USER-RELATED METHODOICAL DEVELOPMENT OF COST OPTIMISED CFRP INTERIOR COMPONENTS FOR DERIVATIVES OF LUXURY CARS

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ABSTRACT

Historically coming from the aerospace industry, the current demand to reduce weight, fuel consumption and hence the carbon dioxide emissions have led to an increase of CFRP parts within the automotive sector. A lot of companies pursue different approaches for implementing composite structures into their products. In contrast to the rest of the industry, the unique visual appearance and the weight saving potential of CFRP parts are not only drivers especially for derivatives of luxury cars. In order to change a current existing design and introduce it as a visual composite part into the interior of a car, a new design process is required to support the unexperienced engineer. The challenge is to picture a process that offers enough flexibility and explains the influences the different steps have on each other. This process is targeting two main attributes - a fibre sympathetic design and the cost optimisation. Every step has to be measured against these attributes in order to develop a CAD-model. The full paper shows the developed process and provides detailed information about the different design steps based on the research and experience gained during the project with Bentley Motors Limited. On the one hand the investigations are centred on the Bentley specific requirements such as the acoustic properties of the parts and on the other hand the necessary changes that are required in order to deliver a fibre sympathetic design.

1 INTRODUCTION

“Structural engineering is the art of moulding materials we don’t wholly understand, into shapes we can’t fully analyse, so as to withstand forces we can’t really assess…” – James E. Amrhein.

Targeting a completely different engineering field, this quote surprisingly accurate describes the challenges when designing composite parts within the automotive sector. This research is targeting that problem and tries to give the unexperienced engineer a tool to support and structure his design work. It must not be mistaken as an extensive methodology but it is a very simplified and authentic try to illustrate such a complex thing like a CFRP design process.

The automotive sector underwent a significant development in the last decades. From 1987 to 2000 the life cycles of vehicles decreased from twelve to seven years and the number of derivatives doubled between 1999 to 2005. This development is overlaid by the negative weight spiral. In dependence on Trautwein [1] it describes the cycle, where an extension of functions leads to rising requirements towards a component and hence an increase of weight.

The different OEM’s try to cope with that development in different ways. One approach is to trying to reduce the portfolio and get rid of inefficient derivatives in order to become the market leader in one specific segment. A different way is trying to expand the portfolio and establish the products in a broader fashion.
BMW tries to break the negative weight spiral by introducing a CFRP passenger compartment structural cage and additional CFRP components. Other high-end automakers like Mercedes-Benz and Lamborghini have committed to increase the use of CFRP component in their vehicles to reduce weight [2].

The VW Group is a very prominent pioneer in regard of the systematic product architecture [3]. By establishing the platform architecture VW-Group realized significant economies of scale. These platform architectures have improved to a modular design technique which VW-Group refined to a modular matrix platform. The current trend of introducing derivatives of high volume cars into the market to satisfy niche markets can also be observed with the introduction of the Ford Puma which was delivered to market in 17 months from concept to production [4].

To satisfy that demand, Bentley introduces special editions of current models with minor expenses in near future. These derivatives are sold for a higher price but in order to justify that the styling changes in comparison to the current model have to be as significant as possible.

In order to create such a unique selling point, CFRP parts are currently the state of the art to alter a current design. Visible composite materials offer the possibility to implement a racing flair and potential weight saving with minor investment costs and minimal effort. These small derivatives established the necessity of very cost efficient developments and tooling for Bentley and only secondary low unit costs. That is an opposing trend to the current approach in the production in the automotive sector. In order to respond to the quickly changing customers’ demands of the luxury car segment, a very short lead time became another very important attribute for manufacturing techniques and the development of special edition derivatives. Hence, the conclusion to research and develop carbon interior parts, especially for derivatives in small series production (250-500 car lifecycle), suggested itself for Bentley Motors Limited.

The development of derivatives in the automotive industry is usually based onto a current car and a current design. Hence, the requirement of using an existing design as a starting point is a reasonable approach for the development of a CFRP interior part. Due to the fact, that Bentley puts a lot of effort on the visual appearance and the acoustic properties of a part, no methodology matching these requirements is available for visible CFRP parts. Within the literature, many methodologies for the development of structural composite parts exist. For Bentley however, the visual appearance and acoustic properties for interior parts are the main attributes and more important than the structural advantages. Therefore a new methodical development process considering the special requirements of Bentley Motors Limited, under consideration of the unit costs, has to be defined and evaluated, that allows the unexperienced engineer to support and supervise such a project.

