Systems Norway
(Raufoss) AS

Eirik M. Browne

Eirik Monteagle Browne
eirik.browne@revolve.no
Team contact
Revolve NTNU

Picture 16 Signed letter of conformity

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Receipt of material

Carbon fiber: Tencate E745

Lindberg & Lund

Fakturaadresse:	Leveringsadresse:	Dato:	24. november 2015
REVOLVE NTNU	REVOLVE NTNU	Vår ref.:	Rikard Kalland
S.P.ANDERSENS V 5	S.P.ANDERSENS V 5 c/o IPK	SOKunde nr:	25569
	Valgrinda		
7031 TRONDHEIM	N-7031 TRONDHEIM	Deres kontakt:	Terje Mork
		Leveringsbet..:	Fra Lager
		Leveringsmåte:	Schenker stykkgods
		Tilbudsreferanse:	SO-11940

Tilbud 11940

Viser til hyggelig samtale med Dem vedrørende våre produkter og har gleden av å kunne tilby følgende:

Prod. nr.	Beskrivelse	Antall	Pris	Enhet	Rabatt	Beløp
18170	FORM PREPREG 650GR/M2 12K 2X2T KARBON	50	741,00	ea	0	37 050,00 NOK
17929	FORM PREPREG 205GR/M2 2X2T 46% KARBON	26,25	133,00	M2	0	3 491,25 NOK
18581	E745-00 IM0223-A CBN 200G 6K IM7 2T	75	1 112,00	M2	0	83 400,00 NOK
		0	0,00		0	0,00 NOK

Totalt eksklusive mva og frakt: 123 941,25 NOK

Eventuell smøreoljeavgift på 1,98 pr. liter
er ikke inkludert i prisen.

Vi håper at tilbudet er av interesse og skulle ytterligere opplysninger være ønskelig er det bare å kontakte oss. Vi gjør oppmerksom på at endelige betalingsbetingelser ikke er satt før kredittvurdering er foretatt av vår økonomiavdeling. Tilbudets varighet er 30 dager fra dagens dato dersom ingen dato er satt i tilbudshodet over.

Eventuelle datablader følger vedlagt.

Med vennlig hilsen

Rikard Kalland
LINDBERG & LUND AS
www.lindberg-lund.no

ALMINNELIGE SALGS- OG LEVERINGSBETINGELSER FOR LINDBERG & LUND AS

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Bankkonto. 9052 11 12602

Side **1** av **1**

Picture 17 Receipt for Tencate E745 carbon fiber

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Core material: Kevlar honeycomb ECA 3.2-80

The Kevlar honeycomb was given to us by our sponsor, Kongsberg Gruppen.


EC®

EURO-COMPOSITES S.A.

Kunde:
Bestellnr. / Bez.:
Auftragsbestätigung:
Fertigungsauftragsnr.: 3528371
Bezeichnung: ECA 3.2-80
Spezifikation: Ohne
Fertigungslos: 15A323MB360

Position: Abruf:
FA Pos. Nr: 1514711
Produkt-/Seriennr.: 12164/137985
Empfänger: EC-V5

Abmessungen: L: 1275 mm W: 2550 mm T: 25.00 mm

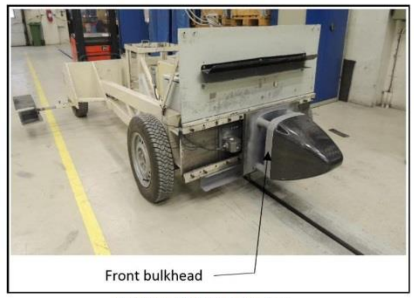
Picture 18 Packing slip for core material ECA 3.2-80

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Attachment 1

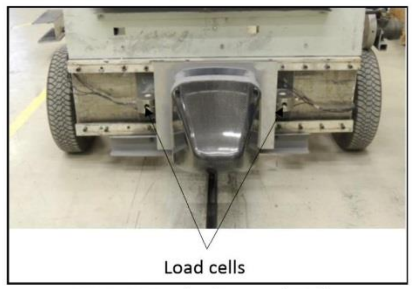
Test setup

The tests were carried out at Benteler Automotive using a trolley crash machine. The front bulkhead crash rig is mounted in front of the load cells, and the anti-intrusion plate and the nose is mounted on the rig using four M8 bolts. The trolley is then accelerated to the desired speed, following a track in the floor. The trolley crashes into a wall, and a high speed camera films the crash in order to let the user investigate the test specimen post-experiment.



