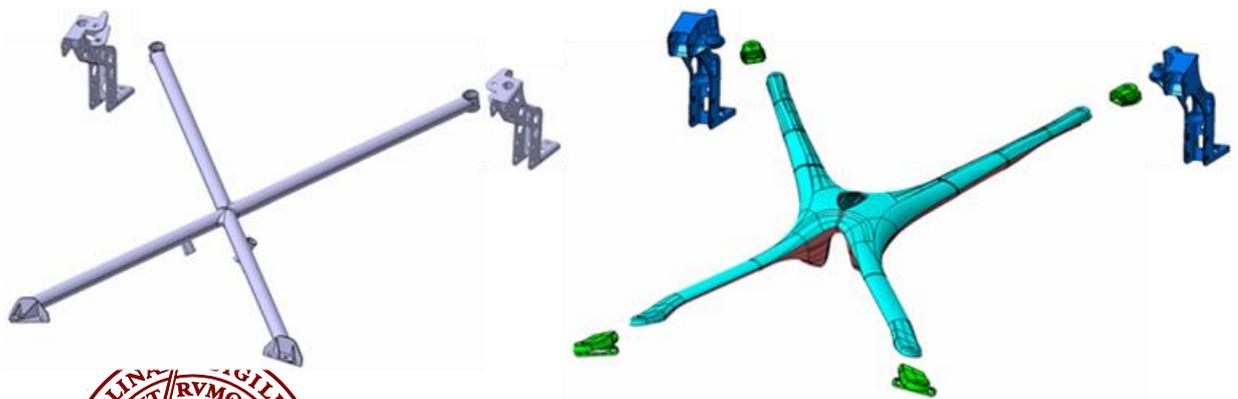


# Rear Cross Frame re-design and optimization in Carbon Fiber

*Marc Òliva*

---

*Division of Machine Design • Department of Design Sciences  
Faculty of Engineering LTH • Lund University • 2014*



**LUND UNIVERSITY**



**Koenigsegg**

www.koenigsegg.com





# **Rear Cross Frame re-design and optimization in Carbon Fiber**

*Marc Òliva*

---

*Division of Machine Design • Department of Design Sciences  
Faculty of Engineering LTH • Lund University • 2014*

Division of Machine Design, Department of Design Sciences  
Faculty of Engineering LTH, Lund University  
P.O. Box 118  
SE-221 00 Lund  
Sweden

ISRN LUTMDN/TMKT 14/5506 SE

## Preface

This report was carried out as a master thesis of a Mechanical Engineering specialization in Product Development from the Faculty of Engineering LTH, Lund University, at Lund, Sweden and Industrial Engineering specialization in Product Design from the UPC in Barcelona, Spain. I have been lucky to get the opportunity to do my master thesis in Koenigsegg Automotive, a world top-class company. Later on the company has offered me the chance to begin my professional career as a part of their company.

During the development of this Master Thesis I counted with the collaboration of the composite manager at Koenigsegg, Lluç Martí and the collaboration of the engineers in Altair Engineering in Lund. These people have been trustful and direct information sources and can be considered as the best references possible. Lluç Martí has given me all the information needed to comprehend the carbon fiber parts production process. The engineers in Altair Engineering in Lund have provide me with all the support in the CAE analyses needed, and let me work besides them for one month.

I would like to give special thanks to:

Lluç Martí, Jon Gunner, Cristian von Koenigsegg, Thomas Johansson and all the engineers and mechanics from Koenigsegg Automotive AB for the their help and the opportunity to perform this master thesis.

Erik Magnemark, Fredrik Nordgren, Henrik Pahlitzsch, Joakim Truedsson, Niklas Edrén and all the staff from Altair Engineering in Lund for their help in performing the analyses.

Per Kristav, supervisor at LTH; Damien Motte, examiner at LTH; and Martin Tunér, professor at LTH that helped me to find this thesis opportunity.

Last but not least I would like to thank my parents Jordi Òliva and Maria José Martínez, my parents, for their strong support during this time and all my life.

Lund, August 2014.

Marc Òliva.



## Abstract

This master thesis covers the process followed in the re-design and optimization of a structural part in a supercar. The part reviewed is the Rear Cross Frame currently in production of all Koenigsegg's supercars. In the new revision of the part, the material is Carbon Fiber. The version currently in production is made of steel. The shape has been modified to fit the Carbon Fiber manufacturing requirements and to fulfill better the load conditions to which the part will be subjected. The Carbon Fiber lay-up has been optimized, to achieve the lightest possible result and retain the same stiffness levels as the current Rear Cross Frame.

The first step in the process has been the detection of the points to improve with respect to the old part. The achievement of a good tradeoff between stiffness improvement and weight reduction has been then set as a goal, as well as a visually appealing part. In this stage the parts involved at any phase of the whole thesis process are introduced to be familiarized with their names.

After that, a package of the area and the design space for the new part has been created. This design spaces take all the available space to define the volume boundaries of the new rear cross frame. A simplified version of the structural parts in the zone of the rear cross frame is as well conceived.

With the design space and the simplified structural geometry a topology optimization has been performed. The adequate load cases have been introduced, representing different driving situations. With the output of the topology optimization some decisions have been taken in order to define some aspects that the final part will include.

Using the topology optimization results as a guideline, the final CAD model has been created. In this step, manufacturing constraints for carbon fiber parts such as de-molding angles have been kept in mind.

Once the final CAD model has been finished a CAE analysis has been performed. This analysis consists in the optimization of the carbon fiber lay-up for the model. The composite plies have been defined in shape, direction and material in order to better fulfill the objectives and Koenigsegg's carbon fiber part standards.

Once the general lay-up has been defined, the mounting areas have been revised. The general approach includes aluminum inserts in the carbon fiber part. These inserts offer good connection and bolting surfaces as well as a nice load propagation to the carbon fiber. The connection with the Rollover Bar Bracket has been re-designed, as well as the Rollover Bar Bracket itself, to achieve a lighter and mounting-friendlier solution.

In the next phase the molds and masters needed to produce the part have been designed. In addition, the steps to generate the molds and final parts have been detailed and has been indicated how to glue the different elements together.

The thesis results present the final part offering the same stiffness, being lighter and better looking that the part currently in production but less cost efficient.

At the moment of the thesis publication, the solution hasn't been implemented in the cars.

**Keywords:**

Rear Cross Frame, Carbon Fiber, Design, Optimization, CAD.

## **Acronyms**

CAD: Computer Aided Design.

CAE: Computer Aided Engineering.

C/F: Carbon Fiber.



# Table of Contents

<b>1 Introduction .....</b>	<b>1</b>
1.1 Company background .....	1
1.2 Description .....	1
1.3 Objectives.....	2
1.4 Boundaries .....	2
<b>2 Method.....</b>	<b>3</b>
2.1 Overall description. ....	3
2.2 Creation of the design space. ....	3
2.3 Performance a topology optimization.....	3
2.4 Creation of the CAD model. ....	3
2.5 Analysis and optimization of the lay-up.....	4
2.6 Design of the inserts for the mounting areas. ....	4
2.7 Re-design of involved parts and create molds.....	4
<b>3 Revision of the current solution .....</b>	<b>5</b>
3.1 Rear cross frame in production .....	5
3.2 Revision of elements involved .....	5
<b>4 Creation of the design space.....</b>	<b>7</b>
4.1 Package of the area .....	7
4.2 Available space body .....	7
4.2.1 Minimum gap. ....	8
4.2.2 Analysis of the behavior of the moving parts.....	8
4.2.3 Anchor points. ....	8
4.2.4 Hot areas .....	8
4.3 Creation of simplified geometry for analysis .....	8
<b>5 Topology optimization .....</b>	<b>11</b>
5.1 Description .....	11

5.2 Topology optimization results .....	12
5.2.1 Bending load case .....	12
5.2.2 Torsion load case.....	12
5.3 Interpretation and decisions made to create the final model .....	13
<b>6 Creation of the CAD model .....</b>	<b>15</b>
6.1 Topology result interpretation .....	15
6.2 CAD Design .....	15
6.2.1 Outer surface .....	15
6.2.2 Upper and lower halves .....	16
<b>7 Analysis and optimization.....</b>	<b>19</b>
7.1 Definition .....	19
7.2 Software .....	19
7.3 Pre-process.....	19
7.3.1 Meshing .....	19
7.3.2 Materials .....	20
7.3.3 Loads and constraints.....	21
7.4 Composite optimization.....	23
7.4.1 Free-size phase .....	23
7.4.2 Size phase .....	23
7.4.3 Shuffle phase .....	24
7.5 Final results.....	24
7.5.1 Lay-up.....	24
7.5.2 Displacement .....	25
7.5.3 Composite stress .....	25
<b>8 Definition of the mounting areas .....</b>	<b>27</b>
8.1 Overall description .....	27
8.2 Front mounting .....	27
8.2.1 Inserts .....	27
8.2.2 Brackets.....	28
8.3 Middle mounting.....	29
8.4 Rear mounting.....	29
8.4.1 Inserts .....	29
<b>9 Production steps .....</b>	<b>31</b>
9.1 Introduction .....	31

9.2 Creation of the molds from the masters.....	31
9.3 Creation of the carbon fiber part halves from the molds.....	32
9.4 Gluing of the carbon fiber halves and the aluminum inserts.....	33
<b>10 Final results .....</b>	<b>35</b>
10.1 Stiffness.....	36
10.2 Weight .....	36
10.3 Cost .....	36
10.4 Aesthetics.....	36
<b>11 Conclusions and reflections.....</b>	<b>37</b>
<b>References .....</b>	<b>39</b>
<b>A. Appendix: Time plan .....</b>	<b>41</b>



# 1 Introduction

*This chapter covers the company background, description, objectives and boundaries of the thesis.*

## 1.1 Company background

Koenigsegg Automotive AB is a Swedish manufacturer of high performance sport cars. The company was founded in 1994 by Cristian von Koenigsegg and the first street-legal car was delivered in 2002. Since then, different models have been produced competing with the world best high performance cars and achieving several world records [1].

In 2005 the model CCR achieved the top speed world record with 388 km/h [1].

In 2008 the model CCX achieved the 0-300-0 km/h world record with a time of 29.2 seconds and the 0-200 km/h world record with a time of 9.3 seconds [1].

In 2011 the model Agera R achieved the 0-300 km/h world record with a time of 14.53 seconds and the 300-0 km/h with a time of 6.66 seconds obtaining a time in the 0-300-0 km/h of 21.19 seconds [1].

In 2014 the company has produced the world's first production car with a weigh-to-power ratio of 1kg/hp, the Koenigsegg One:1 with 1360 hp and 1360 kg [1].

## 1.2 Description

The project consists on the revision of the rear cross frame of the car using carbon fiber as material. The part has been in production for several models. The rear cross frame is a structural part that mostly takes bending forces from the rear powertrain as well as some torsional loads and transfers them to the chassis.

Nowadays Koenigsegg is using a tubular rear cross frame made of steel. Composed by two bars in X-shape that connect the rear part of the gearbox structure with the chassis and has an extra connection in the front part of the gearbox structure, in the suspension fixing point. The part is removable.