2 STATE OF THE ART AND METHOD

The key to a good design process is to do the right thing at the right time with the desired result. The challenge for CFRP parts is, to find and define that process, especially with unexperienced engineers. Most design methodologies or guidelines are a linear process with possible iteration loops especially for composites. Therefore an overview of the different approaches is required to merge and adapt them to deliver a user-related CFRP design process.

2.1 State of the art of design methodologies

Through its origin in the aerospace industry the main driver to apply composite materials has always been the possible weight saving and the superior mechanical material properties in comparison to most metals. Based on that, design guidelines and methodologies are focused onto a lightweight design and the optimisation of that.

One good example for such a guideline is shown in Figure 1 on the upper right side by Friedrich [5] focussing on the weight of a part. The process is divided into the three main lightweight concepts strategic, tactical and operative. The entire design has to be measured against the resulting weight. In dependence on Friedrich [5] the several steps of this methodology must not be applied rigidly but rather be seen as a guideline. With this methodology several approaches to develop a part can be defined and a clear boundary between the different steps cannot be given. All ideas and concepts regarding the weight optimization have to be measured against their costs and risks. The separate
components, the assemble and the overall system result into a theoretical product, which is designed to the point where a first prototype is built. In order to evaluate the properties and functions of the design, this prototype should be built as early as possible. Concepts and ideas that are not implemented have to be documented and filed, to avoid evaluating an idea several times. Are the functions, price or the weight not in the target area, the overall system or an element have to be changed and another iteration must be started. This procedure has to be continued until the functions, the price and the weight are acceptable. It is obvious that the emphasis in this methodology is primarily put on the weight reduction and optimization. Although these attributes help to develop an ideal design, the weighting of these attributes in comparison to the appearance is problematical. The visual appearance plays a minor role within the process.

Figure 1: Overview of three design guidelines “The handbook of fibre reinforced polymers” [6] (left side); Lightweight design (upper right side) [7]; “Muenchner approach” (bottom right side) [5]

A more generic methodology for the dimensioning and development of an FRP part is shown on the left side in Figure 1 [6]. The process shown is quite complex and with the possible iterations it implies the risk of several extensions during the design process. Especially for the design process the focus lies on the fibre sympathetic design. In dependence on “The handbook of fibre reinforced polymers” [7] the anisotropic material properties are the most important thing to consider during the design process. A rethinking into plies and fibre orientations has to take place in order to achieve a satisfying design. The process is based on the classical laminate theory. This theory helps under the premise of the known loads within the design, to find a preliminary dimension for a new designed FRP part. Another main point regarding this approach is the calculation of the design. With a CAD model in place a calculation can proof the fulfilment of the required stiffness and strength. The focus of this approach is onto the calculation and the dimension of the part.

A general approach to solve problems is the “Muenchner approach” by Lindemann [5] which is shown on the bottom right side in Figure 1. The fundamental idea is to give the engineer a process that
can be adjusted considering the current problem. In contrast to a linear approach it allows iterations on different stages and even encourages to use the whole process again if you are struggling with one part of the main process. One problem though, is the lack of time restrictions. The process will find a solution but gives the user no guideline to manage the project timing.

Bearing in mind all advantages and disadvantages of the several methodologies, a process regarding the specific requirements considering a composite design, with the possibility of iterations, guidance regarding timing and the visualization of the dependence of the different design steps needs to be developed.

2.2 Two main attributes (method)

As emerges from the previous chapters the requirements of the project quite differ to usual CFRP design processes and especially its timing. The lead time from project start till start of production should not extend fourteen weeks, which is usually the time frame for prototype constructions. The demands regarding visual appearance and the acoustic properties, on the other hand, are at the highest level. This puts this whole development into a very challenging environment. Within the Luxury Cars segment the project engineers are not highly specialised. They have to supervise many different developments and must not be mistaken as experts for composite designs. Therefore a user-related design process within the context of this project implies a high understanding and a lot of experience of a general design process but not so much regarding the special characteristics of a fibre feasible design by the responsible engineer.