Picture 19 Crash trolley

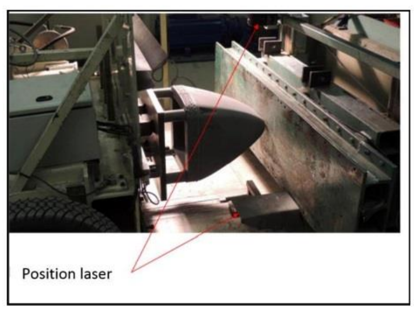
Four 100 kN load cells, two on each side, registers the force exerted on the nose. When the crash nose hits the wall, the plate that the crash rig is mounted on will exert forces on the load cells, which then generates data with high accuracy. The data from the crash is then processed using Microsoft Excel.



Picture 20 Load cells on crash trolley

Two lasers are used to measure distance to the trolley. These readings coupled with the readings from the load cells will produce the data needed for the required graphs.

Note: Pictures used are from last year's test.



Picture 21 Laser positioning

University Name: Norwegian University of Science and Technology
Car Number(s) & Event(s): 63 – FSUK, FSA, FSG

Attachment 2

Rule T3.21.2 Note 2

Force-displacement graph

Figure 1 was created using an Excel spreadsheet provided by the test facility, Benteler Automotive. As previously mentioned, the test rig consists of four load cells. In the spreadsheet, the force values during the test are listed under the columns for "Sidemem." 2, 3, 5 and 6 (see picture 22). Combining all four values for each position of the "Posgiv. 4"-column gives us the force-displacement graph as seen in figure 1. All values until force becomes 0 and after speed becomes 0 has been included in the graph.

Peak and average G

Peak G was calculated using the "MAXA"-command on the combined force column. This command returns the highest value of the marked area.

Average G was calculated by combining every value in the combined force column, and dividing it by the number of fields marked. Seeing that the time interval between each reading is the same, this gives us the average G of the crash test.

Energy-displacement graph

Figure 2 was created by simply coupling the energy ("Energi" in Norwegian) column of the spreadsheet with the position column.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Posgiv. 3	Posgiv. 4	Sidemem. 1	Sidemem. 2	Sidemem. 3	Sidemem. 4	Sidemem. 5	Sidemem. 6	Aksel-Backx	Aksel-FrRx	Aksel-FrLx	Energi
2	0	0	0	0	0	0	0	0	0.54826	-1.909217	0.479057	0
3	0	0	0.0158	-0.044847	0.045834	0.034509	-0.017546	0.013177	0.51895	-1.436366	0.445239	0
4	0	0	0.029112	-0.085241	0.089366	0.063019	-0.039678	0.025926	0.478567	-1.02745	0.402198	0
5	0	0	0.038763	-0.12005	0.128521	0.08265	-0.0673	0.036843	0.423464	-0.719627	0.356206	0
6	0	0	0.044721	-0.147353	0.16256	0.09294	-0.100489	0.04284	0.351963	-0.520693	0.30781	0
7	0	0	0.047602	-0.16679	0.191381	0.095332	-0.138366	0.040123	0.267094	-0.417118	0.260087	0
8	0	0	0.047931	-0.178756	0.214928	0.09219	-0.179082	0.025197	0.17771	-0.389968	0.215765	0
9	0	0	0.045965	-0.184152	0.233173	0.086198	-0.220206	-0.004494	0.096238	-0.420924	0.178062	0
10	0	0	0.041992	-0.184152	0.246283	0.079965	-0.259566	-0.050019	0.034887	-0.488013	0.149946	0

Picture 22 Excerpt from spreadsheet

Deceleration-time graph

The sampling rate of the machine is 5000. This means that the time interval between each row in the Excel spreadsheet is 0.2 ms. By transforming the combined force column to G-forces for the 1017kg trolley and coupling it with the time interval for each row, we can create the deceleration-time graph.