The improvement of the rear cross frame using carbon fiber has the following main milestones:

- Prepare a precise package of the area
- Create the maximum volume available for the part and optimize the shape with Optistruct.

## 1 Introduction

---

- Design & develop a C/F part able to be manufactured.
- Optimize the lay-up using Optistruct.
- Create the tooling needed.
- Create the documentation needed to manufacture the part (lay-up manual & checking spreadsheet, drill and trim, bonding and assembly manuals and drawings).

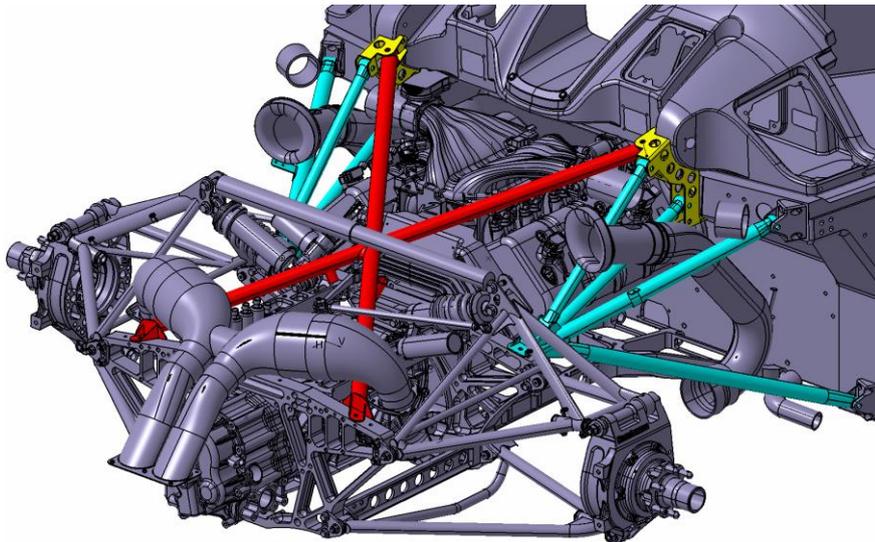
### 1.3 Objectives

After analyzing the current cross frame, it was considered that the new version should be reduced in weight keeping at least the stiffness offered by the current solution. Part of the objective has also been the creation of a visually appealing to Koenigsegg standards carbon fiber part. The intention is to match with the carbon fiber flow visible in the entire car. Koenigsegg offers an exclusive and unique product and give high importance to the aesthetics. The cross frame is partly visible from outside and fully visible with the rear hood lifted.

### 1.4 Boundaries

As a first scope for the project the rear sub frame (light blue in **Figure 1.1**) was also considered inside the boundaries, but the thesis was soon focused on just the rear cross frame (red in **Figure 1.1**).

Apart from the rear cross frame, new parts involved in the process have been re-designed. The rollover bar brackets (yellow in **Figure 1.1**) need a new connection with the rear cross frame. Other parts needed to be designed from scratch as the masters and molds for the carbon fiber parts and all the aluminum inserts. These inserts are used to connect the rear cross frame with other parts of the car.



**Figure 1.1** View of the involved area of the car.

## 2 Method

*This chapter describes the steps followed in the thesis development.*

### 2.1 Overall description.

In every re-design process some methodology has to be followed. The first important thing to do is to be aware of the weaknesses of the current design and know the points that need to be improved.

For the carbon fiber optimization the appropriate approach has been as follows:

- Create full assembly of the area to see the available design space.
- Perform a topology optimization.
- Create the exterior surface used as carbon fiber A-face.
- Analyze and optimize the lay-up.
- Design inserts.
- Re-design involved parts.

### 2.2 Creation of the design space.

The fact that the new cross frame has to fit in the car without colliding with any of the other parts supposes the only shape or space limitations. The first step for that is the creation of a CAD assembly with the parts surrounding the area as well as all the points the new rear cross frame is going to use as connection points.

When the assembly is set, a body taking all the space available can be created. This body is going to be called “design space” from now on. The rear cross frame takes a volume fraction of this design space.

### 2.3 Performance a topology optimization.

In this project, the topology optimization was assisted by software tools from Altair’s HyperWorks. It consists in the use of certain percentage of a design space to better fulfill certain load conditions using the minimum amount of material possible in the most efficient way. These type of analyses help in giving some guidelines of how the optimized part should look like.

### 2.4 Creation of the CAD model.

Once the space available has been optimized for the load conditions that the part will be under, it is time to create a nice and smooth surface with CAD software. The

software used in the project is CATIA V5 [2]. Using the result of the topology optimization as a guideline, the surface has to fulfill all the manufacturing constraints and should be visually appealing.

### **2.5 Analysis and optimization of the lay-up.**

At this stage, the newly created surface and the other structural parts that transport the loads to the chassis are imported to a CAE software, in this case Altair's HyperWorks. The desired objectives and constraints are applied in the model and the carbon fiber layers are in different stages optimized in shape, number and order. With some interpretation of the optimized layers the lay-up can be created.

### **2.6 Design of the inserts for the mounting areas.**

The carbon fiber cross frame needs aluminum inserts in the mounting points. These inserts are glued to the carbon fiber and offer perfect points to bolt the part to the mounting areas.

### **2.7 Re-design of involved parts and create molds.**

With the new cross frame design other parts are susceptible to be changed or modified in case of conflict or changes in the mounting areas.

In addition the tools that are needed to manufacture the carbon fiber part such as molds and masters have to be designed.

## 3 Revision of the current solution

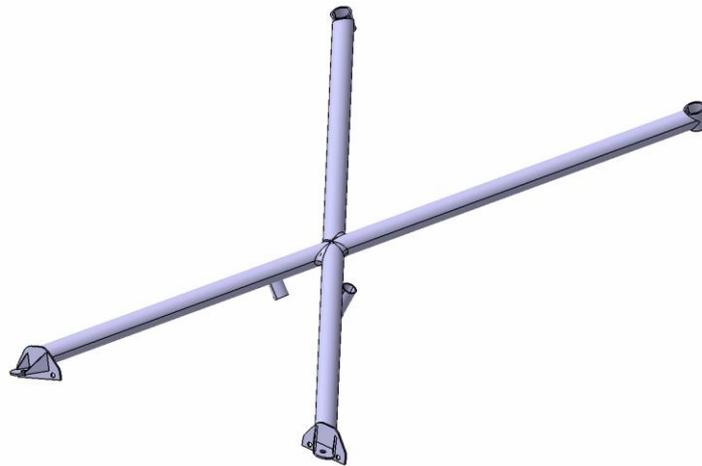
*This chapter analyzes the rear cross frame in production and surrounding elements.*

### 3.1 Rear cross frame in production

The rear cross frame in production (**Figure 3.1**) is a part constituted by two steel tubes forming an “X-shape”. In addition to the tubes there are steel plates welded that facilitate the mounting through bolts of the rear cross frame.

At a first scoop, the points to improve set have been:

- Weight reduction.
- Mounting connection with the rollover bar brackets.
- Aesthetics.
- Stiffness improvement.
- Mounting ease increment.



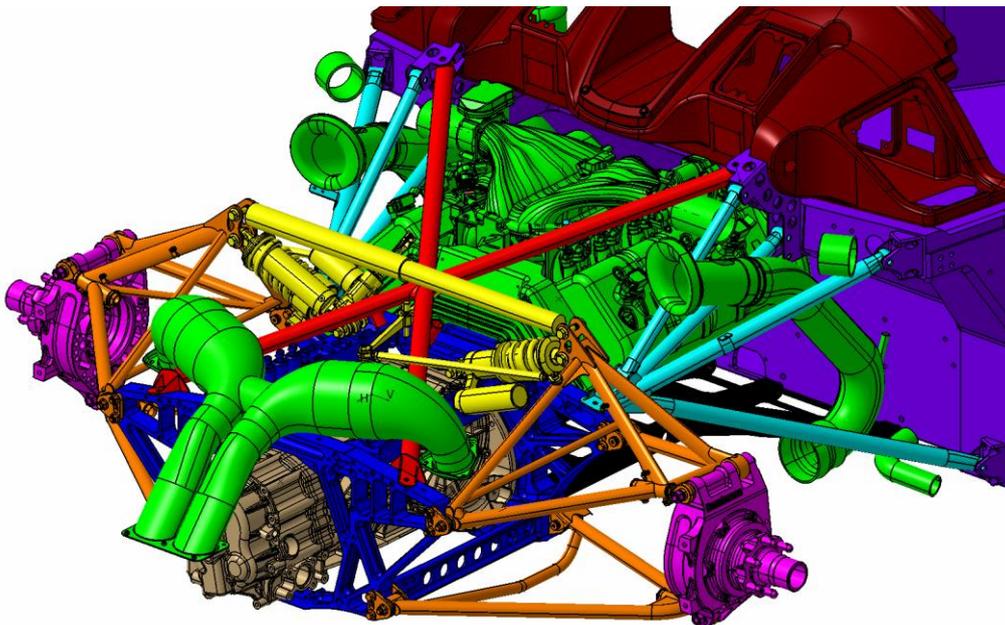
**Figure 3.1** View of the current rear cross frame

### 3.2 Revision of elements involved

Besides the rear cross frame, there are other elements (**Table 3.1** and **Figure 3.2**) to bear in mind in the development of the thesis. Some of them have been simplified and included in the analysis. There are other parts that have been taken in mind due to their proximity to the rear cross frame in order to properly define the design space.

**Table 3.1** List of elements around the rear cross frame seen in Figure 3.2.

Part	Color
Rear cross frame	Red
Rear sub-frame	Light blue
Rollover bar	Dark red
Chassis	Purple
Engine	Green
Dampers	Yellow
Wishbones	Orange
Gearbox frame	Dark blue
Gearbox	Light brown
Wheel hubs/uprights	Pink



**Figure 3.2** Elements around the rear cross frame listed in **Table 3.1**.

## 4 Creation of the design space

*This chapter covers the creation of the design space and a simplified version of the structural parts, elements needed to perform a topology optimization.*

### 4.1 Package of the area

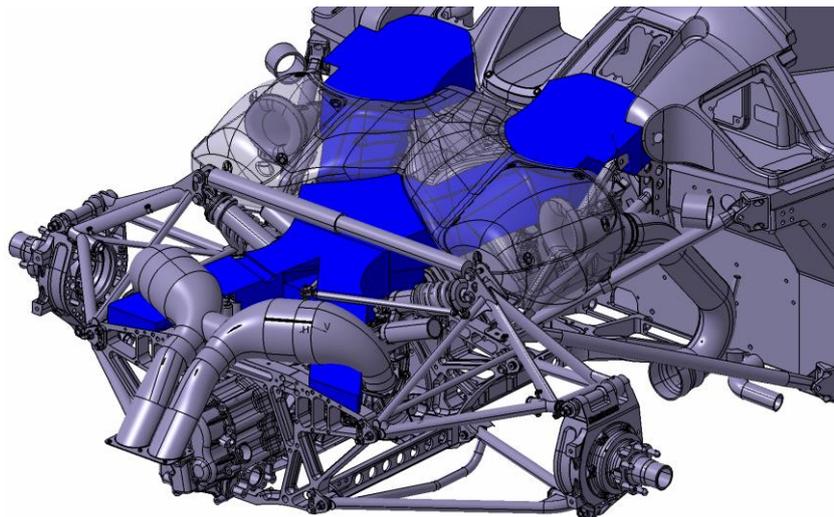
One important step to take when a re-design of a part is done is the definition of the volume boundaries. To set the available space for design, a package of the area affected by the new part has been done (**Figure 4.1**).