One of the key words when designing with composites is integration. It might be the integration of functions or systems and is hence one of the special characteristics mentioned above. But the general opinion that an integral “unit body construction” lowers the cost by simplifying assemble and lowering the weight of the car, which, in turn, lowers materials and operating costs [8] has to be relativized. CFRP structures offer a great potential of integrating and simplifying designs, but as shown in Figure 2 in dependence on Benz, Hutterer, & Roth [9] the manufacturing costs for CFRP parts rise with increasing integration of parts. The perfect balance between integration and differential design is influenced by the manufacturing technique, the production numbers and possible savings through the assembly and material costs.

![Figure 2: Costs vs. number and size curves of individual components (not in scale)](image)

One of the main attributes mentioned before is the fibre feasible design. Achieving such a design implies finding the compromise zone between an integral and differential design and not only the right
geometry, fixing strategy and assemble process. Therefore carry/over parts have to be assessed and a decision based on facts has to be made whether it is beneficial to integrate their functions within the composite structure or alternatively allow the attachment of the carry/over parts into the new design.

To do this and to critique the design regarding its integration, it is important to find an easy and quick way to assess the different designs. Depending on the scope of an assembly a pragmatic and constructive way to do that is to develop a various number of proposals until they reach concept design status. With these designs the next main attribute called the “cost optimization” can be targeted. Therefore the unit cost is only one subitem. Assembly costs, Investment costs and not least the shipping and handling costs have to be taken into account.

In order to evaluate the developed methodology the obvious next step is to apply it to a real part and critique not only the methodology but also the developed designs. Therefore it is decided to use a current interior door assembly of a Bentley Continental GT, bring two different CFRP-designs to concept design status and manufacture and compare them. One design is supposed to be a highly integrated fibre feasible design – ideally as one part. The other is a so called semi-integral design with more parts, more functions and hence more carry/over parts. With those two different approaches the impact on costs and delivered functions will be evaluated and the methodology can be applied and improved. In order to compare both doors in one car, the semi-integral door will be built for the left side of the car and the highly integrated design for the right side. Due to the targeted volume of 250-500 cars/lifecycle the used manufacturing process will be a prepreg hand layup process. This manufacturing technique delivers a good A-surface finish combined with low investment costs.

3 RESULTS

The challenge of the user-related visualization of the methodology for the executive engineer is to show the dependence of all the mentioned attributes above. At first this visualization will be shown and explained. Thereafter an abstract of the results of the implementation will be presented using the two different door designs.

3.1 Methodology

In contrast to a common design process, the outline of the different steps of a CFRP design process cannot be traced clearly. Many steps influence each other and depending on which attribute is determined at the beginning, the outcome can vary significantly. In order to leave the designer and the supplier as much freedom as possible, the new process shown in Figure 3 is developed. Basis of the development is the “Muenchener approach” shown on the bottom right side in Figure 1. It is used in an altered way to still show the dependence of the different steps but it must not be seen as a predefined approach. Based on a list of requirements, which is established in the concept phase, a rendered picture from styling marks the starting point of the process. Two gateways have to be completed during the process and the outcome is the final CAD data for tools and parts.

Due to the interaction between the different steps, a strict chronological order cannot be determined. Hence every project leader is able to define, a unique way in cooperation with the supplier of designing the components. The grey circles show the steps that have to be completed before passing a gateway. Thereby the diameter of the circles is no measurement of the duration of each circle but shows the interaction between the different steps. Whenever a circle overlaps with another circle the steps influence each other. Hence the impact of a change or determination in one circle has to be validated and measured by the impact it has on the overlapping circles.
The two main attributes of every CFRP part are emphasised by the red colour in Figure 3. Before passing the first gateway, “split lines”, every decision has to be measured against its fibre sympathetic feasibility. Therefore a design guideline is developed. This design guideline gives a basic understanding of what to consider when designing with CFRP and how small changes to a common design create a fibre sympathetic design. Nevertheless the tooling design and the influences from the manufacturing process have to be kept in mind. During that phase, the main question is where to draw the line, between a differential and an integration design methodology. Due to the unique anisotropic material properties, CFRP is predestined to integrate several parts and functions into one more complex structure. However, every circle has to be considered and a potential part combining all functions might not be feasible due to the carry/over parts or the trim feasibility. Once all requirements and steps are implemented into the design, a decision on the number of parts is made.

The second main attribute is cost optimization. As shown by the overlap between the two red circles, the decision of the split lines interacts with the unit costs. Nevertheless, a starting point for the cost optimization has to be defined, whereby the step “cost optimization” takes place after the gateway “split lines”. Related to the first process, every circle has to be completed before a decision about the lay-up strategy is made and the design process is finished.

