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Effects of manufacturing constraints on the cost and weight efficiency of integral and differential automotive composite structures

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Abstract

The introduction of carbon fibre composites into the high volume automotive sector challenges the design process, since these components not only need to be light but also producible in a cost-efficient manner. One way forward is to introduce manufacturing constraints into the design process, but such constraints affect the freedom of design and opportunities to tailor material properties. This work examines the trade-offs between cost-effective design for manufacturing and the weight optimization of composite structures. This will be achieved by introducing restrictions to the number of plies allowed in structural optimization in order to simplify pre-operations and reduce overall manufacturing investments. Both integral and differential design solutions are considered. It was observed that differential solutions were always more cost and weight efficient than the integral solution, however too severe manufacturing constraints result in an expensive final part due to the additional weight.

Keywords: Manufacturing constraints, weight optimization, composites, automotive, multi objective optimization, cost

Introduction

The cost and weight efficiency of a composite structure is greatly influenced by the global architecture, structural design, manufacturing process and expected annual volumes. Few would question whether carbon fibre composites are able to reduce the structural weight of an automotive body structure compared to the more traditional steel design. In fact, for some components the potential weight reduction could be as high as 80%[1]. The structural optimized composite design, however, comes with a considerable increase in cost since its manufacture is commonly both labour intensive and slow. In a low volume scenario, scrap and material utilization, as well as cycle time, are considered subsidiary as the primary cost drivers are investments in tools and high labour costs[2]. It is therefore beneficial to produce carbon fibre composite structures in low volume series in integral designs, since the single tool approach[3] minimizes both investment cost and expensive assembly operations.

However, the automotive industry requires high manufacturing volumes, which results in a different cost breakdown for composite manufacturing[4]. Fuchs et al[5] describe the feedstock cost as the main cost driver of

highly-automated, composite manufacturing aimed at high volumes. Hence, material utilization becomes one of the most important factors when designing cost effective structural parts. Mårtensson et al[6] showed that geometric complexity drives scrap levels, consequently for high volume manufacturing, cost benefits can be found by dividing the structure with the aim of reducing complexity, and thereby also scrap.

Material costs are naturally also a function of the weight of the final structure. However, an optimized composite structure might not be producible in an automated and cost effective process due to limitations in the manufacturing. Manufacturing constraints therefore need to be introduced into the structural optimization loop. Composites are especially sensitive to such constraints since the composite material itself is created during part manufacturing and since these constraints often limit the potential of tailoring their material properties. Sorensen et al[7] emphasize the importance of including manufacturing constraints (MC) in structural optimization to create acceptance and industrial relevance for the results. The authors considered constraints on allowed thickness variations and number of identical plies in the layup, which is relevant for the structural performance of the part. Costin et al[8] and Wang et al[9] examined the influence of manufacturing constraints on the optimal design of a wing structure. It was observed that constraints on allowed ply drop off and ply fibre angles increased the weight of the structure. Park et al[10] studied the multi-objective optimization problem arising when including constraints from both structural design and manufacturing process. The object studied was a composite plate produced using resin transfer moulding, RTM. The objective of the optimization was to minimize plate displacement and manufacturing cycle time while ensuring high structural quality. Kristinsdottir et al[11] looked at the influence of manufacturing constraints on the final weight, part cost and overall life cycle cost of a composite aerospace structure. In addition to examining manufacturing tolerances based on the precision of the fibre lay-up and its effect on the performance of the part and the manufacturing cost, a trade-off study was included where the weight of the aeronautical structure was valued in financial terms and an ideal acceptance for lay-up tolerance was defined. In the automotive industry such studies are important in order to define the ideal trade-off between an optimized structure and an optimized process. Consequently, design and manufacturing constraints that improve the overall weight and cost efficiency must be defined and integrated into the overall concept design phase.

Manufacturing constraints are vital to ensure the cost effectiveness of the composite manufacturing process, however they will also influence the performance of the structure. When producing composite components at a high annual production volume, manufacturing often starts by stacking the fibre reinforcement into a preform. This is more efficient than draping directly into the tool. A preform is built up from a number of plies, each with specific thickness and shape according to structural optimization. This is a time-consuming and costly sub-process limiting flow through the production chain. By restricting the allowed number of plies in the structural optimization, the stacking operation is simplified, but at the same time the design freedom of the structural design also becomes restricted. In this paper we analyse how the final manufacturing cost and structural weight are influenced by applying manufacturing constraints limiting the number of plies allowed in the preform. Furthermore, in previous work[12] it was seen that differential designs show advantages considering both cost and weight compared to an integral design when introducing design constraints. This paper therefore includes both integral and differential design solutions in the scope of the analysis in order to further investigate their differences. The work was performed as a case study and multi-objective cost and weight analysis was conducted considering the implementation of manufacturing constraints in the structural optimization of a composite structure.