In this assembly some considerations are taken into account:

- Detection of close elements
- Detection of moving parts and range of movement.
- Detection of hot areas.

### 4.2 Available space body

After the assembly with all the elements is finished, a body taking all the space available has been created (blue body in **Figure 4.1**). This body represents the volume boundaries for the topology optimization covered in the next chapter.



**Figure 4.1** Package of the area with design space (blue). (Air intake to engine in transparent for viewing ease).

### 4.2.1 *Minimum gap.*

A minimum gap of 5mm within other non-moving parts of the car is set as a general dimension to avoid collisions with them.

### 4.2.2 *Analysis of the behavior of the moving parts.*

Three elements detected as nearby moving parts have been carefully analyzed:

- The rear dampers apart from contraction and extension, rotate due to the wishbones geometry in an area close to the design space.
- The Triplex or third damper has a contraction and extension movement combined with a translation in the vertical axis of the car when the rear dampers move.
- The stabilizer bar rotates through its mounting point in the rear damper bracket when the rear dampers are either extended or contracted.

For all these three elements maximum and minimum positions are detected and taken in consideration in the creation of the design space.

### 4.2.3 *Anchor points.*

Contact has been allowed between the design space and the mounting parts. This ensures load propagation and the mounting points are one of the last steps in the design process.

### 4.2.4 *Hot areas*

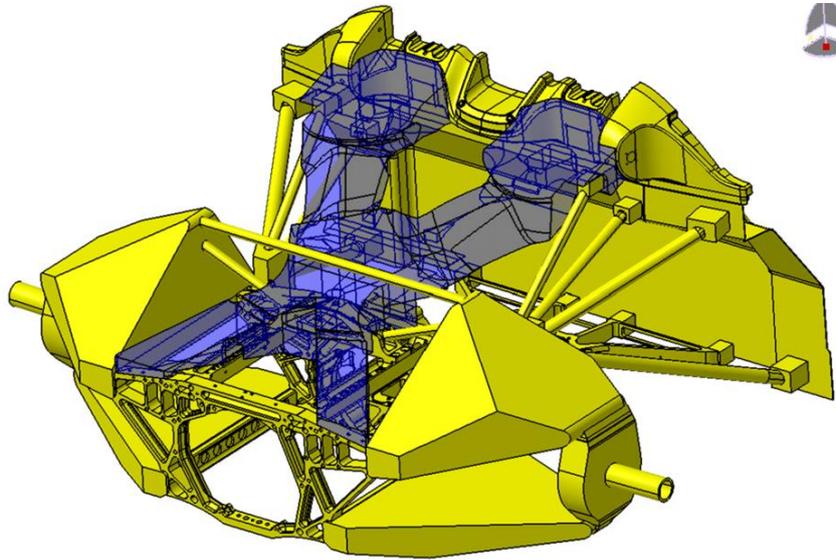
The hot areas detected are the zones close to the exhaust in the rear area. Some isolation can be added to avoid carbon fiber miss-function.

## 4.3 Creation of simplified geometry for analysis

For the simulations carried out in further chapters a simplified version of the structural parts of the area is created. The simplifications allow easier mesh and faster calculation times.

In **Figure 4.2** the yellow body is the result of this simplification with the main simplifications as:

- Fraction of the chassis and rollover bar.
- Simplified geometries for the wishbones and wheel hubs.
- Simplified rear damper configuration.



**Figure 4.2** Design space (blue) and simplified structural geometry (yellow).



## 5 Topology optimization

*This chapter explains the procedure followed in the topology optimization and the considerations made after it to create the final model.*

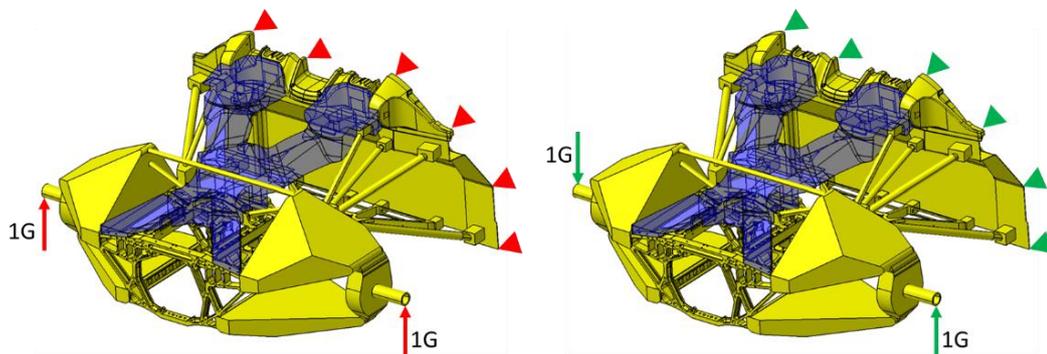
### 5.1 Description

In this phase of the thesis a topology optimization has been carried out using the design space created in the previous stage. The topology optimization uses the fraction of the space that offers best stiffness under a certain load condition to create an optimal-shaped part. For the procedure the software Inspire from HyperWorks has been used.

In this step an important simplification has been done. The material used for the optimization is aluminum which has different properties than carbon fiber but it is the material that fits better for this analysis. In this stage is not possible to use carbon fiber as the lay-up is not known and the software don't have the tools to simulate it. In further optimizations carbon fiber is used as material.

Two analyses with different load conditions have been performed (**Figure 5.1**), bending and torsion load cases. The performance of two different analyses permit the visualization of the effects of each of the load cases separately. For the last optimization a weighted compliance between both load cases will be used. With the weighted compliance it is possible to give more importance to one of the two load cases.

For the result, symmetry along the longitudinal plane of the car (right hand-left hand) has been required. The simulation is done with 1mm elements and the desired volume fraction has been set as 15% of the total.



**Figure 5.1** Loads and constraints for bending (left) and torsional (right) load cases.

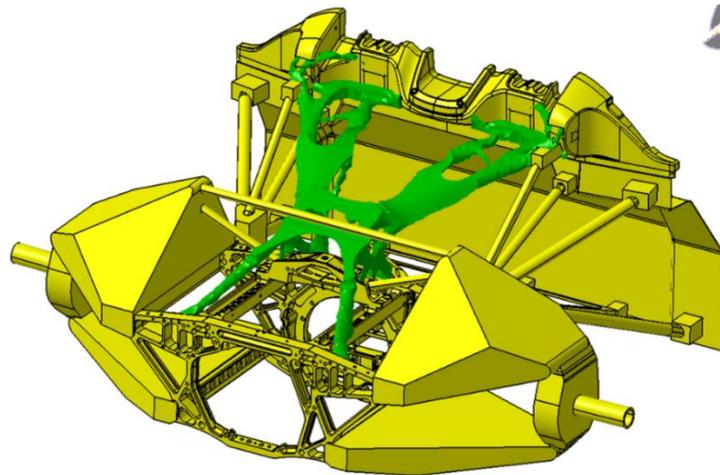
From now on the 3 main areas of the rear cross frame are referred as front, middle and rear referenced to the overall orientation of the car. The front area is the connection zone with the Chassis/Rollover bar. The middle area is the zone where the X-shape crosses in the central point. The rear area is the connection zone with the rear part of the gearbox frame.

### 5.2 Topology optimization results

#### 5.2.1 Bending load case

The results obtained in the bending load case are shown in the **Figure 5.2**. Some characteristic points have been observed in order to create the most optimized possible shape in the final design:

- Similar connecting points in the middle and rear areas as the part in production.
- Possibility of extra connections with the chassis/rollover bar in the front area.

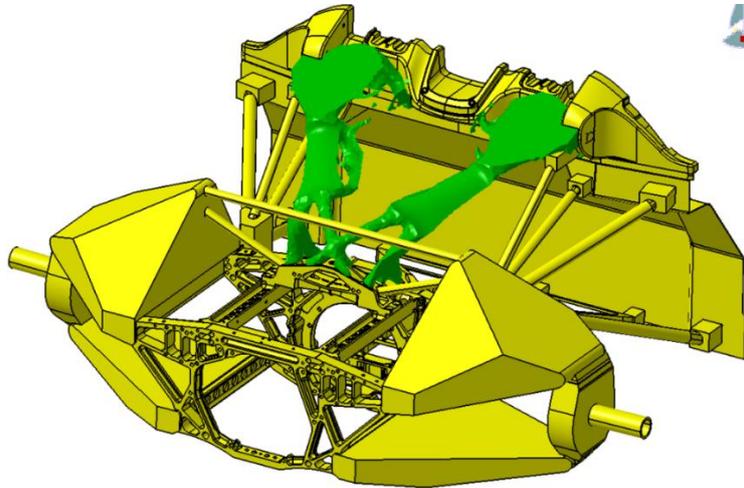


**Figure 5.2** Topology optimization for bending load case.

#### 5.2.2 Torsion load case

Under torsional load conditions the result obtained of the topology optimization is shown in the **Figure 5.3**. The main characteristics for this load case are:

- Lack of material in the rear area.
- More contact/connections with the chassis/rollover bar than the part in production.
- More robust connection with the rear damper bracket in the middle area.

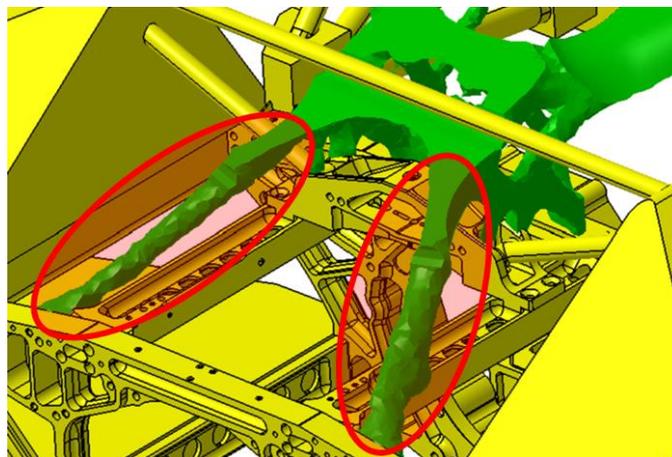


**Figure 5.3** Topology optimization for torsion load case.

### 5.3 Interpretation and decisions made to create the final model

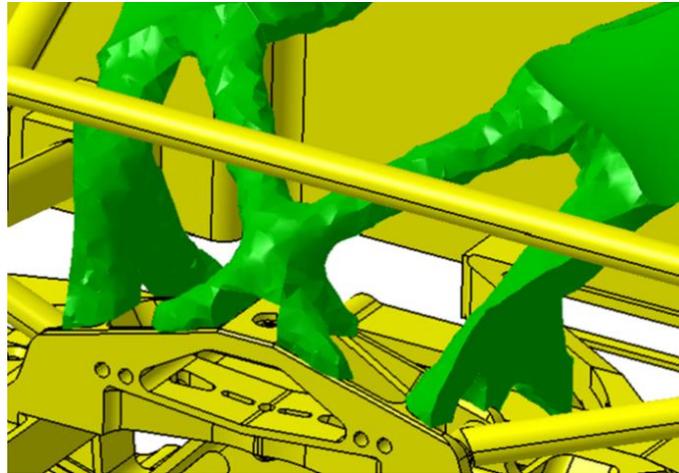
With the results of the topology optimization it has been possible to determine a few main guidelines for the final design.