Based on the picture delivered by “Styling”, the left hand side door is developed as similar to that design as possible. Under this restriction, all split lines are drawn by still integrating as many functions and parts as possible. This leads to a 3-part design for the semi-integral design. The right hand side door is designed to integrate the whole A-surface into one part, trying to design a door as highly integrated and light as possible. All attributes are determined to deliver a door, that considers the usual values on the one hand, and trying to push the envelope as far as possible into the integration of functions of the former design. Therefore the style of the door has to be compromised, but a significant weight difference should be observed. Required c/o parts have to be considered but common luxury features might get disposed.

3.2 Trim feasibility

One requirement of the new CFRP-door is the implementation of hide into the design. The execution of the integrated leather has to contain the current quality and must not be compromised. The easiest way to deliver a nice split line between two surfaces is to design a separate part that allows wrapping
the leather around and attaching the new part to the assembly. This highly compromises the idea of the integration of functions and parts. Therefore an alternative that allows the implementation of hide in one part needs to be developed. The best solution is a so called “tuck groove”, which can be seen in Figure 4. For this technique the carbon parts, where the leather is applied, have to be pre-treated. The lacquer has to be grinded in order to spray the adhesive onto the area where the leather is applied. The used adhesive is a two-component glue, so the B-surface of the leather is pre-treated as well. Starting at one specific point, the leather is applied using heat and pressure in order to combine the two components. The raw edge of the leather is then tucked into the groove in the substrate to deliver an aesthetic finish. The challenge for a CFRP part is to find a fibre sympathetic design to manufacture a trim feasible tuck groove. The sharper the radius of a tuck groove is, the better its finish is due to the fact that the leather itself has already a thickness of 1.2 mm. These small radii are not producible with prepreg lay-up materials. Due to the carbon fibres inside the prepreg material, long organic shapes should be used, so that the fibres do not break. Based on the experience of the manufacterer, the material and the manufacturing method, different radii are producible. Whenever the resin is infused during a manufacturing process, the radii can be very small due to the fact that the resin will flow into the shape and fill the tool. Using an autoclave prepreg hand lay-up based manufacturing technique, the pressure during the curing process is not high enough to hold the fabrics close enough to the tool. The result is an uneven radius which is not acceptable. Since no experience exists with regard to the smallest producible radius with the applied material and manufacturing method, a prime example reproducing the potential conditions on the door is developed and can be seen in Figure 4.

![Figure 4: Prime sample to validate the tuck groove size](image)

The width of the tuck groove varies up to 100% in order to evaluate the best finish. The lower left picture in Figure 4 shows the problem with a too narrow tuck groove. The raw edge of the hide is visible and leaves a condition that is not acceptable for a Bentley. The best condition is observed in the middle of the prime sample as seen in the lower right picture in Figure 4.

### 3.3 Fibre feasible design

The main attributes of the already mentioned design guidelines and their application are shown in Figure 5. Within a current car, almost every interior part is a moulded plastic part which is a very cost...
efficient way of delivering parts in mass production. The designs of the parts are however not adoptable for CFRP parts. The material properties, and hence the structure, have to be taken into account. Since composite parts are manufactured using fabrics the drapability of parts has to be considered. Often small changes like the standoffs shown in the first two pictures make the difference between a fiber sympathetic design and an unsympathetic design.

**Specific application:** Manufacture in CFRP to understand issues complex parts

**Feature consolidation** material drapability

**Moulded standoffs**

**Design Guideline:**

Combine parts, remove unused features, delete fixings

Combine parts, remove unused features, simplify design

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Figure 5: Application of developed Design Guideline for the main parts

The application of the design guideline for the semi-integral approach leads to a 3-part design. The door trim panel and the waisttrail are integrated into one part which saved the former fixings. The combination of the door back panel and the insert panel and some smaller parts is another step of the integration of parts.

As mentioned in the previous chapter, the highly integrated door is designed to be as light as possible. Therefore the integration of parts is pushed as far as possible and the whole A-Surface is manufactured as one part which results in some deductions in the functions but offers the possibility to validate the changes and the resulting cost differences.