Method

The objectives of this paper are to assess the influence of manufacturing constraints on both the cost and the weight of a composite structure. The manufacturing constraints considered are applied in the optimization of the structure. The method presented is generic but is here described as a case study aimed at identifying the lightest and cheapest design for a composite floor structure. Towards the end, a multi objective trade-off study was conducted to analyse the ideal cost-weight balanced solution depending on the financial appreciation of a weight decrease. This problem is defined as a value function[13] formulated as

$$\text{Minimize} \quad f(v)=C+v*W \quad (1)$$

where C is the final manufacturing cost, W the weight of the complete structure and v the financial appreciation of the weight decrease i.e. the value of weight.

This study is part of a larger, generic but conceptual, framework on how to design an optimal automotive composite component including the following:

- Material selection and process selection models[4]
- Cost models for automotive high volume processes[6]
- Component size analysis aimed at identifying the most cost-efficient part size, an integral design or partitioned, including a complexity formulation[4], [6]
- Analysis of different partitioning strategies, i.e. positioning the joints in areas of low stress or with the means to reduce the complexity of each partitioned sub-component [12]
- Joint analysis[12]

Since considering the same composite floor geometry, some results from previous studies are re-used; these are described in detail below. However, the purpose of this work is also to challenge the outcome of studies on the conceptual level and build new information into the framework by addressing issues related to real part design and manufacturability.

Influence of manufacturing constraints on the optimal composite floor structure

Table 1. Requirements and design constraints for optimization routine

Requirements/Design constraints	Data
Max laminate thickness	20 mm
Min ply thickness	0.1 mm
Allowed fibre angles	0°/90°/45°/-45°
	Balanced layup
Adhesive thickness	1 mm
Adhesive joint overlap length	50 mm
Requirements Torsional Stiffness	1.39 kNm/deg
Annual volume	100 000 ppy

The method developed in this paper is visualized on a composite automotive floor structure, shown in Figure 1, aimed for high volume production. Table 1 presents structural design criteria and constraints as well as the annual volume considered in the cost analysis.

Figure 1, Initial geometric definition or structural area suitable for RTM process with carbon fibre epoxy material system.

Global Design

Previous research comparing the cost and weight effectiveness of integral versus differential design^{6,12} showed that there is a conceptual relationship between the geometric complexity of a structure and the cost benefits of dividing it. This complexity was described using the following factor

$$c_f = A_c / A_p \quad (2)$$

based on the relationship between the projected area, A_p , and the complete area, A_c , of the structure as well. Using structural optimization of the partitioned structure in combination with cost modelling, a methodology was developed defining the most cost-effective number of parts from a cost and weight perspective. The framework methodology was defined as *partition analysis*. The method developed showed that the structure should be parted in order to obtain maximum reduction of geometric complexity i.e. striving for flat structures and therefore dividing in corners or areas of difficult draping. Such an approach challenges the general opinion on where to place joints in composite structures[14]–[16], where it is claimed that partitions should be placed to reduce stresses and strains over the joint. Consequently, in the previous work[4], [6], [12], partition analysis was performed on two different structural differential designs: one aimed at minimizing stresses in the joints, termed MinStress, and one aimed at maximum reduction in complexity in each partitioning, termed MinComp. The results of the partition analysis are shown in Figure 2, showing that the optimum number of parts is 5 in the MinStress design, but only 4 for the MinComp design. The weight of partitioned designs also differed, 61.2kg for MinStress against 53.7kg for MinComp, which can be related to 57.8kg for an integral design. These optimized, differential designs are revisited in this case study together with an integral design termed Integral.

Figure 2. Differential partitioning designs, a) MinStress, b) MinComp.

Adhesive bonding

Adhesive bonding was considered for all joints with an overlap length of 50 mm succeeding previous work[6] and the bond gap to 1mm, see Table 1.

Cost model

A cost model for high volume RTM manufacturing of components of different complexity factors was used in this case study. The cost model is presented in detail in[6] and incorporates a manufacturing, as well as an assembly, module to address both integral and differential design solutions. The manufacturing cost is affected by the complexity factor of the structure as well as the individual parts if divided. For this study, an annual volume of 100 000 units/year is assumed.