First of all, as the bending load case is considered as very important for the rear cross frame, it is decided to extend the cross until the rear part of the gearbox frame (**Figure 5.4**) trying to keep the same connections as the cross frame in production has.



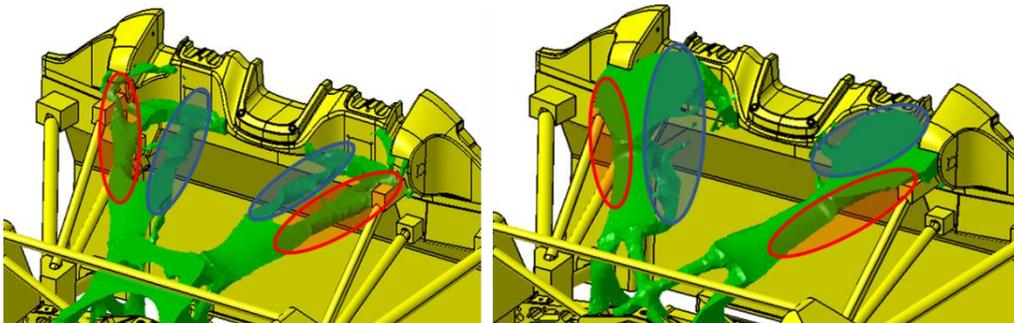
**Figure 5.4** Detail view of the rear part of the cross frame topology results for bending load case.

In the central area a better connection with the rear damper bracket has been set as an objective. In both load cases, especially in torsion (**Figure 5.5**), the topology optimization shows a material dense area. In this area is important to keep in mind the space needed for the dampers and stabilizer.



**Figure 5.5** Detail view of the middle area of the cross frame topology optimization for torsion load case.

In the frontal area (**Figure 5.6**), both load cases suggest the creation of an extra attachment to the rollover bar apart from the current one that attaches to the rollover bar bracket. This extra attachment (blue area in **Figure 5.6**) was initially considered but later dismissed for simplification reasons, manufacturing costs and weight.



**Figure 5.6** Detail view of the topology optimization front area of the bending (left) and torsion (right) load cases.

The final approach for the area has then been an attachment to the rollover bracket (red area in **Figure 5.6**). With a re-design of this attachment system a better mounting system than the one in production can be achieved.

## 6 Creation of the CAD model

*This chapter details the process followed through the creation of the CAD model.*

### 6.1 Topology result interpretation

The topology optimization outputs a clumsy-shaped body that needs a lot of refinement and interpretation but offers good guidelines to start modeling the surface of the new rear cross frame.

In the case of the design of the new rear cross frame the topology optimization helped to define that the X-shape was the most appropriate shape. In addition, some more material was needed in the middle area.

For simplicity reasons, the higher amount of mounting points possible were tried to keep as the same as the original rear cross frame ones.

### 6.2 CAD Design

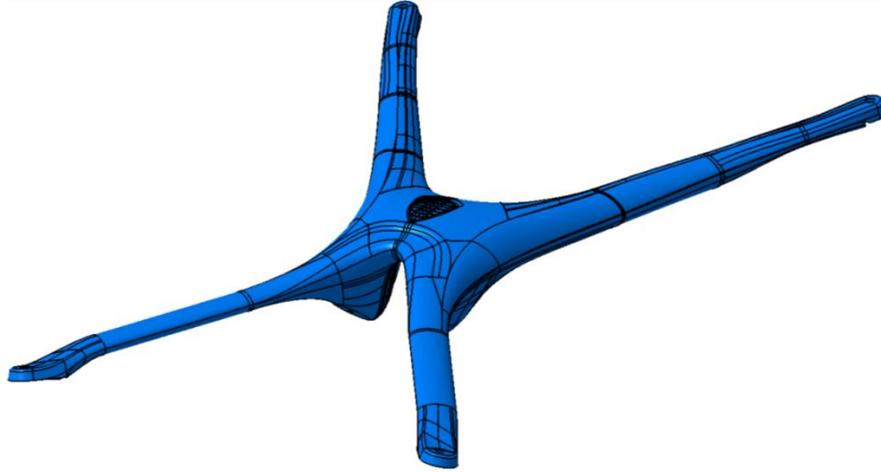
For this step, the parametric design CAD program used has been CatiaV5. The Generative Shape Design tool offers all the needed freedom to create the desired shape and features in the model.

In the design of any part, it is always important to keep in mind the manufacturing process used to produce the part. In this case, as carbon fiber parts use molds to be produced, the feature needed to be designed is the outer surface. This is the contact surface between the carbon fiber part and the mold.

#### 6.2.1 Outer surface

For aesthetic reasons, the A-face of the carbon fiber part has to be facing outwards as it is a visible part in the car. The A-face is the side of the laminate that touches the mold. It is smooth and better-looking than the side that touches the vacuum bag named B-face. The thickness depends on the final lay-up and it changes between the different areas. It is therefore only the outer surface (**Figure 6.1**) that needs to be designed. The same surface has been later used to design the molds.

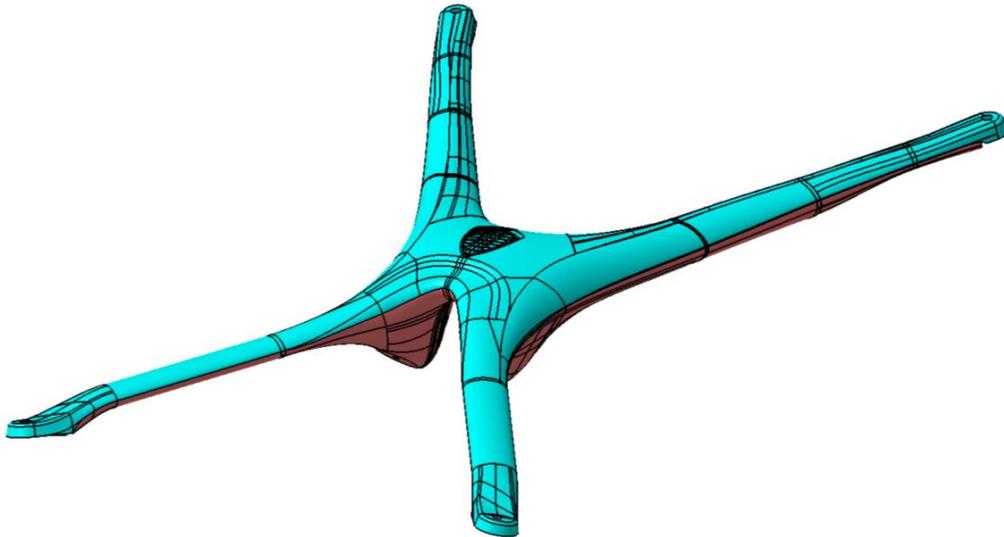
A logo in the central part of the cross frame has been added for company requirements. With 0.6 mm depth it allows the possibility of painting on it. It is on a visible area from the outside of the car.



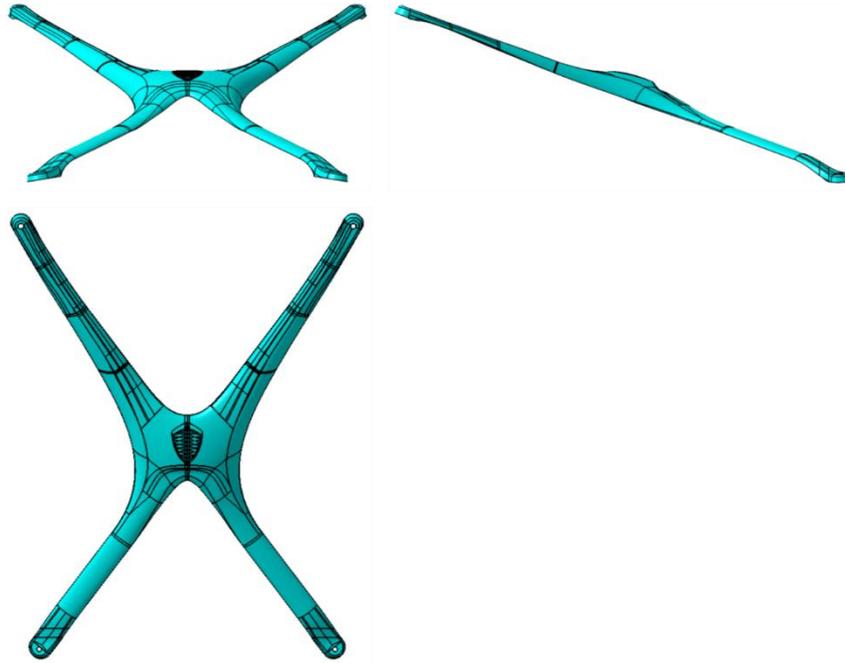
**Figure 6.1** CAD surface created.

#### 6.2.2 *Upper and lower halves*

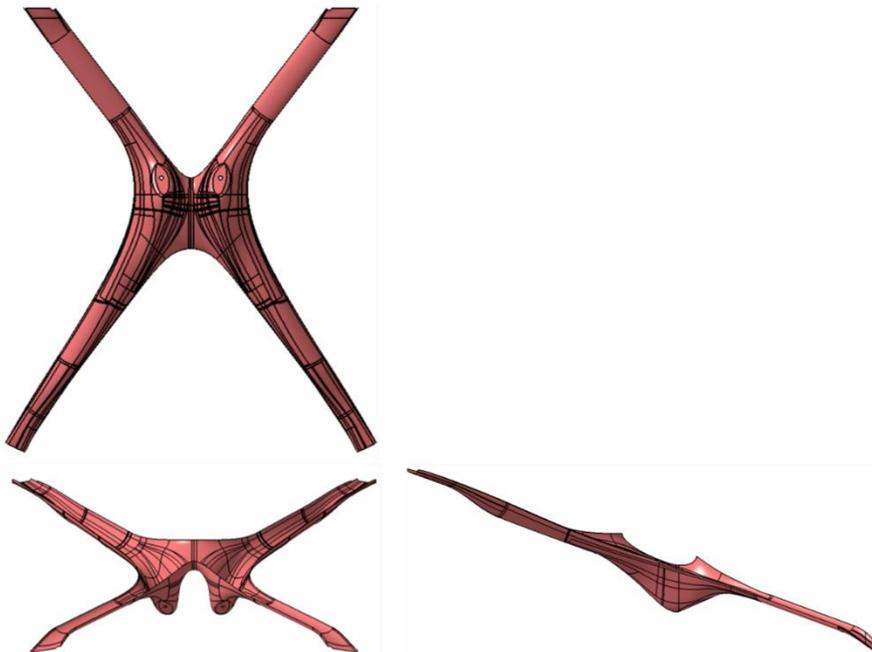
For manufacturing constraints the part has been split in two halves (**Figure 6.2**), the upper and lower (**Figure 6.3** and **Figure 6.4**). The reason for it is that carbon fiber parts are manufactured using molds and cannot have negative angles from the de-molding direction (vertical axis in this case). The final part is the result of gluing both halves as well as the aluminum inserts together, shown in further chapters.