### 3.4 Cost optimization

The decision on the number of parts and the recommended lay-up strategy by the FEA allows a first cost estimation for both designs. At this point, many variables that affect the manufacturing, material and labor costs can still be significantly changed. A first cost breakdown of both doors can be seen in Figure 6. A cost difference in total of 33,7% between the integral and semi-integral door can be observed. Although a prepreg hand lay-up process is a labor intensive manufacturing technique, the major cost saving between the two doors results through the position “material”. Considering the fact that both designs have the same size, the difference is unusual and led to further examination.
Regarding the lay-up strategy recommended by the FEA, a first nesting estimation is done. Due to the anisotropic properties of the material, every ply has to be defined by its weave angle and hence the fiber orientation (mainly 45°). The requirement of the fibers to lie in the direct load path of the different parts leads to no room for optimization. Nevertheless, the basis of the first cost breakdown is a manufacturing process for a pre-series (five doors in total). A calculation for series production offered additional cost savings, due to the fact that more parts have to be cut and this gives a new degree of freedom regarding the nesting strategy.

Another attribute that affects the material costs is the difference in the number of parts between the two designs. Although the integral door has several recommended plies to reinforce the door, the material costs and the resulting waste for a part like the armrest has a bigger impact on the unit costs. An integration of parts thus has a major impact on the material costs but less impact on the labor costs.

3.5 Special drivers

Referring to chapter two, the acoustic properties are very important in the Luxury Cars sector and a lot of effort is put into the calculation and validation. Therefore one requirement of the CFRP parts is to not influence the acoustic properties during a dynamic transmission loss test by more than 20%. Due to the roots of CFRP parts in the aerospace industry many damping materials are already in place for composites. Beside core elements that have to be implemented in the lay-up strategy, the most promising damping material is a rubber foil, which is available in different thicknesses. Due to the fact that costs and weight increase with growing thickness, the decision to use the 1 mm foil is made and to manufacture one set of doors with the damping material.

In order to validate the acoustic properties of the composite doors they have to be measured against a current Bentley Continental interior door. To eliminate potential outside influences from other parts of the vehicle or the environment, the two sets of CFRP doors are tested in the same car and compared to the original parts.

For both tests three microphones are positioned in close proximity to the door and two accelerometers are positioned on the two largest door substrate panels, to investigate the levels of vibration within the part. During the dynamic tests, all door pad derivatives are assessed on both coarse and smooth roads at 70 km/h, 100 km/h and 120 km/h.

The dynamic test results, shown in Figure 7, are measured within 3 days. In order to eliminate any outside influences, it is required that no condensation affects the outcome of the tests. The different graphs show the different microphones for the tests. The red curves show the figures of the current Bentley Continental GT door. The green curves represent the CFRP doors without the damping material and the blue curves the version with the damping material.

![Cost breakdown of both designs for one door](image)
Figure 7: Amplitude vs. Hertz curves of the dynamic transmission loss tests

The results shown in Figure 7 fall in line with the usual run-to-run repeatability, when testing is done over multiple days. There are no significant differences regarding the damping properties of the rubber foil, when looking at the narrowband data. This objective assessment also agrees with the subjective impression of the sound engineer, that there are no transmission loss concerns with the side zone of the vehicle with the parts tested.

4 CONCLUSION AND OUTLOOK

The new design process shown in Figure 3 allowed and enabled the responsible engineer to develop two CFRP interior door systems within 14 weeks including the following validation of the parts. It is shown that the newly developed methodology delivers a fibre sympathetic and cost optimized design with a short lead time. The attached Design Guideline for the use of Carbon Fibre Reinforced Polymers for Interior Trim Substrates is applied and implemented. The development of two different designs allowed for the evaluation of the main attributes and requirements. The implementation of 23 carry over parts delivered the same functions within the door system as the current one. The areas of concerns and problems are identified and evaluated. It is shown where the advantages and disadvantages of an integration of functions and parts are, and where the former design has to be changed to deliver a fibre sympathetic design. The main attributes of a Luxury Car interior, such as the implementation of hide into the design, the acoustic properties and the high standards for the visual appearance are verified for CFRP interior parts. A trimming strategy for hide is developed and validated regarding the cost optimization and the resilience. Regarding the desired racing flair for diversification, the weight saving possibility of up to 64% is proven with the results of this project. It is shown that the developed methodology is capable of delivering a cost optimized CFRP interior with a short lead time and a significant weight saving opportunity, which is ideal for a small series derivative production.

In the future the learnings of this project can be used to apply the methodology to a whole car interior and deliver a new derivative with a short lead time, fiber feasible design and significant weight saving.

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