13.17. Task description

NTNU - NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS SPRING 2016
FOR
STUD.TECHN. EIRIK MONTEAGLE BROWNE

Carbon fiber composite impact attenuator for the Revolve Formula Student car

Revolve NTNU is an independent student organization at the Norwegian University of Science and Technology. The team consists of 50 members who work voluntarily parallel to full time engineering studies. The members are from over 10 engineering fields and all years of study. To develop and build a race car from scratch in one year is a challenging task that demands numerous engineering fields, extraordinary dedication and hard earned resources. Every year a new team of students take on the complex and comprehensive project to make the transition from students to fully capable engineers.

The impact attenuator (crash nose) protects the driver during front collision by limiting the negative acceleration at impact. The structure shall comply with relevant rules for structural integrity and safety as well as being optimized for minimum weight.

The master thesis work will included, but is not limited to:

1. Review of requirements, rules and regulations
2. CAD models of structural components
3. FEA Simulations (buckling and fiber layup)
4. Production and testing methods
5. Physical testing of test panels and crash nose

The work is expected to be an iterative process where redesign, alternative materials and test methods should be continuously assessed with respect to the objectives and possible interference with the rest of the Revolve development team.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site (see https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

The contact person is Roy Iversen, Revolve NTNU

Torgeir Welo
Head of Division

Nils Petter Vedvik
Professor/Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

13.18. Risk assessment

NTNU / HSE	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: IPM **Date:** 18.04.2016

Line manager: Torgeir Welo.

Participants in the identification process (including their function)**:** Nils Petter Vedvik, Roy Iversen.

Short description of the main activity/main process: Production of carbon fiber crash nose for Revolve NTNU

Master project for student Eirik M.Browne.

Optimized carbon fiber energy absorber for high performance Formula Student racecar.

Is the project work purely theoretical? No.

Signatures: Nils-Petter Vedvik

Responsible supervisor: Nils Petter Vedvik
Student: Eirik M. Browne Eirik Browne

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment

NTNU	Risk assessment	Prepared by	Number	Date
		HSE section	HMSRV2603E	04.02.2011
		Approved by		Replaces
HSE/KS		The Rector		01.12.2006

Unit: IPM **Date:** 18.04.2016

Line manager: Torgeir Welo

Participants in the identification process (including their function)**:**

Short description of the main activity/main process: Production of carbon fiber crash nose for Revolve NTNU

Master project for student Eirik M.Browne.

Optimized carbon fiber energy absorber for high performance Formula Student racecar.

Signatures:

Responsible supervisor: Nils Petter Vedvik

Student: Eirik M. Browne Eirik Browne

Activity from the identification process form	**Potential undesirable incident/strain**	**Likelihood:**	**Consequence:**			**Risk Value (human)**	**Comments/status Suggested measures**
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

Potential undesirable incident/strain

Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork

Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

NTNU	Risk assessment	Prepared by	Number	Date
		HSE section	HMSRV2603E	04.02.2011
		Approved by		Replaces
HSE/KS		The Rector		01.12.2006

Risk = Likelihood x Consequence
Please calculate the risk value for “Human”, “Environment” and, if chosen, “Economy/materiel”, separately.

About the column ”Comments/status, suggested preventative and corrective measures”:
Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE						
	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour	Description
Red	Unacceptable risk. Measures must be taken to reduce the risk.
Yellow	Assessment range. Measures must be considered.
Green	Acceptable risk Measures can be considered based on other considerations.