**Figure 6.2** Part split in upper and lower halves.



**Figure 6.3** Projected views of the upper part.



**Figure 6.4** Projected views of the lower part.



## 7 Analysis and optimization

*This chapter defines the optimization process followed and offers a lay-up proposal.*

### 7.1 Definition

Once the final desired surface has been designed, an analysis to check the performance of the new part has been done. This analysis includes a carbon fiber lay-up optimization.

### 7.2 Software

The CAE software chosen for this stage was Altair's HyperWorks with the pre-processor HyperMesh, the solver Optistruct and the post-processor HyperView. Optistruct is an advanced Structural Analysis Solver both for linear and non-linear cases; market-leading solution for structural design and optimization [3].

### 7.3 Pre-process

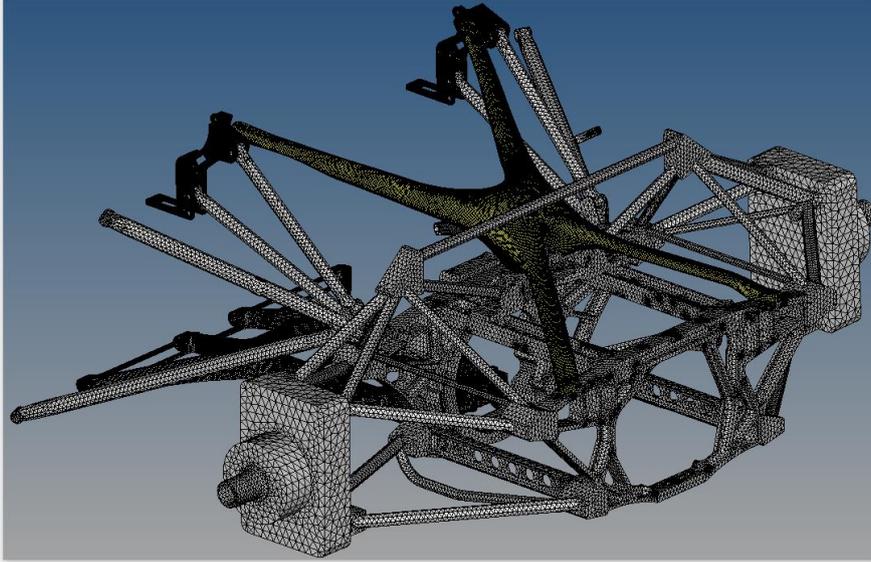
The first stage in any CAE simulation/optimization is the pre-processing. In this stage the CAD model has been imported and meshed, the materials have been defined and assigned to the different parts and the load conditions and constraints have been applied.

#### 7.3.1 Meshing

To properly mesh the model, different types of elements have been used.

The subframe bars, the rollover bar brackets, the wishbones, the gearbox-frame the uprights and the damper geometries have been 3D tetra-meshed (**Figure 7.1**).

The rear cross frame has been 2D meshed (**Figure 7.1**) since the composite laminates have to be applied to surfaces.



**Figure 7.1** Mesh with 3D elements (grey) and 2D elements (yellow).

### 7.3.2 Materials

To properly define the model, five materials have been created, two 3D materials and three 2D materials (**Figure 7.2**):

- Steel: Applied to the rear sub-frame bars.
- Aluminum (7075-T6): Applied to the gearbox-frame, wishbones, uprights and inserts in the cross-frame.
- Carbon fiber (630-TWILL), (280-TWILL), (600-UD): The different type of carbon fiber materials will be further assigned to different plies that form the laminate of the cross-frame and will be subject of the composite optimization.

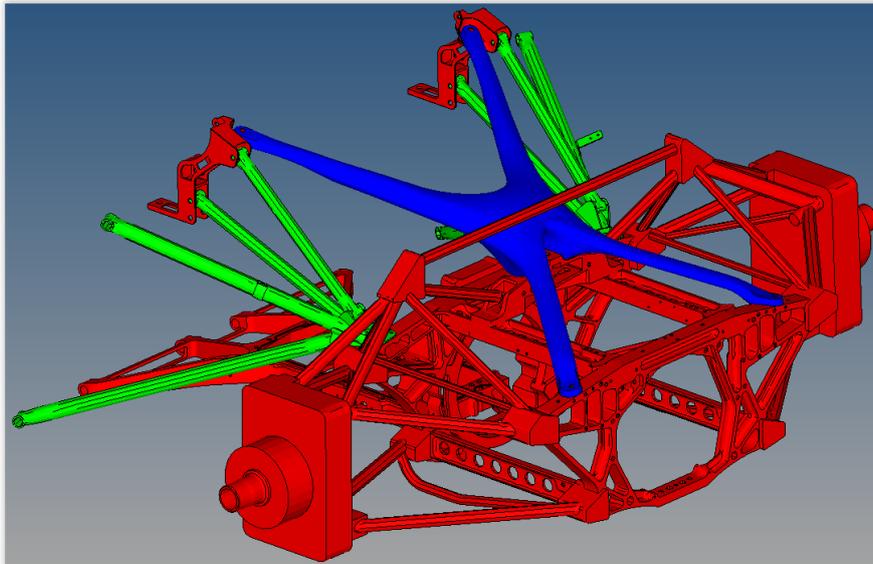
To properly apply the carbon fiber material to the rear cross frame, several plies with different materials and orientations and a laminate to tie them together have been created (**Table 7.1**):

- Composite laminate: All the plies have been applied to all the elements conforming the rear cross frame geometry. In the further optimization process some plies have been restricted to a few elements. The goal has been the creation of an optimal lay-up to better satisfy the load conditions.

**Table 7.1** Laminate stack with all the plies.

Ply ID	Material	Orientation	Manufacturing thickness
1	280-TWILL	0/+90°	0.328mm
2	630-TWILL	±45°	0.65mm
3	600-UD	0°	0.6mm

4	140-UD	+30°	0.6mm
5	140-UD	-30°	0.6mm
6	140-UD	+60°	0.6mm
7	140-UD	-60°	0.6mm

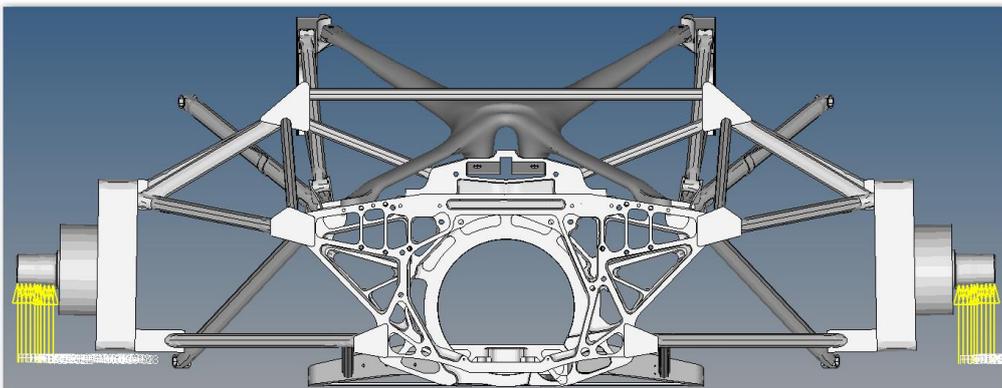


**Figure 7.2** Material definition for steel (green), aluminum (red) and carbon fiber (blue).

### 7.3.3 Loads and constraints

#### Bending load case:

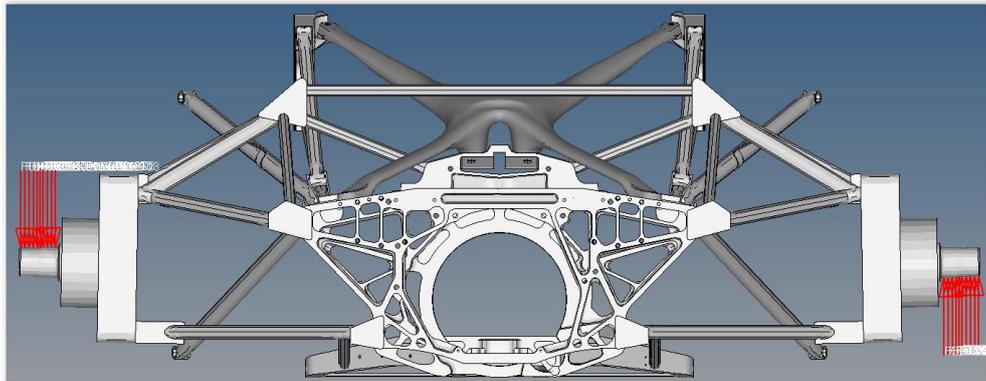
In the bending case 16000N have been applied in each wheel axle (**Figure 7.3**).



**Figure 7.3** Bending load case (yellow).

Torsion load case:

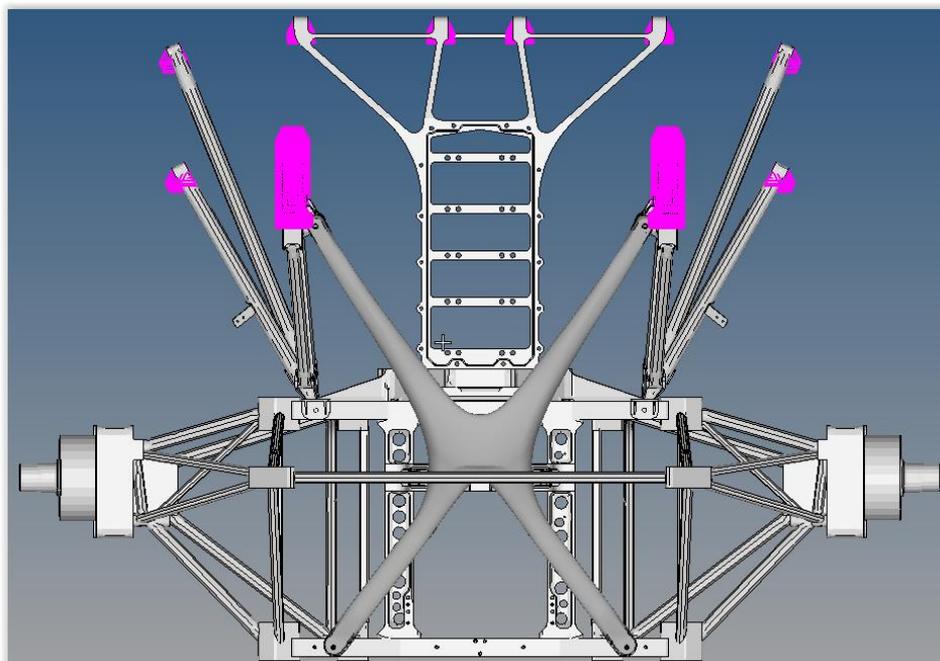
In the torsion case 16000N have been applied in each wheel axle (**Figure 7.4**).



**Figure 7.4** Torsion load case (red).

Constraints:

The constraints applied to the model can be seen in **Figure 7.5**. These ones simulate the attachment with the chassis and rollover bar, which for simplification reasons have been not included in the model.



**Figure 7.5** Constraints (pink) applied to the model.

## 7.4 Composite optimization

The approach for the composite optimization with Optistruct consists in three phases; the free-size phase, the size phase and the shuffle phase.

### 7.4.1 Free-size phase

In this phase, the shape of the plies has been optimized for the load cases. The thickness of each ply has not been taken into account in this first stage of the optimization.

#### Design variables:

- For plies with ID 3 to 7 in the **Table 7.1**, use or not the elements available to create the optimal shape.

#### Optimization responses:

- Weighted compliance. Applied to the two load cases, giving the same importance to both load cases in the analysis.
- Volume fraction. Applied the Carbon fiber materials.

#### Optimization constraints:

- Volume fraction = 0.3. The result will use the 30% of the volume. The fraction number is not important as any fraction works in this phase.

#### Objective function:

- Minimize weighted compliance. In order to get the result that suits better both load cases.

### 7.4.2 Size phase

In this second phase of the optimization, the shapes obtained in the first stage have been used as an input and the thickness of these shapes has been optimized to better fulfill the load demands. The resulting thickness has been used to determine the number of repeated plies as each material has a specific manufacturing thickness.

#### Design variables:

- Thickness of each ply obtained in free-size phase. Incremental steps with a value of the manufacturing thickness of each ply.

#### Optimization responses:

- Weighted compliance. Applied to the two load cases, giving the same importance to both load cases in the analysis.
- Mass. Applied the Carbon fiber materials.

#### Optimization constraints:

- Mass = Desired weight.

#### Objective function:

- Minimize weighted compliance. In order to get the result that suits better both load cases.

#### 7.4.3 Shuffle phase

This phase is used to optimize the order in which the different plies are stacked. Since there are a lot of manufacturing constraints and low amount of plies, this step has been manually optimized, keeping in mind:

- Symmetrical lay-up
- First layer 280-TWILL@0-90 for visual aspects.
- Maximum 3 equal layers together.

### 7.5 Final results

#### 7.5.1 Lay-up

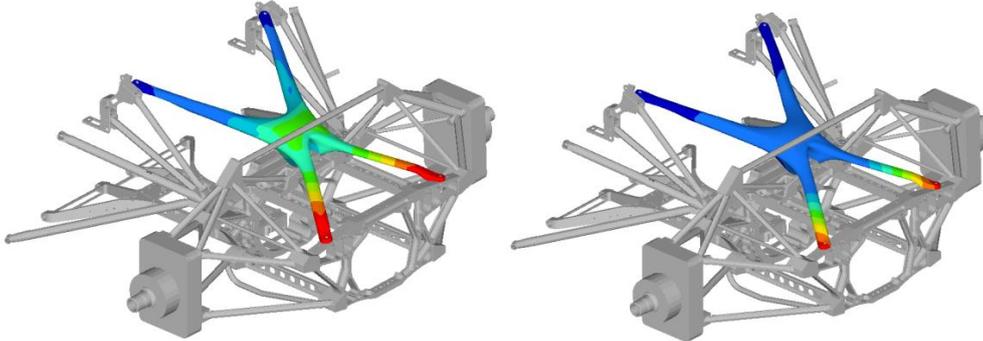
After some analyses varying the layers configuration and keeping in mind the company requirements for the carbon fiber parts, a final lay-up has been proposed (**Table 7.2**) and tested.

**Table 7.2** Proposed lay-up of the rear cross frame. Layers 1, 4 and 7 are applied to all the part. Layers 2, 3, 5 and 6 are only applied to the zones obtained from the optimization.

Layer	Material	Orientation	Zone
1	280-TWILL	0°/+90°	All zones
2	600-UD	+30°/-30°	Reinforcement zone
3	600-UD	+30°/-30°	Reinforcement zone
4	650-TWILL	+45°/-45°	All zones
5	600-UD	+30°/-30°	Reinforcement zone
6	600-UD	+30°/-30°	Reinforcement zone
7	280-TWILL	0°/+90°	All zones

### 7.5.2 Displacement

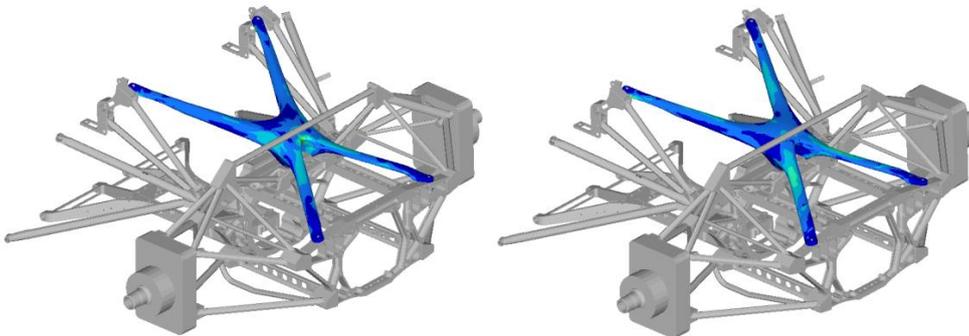
The displacement obtained for the new rear cross frame (**Figure 7.6**) presents the same values as the original cross frame<sup>1</sup>.



**Figure 7.6** Contour plot of the displacement of the rear cross frame under bending (left) and torsion (right) load cases.

### 7.5.3 Composite stress

The results obtained for the composite stress from the simulations are shown in **Figure 7.7**.



**Figure 7.7** Contour plot of the element stress in the rear cross frame for bending (left) and torsion (right) load cases.

<sup>1</sup> No numerical results are shown due to the company's confidentiality requirements.



## 8 Definition of the mounting areas

*This chapter explains the mounting areas of the rear cross frame to the rest of the car.*

### 8.1 Overall description

The new rear cross frame keeps the three mounting areas to the rest of the car that has the part in production. Some of the mountings have been updated or re-designed for constraint or mounting ease. The front part is attached to the rollover bar brackets, the middle one to the rear bumper bracket in the top front of the gearbox frame, and the rear mounting area is attached to the rear part of the gearbox frame.

In the mounting connections aluminum inserts have been included. These inserts are glued to the carbon fiber part and fastened to the mounting points.

### 8.2 Front mounting

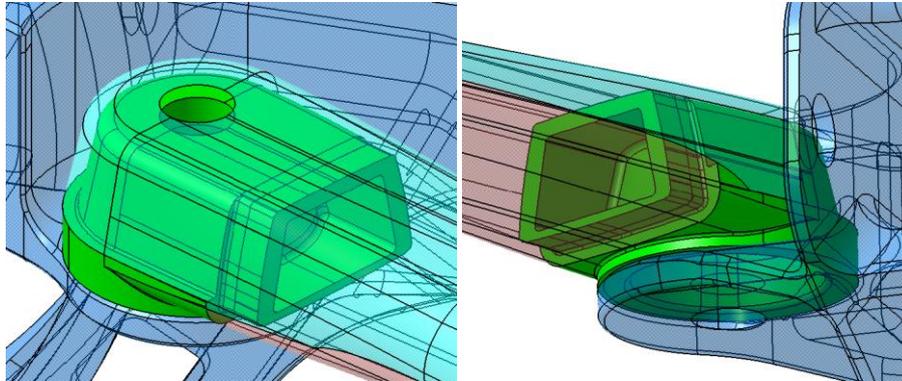
The part currently in production is mounted in its front part to the rollover bar brackets by bending slightly the steel tubes and inserting it in-between two flaps. The cross frame is afterwards bolted through these flaps to the rollover bar brackets.

In the installation process it is not possible to bend the carbon fiber part due to the material properties. A new mounting system has therefore been ideated. In addition, the rollover bar brackets have been revised and updated.

A cone-shaped mounting system has been chosen. It allows load propagation in several directions while connecting only one side. It offers commodity to mount the part in the car, since no bending is needed.

#### 8.2.1 Inserts

The inserts (**Figure 8.1**) are machined aluminum parts. They are glued at the same time as the upper and lower halves of the carbon fiber parts.



**Figure 8.1** Detail views of the front insert.

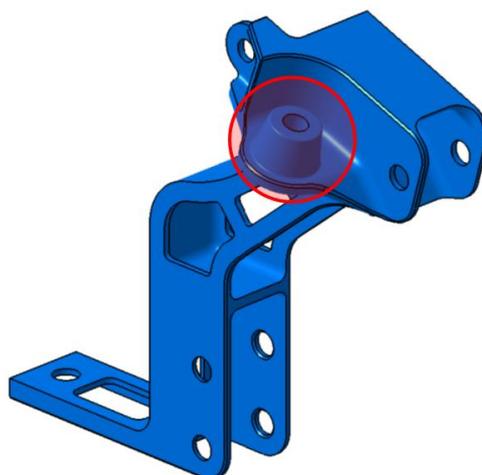
### 8.2.2 Brackets

A whole revision of the rollover bar brackets has been carried out. After some examination of the currently produced ones, some facts have shown a needed revision:

- Made of folded steel sheet metal.
- Too heavy.
- Not perfect fit with the rollover bar.
- Updated mounting system with the new rear cross frame needed.

The new revision of the part (**Figure 8.2**) offers the following features/improvements:

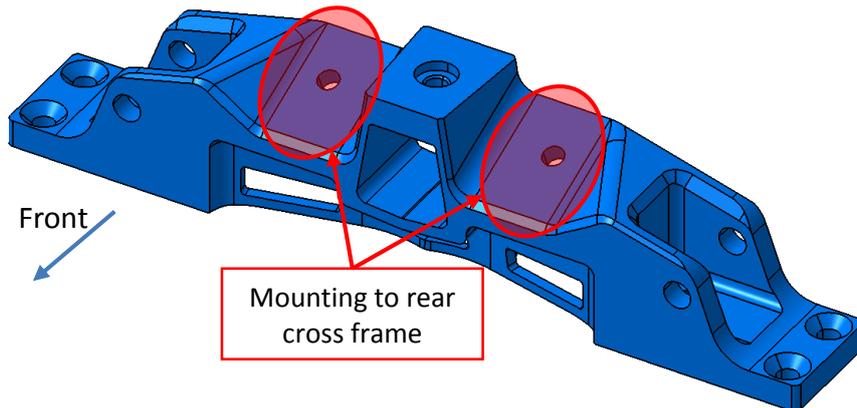
- Made of mechanized aluminum.
- 50% lighter.
- Perfect fit with the rollover bar.
- Modified cone-shaped mounting system with the rear cross frame (red area in **Figure 8.2**).



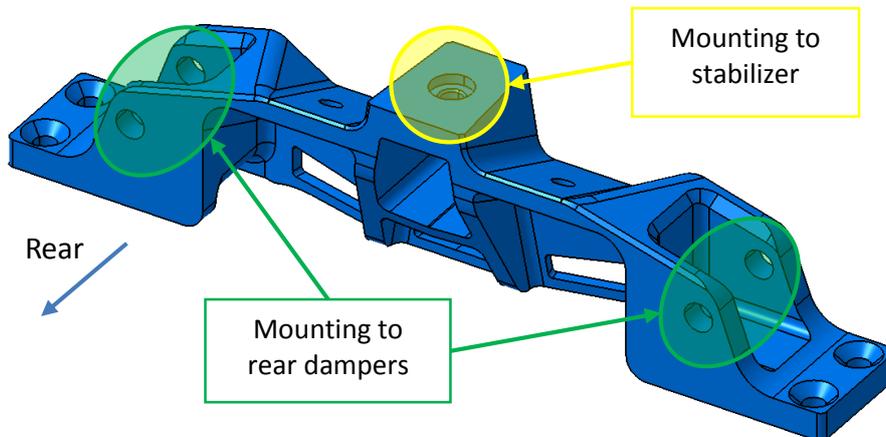
**Figure 8.2** New revision of the Right hand rollover bar bracket.

### 8.3 Middle mounting

The central mounting area has been slightly redesigned for mounting commodity and manufacturing ease of the carbon fiber part. The rear damper bracket needs a re-machining process in the central area (**Figure 8.3**), keeping the mounting system with the rear dampers and rear stabilizer as it is now in the part in production (**Figure 8.4**).



**Figure 8.3** Front view of the new rear damper bracket revision.



**Figure 8.4** Rear view of the new rear damper bracket revision.

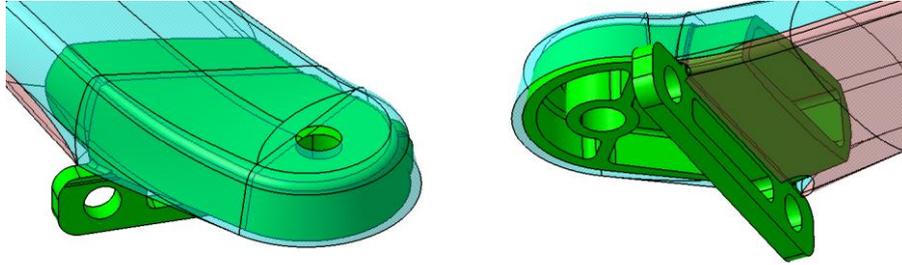
### 8.4 Rear mounting

The rear area of the part is bolted to the same holes as the currently produced part. There are no changes in the gearbox frame. In substitution of the flaps welded in the current cross frame, aluminum inserts are glued to the carbon fiber version.

#### 8.4.1 Inserts

The rear inserts, as the front ones, are machined in aluminum and glued to the carbon fiber at the same moment as the upper and lower halves. The inserts have a perfect

match with the gearbox frame, to which the cross frame is bolted to, and transmit the forces into the carbon fiber part.



**Figure 8.5** Detail views of the rear insert.

## 9 Production steps

*This chapter discusses all the process from the purchased machined parts to the final resulting part.*

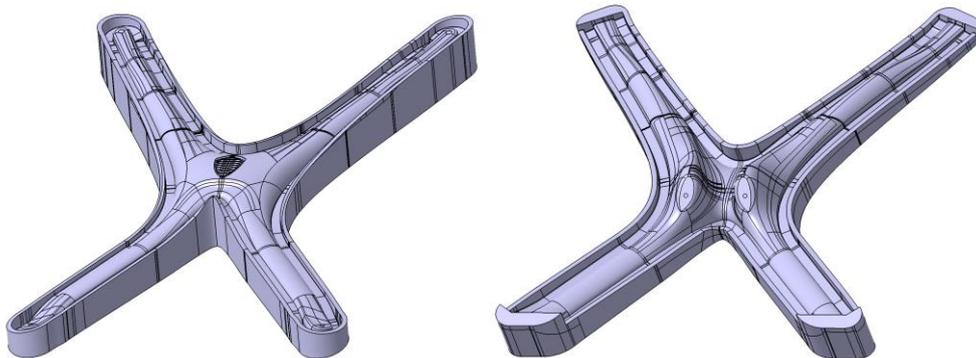
### 9.1 Introduction

For the creation of a carbon fiber part, a mold is used to apply the desired fiber materials and resin. After vacuum and curing process the desired final shape is obtained.

The molds used in the creation of the rear cross frame are made of carbon fiber itself and therefore have to be manufactured beforehand. Only one mold for the upper part and one for the lower are needed since the same ones are about to be used to manufacture all the cross frames needed. In order to create the molds a master is required.

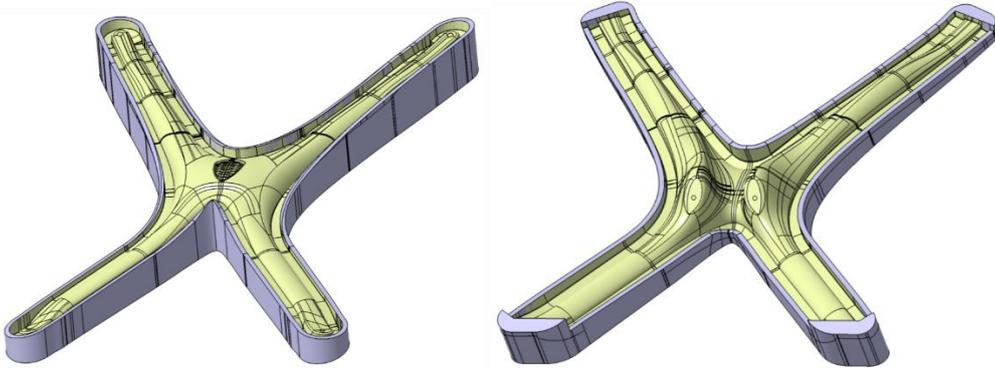
### 9.2 Creation of the molds from the masters

The masters (**Figure 9.1**) are the molds of the molds. They are machined in aluminum or a specific polymeric material and have the same shape as the final parts plus some extra features. These features are needed in the manufacturing process of the mold and final parts.



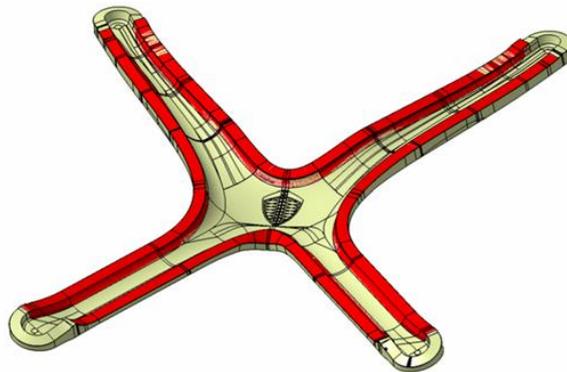
**Figure 9.1** Master for upper mold (left) and master for lower mold (right).

The molds are then created following the same process as any other carbon fiber part. As it can be seen in **Figure 9.2**, the molds have a flap in the trim-line area. This flap is used to have some more laminating surface and facilitate a clean trim in further steps of the production.



**Figure 9.2** Upper (left) and lower (right) masters (grey) with corresponding molds (yellow).

Besides the upper and lower mold, a third mold (**Figure 9.3**) is needed. This third mold is used to create an overlapping area between the upper and lower parts. This overlapping area is part of the final lower part. In further steps, the overlapping flap will be used to glue both halves together. Otherwise is not possible to glue them.



**Figure 9.3** Overlapping mold (red) created using the upper mold (yellow). This mold is used to create the surface to glue upper and lower parts together.

To create the overlapping mold, the upper mold is used as a mold and only the borders of the part are laminated.

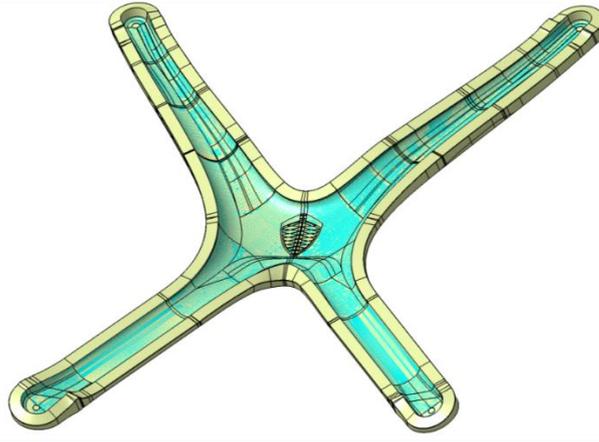
### 9.3 Creation of the carbon fiber part halves from the molds

The final carbon fiber parts can be created using the molds manufactured in the previous step as tooling.

For the upper part, the upper mold is used (**Figure 9.4**). The lamination has to extend a couple centimeters more than needed, through the flaps created in the mold. When the process is finished, the part can be precisely trimmed. The reason for the lamination extension and posterior trim is to achieve a higher finish quality. If the lamination

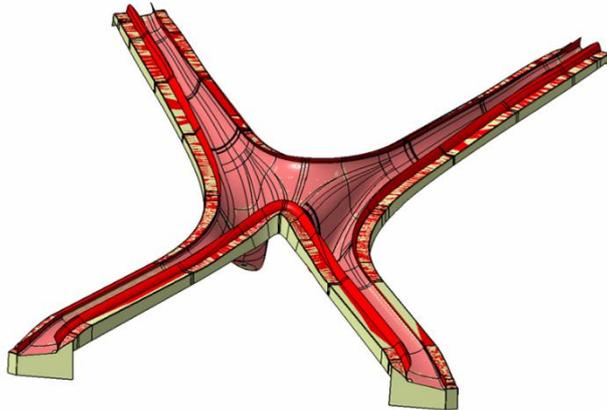
would finish in the trimming line without trimming needed, the edges of the part would have a low quality.

In this process the lay-up used is very important as it will determine the final part properties.



**Figure 9.4** Final upper part (light blue) and upper mold (yellow).

For the lower part, the lower mold and the overlapping mold are attached together (**Figure 9.5**). In the lamination process the fiber extends through both molds creating a single smooth surface. The part laminated on the overlapping mold is slightly offset inwards (thanks to the overlapping mold thickness), so it gets inside the upper part leaving a small gap to glue them when both are put together.

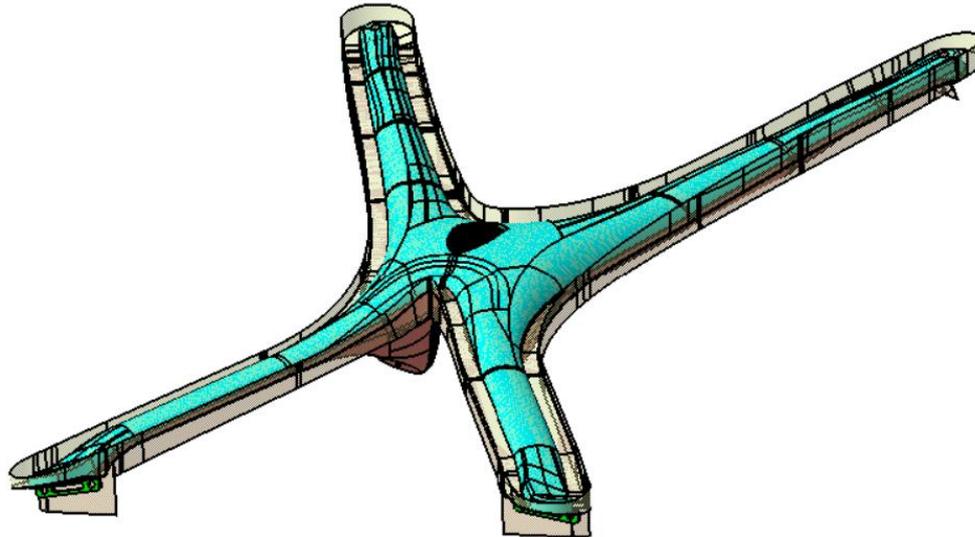


**Figure 9.5** Final lower part of the cross frame (light red) obtained with the lower mold (yellow) and the overlapping mold (red).

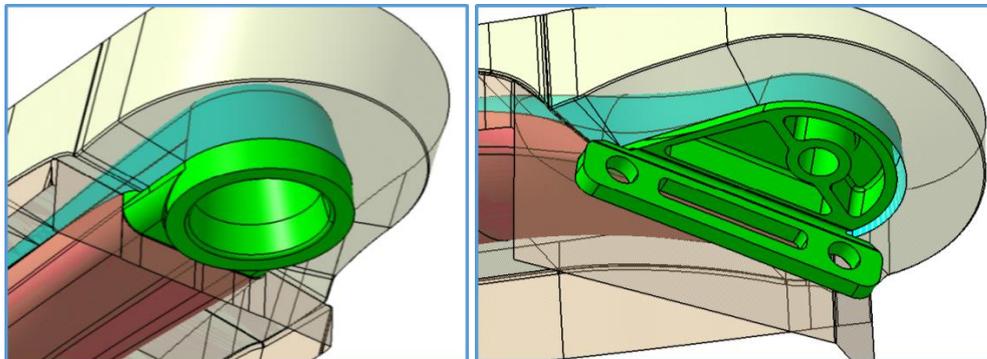
#### 9.4 Gluing of the carbon fiber halves and the aluminum inserts

At this point both the upper and lower parts are manufactured and can be glued together (**Figure 9.6**). The overlapping part in the lower half fits inside the upper half offering

a gluing surface. Apart from both halves, the four aluminum inserts are glued in the same process (**Figure 9.7**). For a perfect and precise positioning in the gluing process, the parts are inserted in the molds as both molds fit perfectly together.



**Figure 9.6** Final upper (blue) and lower (light red) parts with aluminum inserts (green) inside the carbon fiber molds (transparent light yellow).

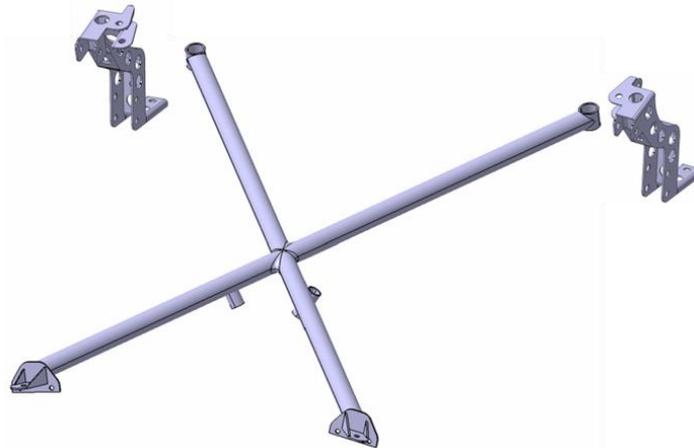


**Figure 9.7** Detail view of the front (left) and rear (right) inserts gluing process. Inserts (green), upper part (blue), lower part (red) and molds (transparent light yellow) are showed.

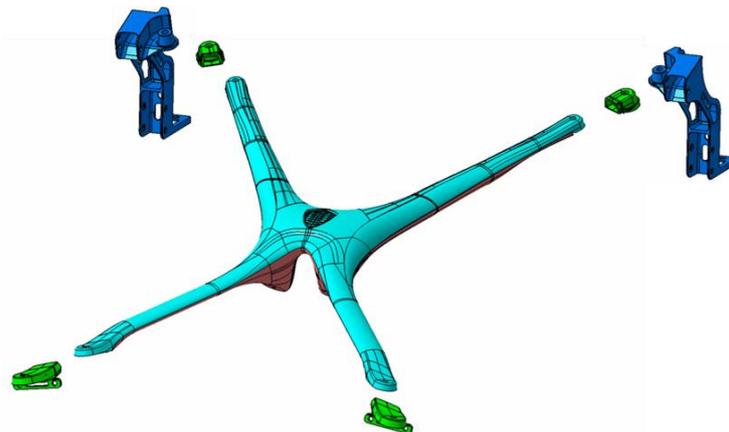
## 10 Final results

*This chapter covers the final results.*

In the results of the product, both the rear cross frame and the rollover bar brackets are included. A comparison between the current and new proposal can be seen in **Figure 10.1** and **Figure 10.2**.



**Figure 10.1** Current rear cross frame and rollover bar brackets.



**Figure 10.2** C/F rear cross frame proposal, re-designed rollover bar brackets and inserts.

The results are based on four main aspects:

### **10.1 Stiffness**

With the new version of the rear cross the same stiffness has been achieved, when mounting the part in the car and running the same analysis as with current part.

### **10.2 Weight**

The new rear, cross frame in addition with the revision of the rollover bar brackets save 33.3% of weight, in comparison to the same set which is currently in production.

### **10.3 Cost**

The black spot of the optimization is the cost. The carbon fiber manufacturing process and the materials have a higher cost than welded steel tubes and blended sheet metal. The cost for the new set supposes an increment of 232.2% if compared with the currently in production parts.

### **10.4 Aesthetics**

The new carbon fiber version of the rear cross frame is more visually appealing than the current one. The visible carbon fiber offers a high-tech sensation which the steel does not present. In addition the shape is more organic and the material follows the flow of the carbon fiber coming from the chassis and body panels in the car.

## 11 Conclusions and reflections

The thesis is a walkthrough of the steps followed in the revision of a structural part of a supercar. The main impact of the revision has been the change of the material used, switching from steel to carbon fiber.

The goals for the project are the achievement of a lighter and stiffer part. In the supercar industry price takes a side role leaving more importance to performance given by lightness and stiffness in the case of this thesis.

As a starting point, a topology optimization has been done using the load cases that the car is has to take, in order to see possible geometry changes from the current steel part and use it as guideline to create the CAD model.

With this guidelines a CAD model has been created and modeled.

Later on a lay-up optimization for the carbon fiber laminate has been performed to achieve the best stiffness possible keeping in mind the weight reduction.

The next stage has been the definition of all the mounting areas for an easy-mounting and robust solution. Some changes have been done in other parts of the car affected by the new rear cross frame.

The last step has been the creation of the tooling needed to manufacture the part such as molds and masters.

On one hand, the obtained results present in general terms the same stiffness offered by the current rear cross frame, a reduced weight of 33% and a better visual appeal. On the other hand the cost increases at 232%, as manufacturing in carbon fiber is much more expensive than steel.

Once the part is completed it is possible to step back and revise the resulting part from a wider perspective. The proposed solution fulfils the functionality requirements and working conditions. It offers additional hi-tech feeling once the rear hood is lifted. Due to the brand exclusivity, this is a characteristic that Koenigsegg clients call for. The carbon fiber flow has been now extended from the chassis through the rear cross frame. With further revisions of parts such as the rear sub-frames and the rear wishbones, this flow could extent through the whole car length, offering as well the best possible technology in parts not as visible as the body panels.

This master thesis began as an optimization for the rear cross frame and the rear sub-frame. Owing to time issues, it was later on focused on the rear cross frame to be able to obtain a finished product, ready to put on production if desired by the company. The

revision of the rear sub-frame could be soon faced as a side project from the one discussed in this master thesis.

As a personal opinion, the revision created for the rear cross frame improves the part in Koenigsegg standards. Weight and aesthetics are key aspects for the company. However, because of the price, Koenigsegg should investigate if the cost/weight reduction ratio fits their requirements, in order to put the optimized carbon fiber rear cross frame in production.

During the development of the project a lot of knowledge has been acquired. If the project would begin now, some aspects would be faced in a different way. In several phases, some of the procedures have been repeated due to changes in the inputs. This has taken a lot of extra time that could have been reduced by dedicating more time in the proper setting of these inputs. Putting some extra attention in small details can save a lot of time and troubles.

The result of the thesis hasn't been implemented at the moment of the publication of this thesis.

Overall, the whole experience has been positive and the result come up with is satisfactory.

## References

### *Online sources*

- [1] Koenigsegg home page. <http://www.koenigsegg.com/koenigsegg/>. Last time checked 12 August 2014.
- [2] CATIA home page. <http://www.3ds.com/products-services/catia/welcome/>. Last time checked 12 August 2014.
- [3] Altair Hyperworks home page. <http://www.altairhyperworks.com/>. Last time checked 12 August 2014.

### *Oral information*

During the development of the thesis most of the information was directly obtained through experts from Koenigsegg Automotive and Altair Engineering:

- [4] Martí, Lluç. Composites Manager at Koenigsegg Automotive. Everyday personal conversations from 9 January 2014 until 11 July 2014.
- [5] Nordgren, Fredrik. Application engineer at Altair Engineering. Telephone conversation 2 April 2014.
- [6] Magnemark, Erik. Application Engineer at Altair Engineering. Everyday personal conversations from 28 April 2014 until 23 May 2014.
- [7] Truedsson, Joakim. Application Engineer at Altair Engineering. Everyday personal conversations from 28 April 2014 until 23 May 2014.
- [8] Edrén, Niklas. Composite expert at Altair Engineering. Telephone conversation 23 May 2014



## A. Appendix: Time plan

- Beginning: 9 January 2014.
- Progress:
  - Preparation: 9 January 2014 – 15 February\*
  - Topology optimization: 16 February 2014\* – 15 March 2014\*
  - CAD design: 16 March 2014\*– 15 April 2014\*
  - Lay-up optimization: 16 April 2014\* – 3 June 2014.
  - Final parts design: 3 June 2014 – 10 July 2014.
  - Writing: 11 July 2014 - 15 August 2014.
- Finish: 15 August 2014.
- Presentation: 19 August 2014.
- Last changes after correction: 14 October 2014.

\*Approximate dates