Optimization routine

A hyper works optimization loop for composite laminates[17] is utilized for the structural optimization when studying the influence of the manufacturing constraints (MC). This routine is aimed at defining the optimal cutting pattern, shape and thickness for each ply as exemplified in Figure 3. The number of plies permitted is limited by choosing the number of fibre angles allowed in the structural design and the number of plies allowed for each fibre angle. The MC used are described in further detail below.

Figure 3. Hyper works optimization routine in sequence (courtesy of Altair Engineering).

When modelling the cost of the optimized component, plies are considered stacked in the pre-form operation and created after injection and cure of the final laminate.

Manufacturing constraints

The MC considered in this work focused on the number of plies in the stack creating the composite laminate as shown in detail in Table 3. In all structural designs with different MC, a minimum of 8 full sized plies was always used, i.e. two plies in each direction [0], [90], [+45] and [-45] in order to obtain symmetric lamina. Each ply possessed a uniform thickness, but the structural optimization provided a unique thickness for each fibre angle. When allowing for local reinforcement, the constraints on symmetric lamina and uniform thickness for all plies with the same fibre angle remained.

The greatest restriction of the structural design optimization is found for simulation MC1 where only the 8 full sized plies were used, creating a laminate of uniform thickness over the entire part. In simulation MC2, the optimization potential is improved by allowing for local reinforcement using two more plies in each fibre direction, i.e. in total 8 plies of full size, plus another 8 layers placed in patches where thickness increases are necessary. Finally, in simulation MC4, six plies in each fibre direction are added for local reinforcement; MC4 thus has a design of 8 full size plies and another 24 layers placed in patches. This allows for greater thickness variations over the part and should thus potentially save weight, however, it also implies more complicated preforming and stacking potentially leading to higher manufacturing cost. The manufacturing constraints are applied in sequence together with the common design constraints presented in Table 2. A balanced and symmetrical lay-up is always considered.

Table 2. Manufacturing constraints applied in the study

Manufacturing constraint	Number of plies allowed per fibre angle
MC1	2 full sized plies in each direction, uniform thickness
MC2	2+ 2 plies in each direction
MC4	2+6 plies in each direction

Figure 4. Schematic of load case used in case study. Torsional loads are applied at the front wall and boundary conditions are applied at the rear axle assembly.

Finite element analysis and load case

The structural optimization was carried out with a torsional stiffness requirement as shown in Figure 4 and in Table 1. As shown, the translation of the right rear wheel axel attachments point is restricted in the x-axis (red arrow), y-axis (blue arrow) and z-axis (green arrow), but the right rear axle attachment point only in x-axis and z-

axis. The load is applied as two parallel vertical loads (along the y-axis) introduced via rigid attachment surfaces in the front wall.

Value of weight

For the trade-off analysis, in order to define an ideal balance between the objectives weight and cost, the value of weight is set at 9 €/kg in this study. The study argues for a higher value compared to today's approximations of 0.3-6 €/kg[18] for the automotive industry since the tightening of emission legislation and an increase in the use of expensive batteries are anticipated in the future.

Results and discussions

The results of the different optimized designs with MC are presented, focusing on each of the following outcomes: weight, structural design, cost efficiency and part cost. Based on this and finally, the weight and cost trade-off analysis is shown.

Figure 5. Structural optimized weight for structural designs influenced by the different manufacturing constraints.

Considering the weight of the different designs, Figure 5 shows that the overall weight increases with increased design limitations/manufacturing constraints for all the designs. This is not unexpected since allowing thickness to vary over the part drastically reduces its weight. The increase in weight between designs MC4 and MC2 is low, around 1.5-3% depending on design, while the very severe constraints added to the MC1 design increases the weight by more than 150%. The MinComp partitioning strategy, aimed at low complexity parts, provides the lightest solution since the additional material required in the joints also contributes to the global stiffness. The MinStress design on the other hand, in which the joints are positioned in low stress areas, results in the heaviest solution for the MC2 and MC4 designs. The Integral design becomes slightly lighter than MinStress for all designs except for MC1, where uniform thickness is used over the entire, integral floor.

Figure 6. Laminate thickness distribution in the weight-optimized structural designs MC4, MC2 and MC1; a) Integral, b) MinComp, c) MinStress.

Figure 6a-c shows the laminate thickness distribution for the three different designs, Integral, MinComp and MinStress, depending on the MC applied. For MC1, uniform thickness is obtained in each part - a unique thickness for each design since no local patches are allowed. Partitioning, subsequently creates increased design freedom for the differential design solutions and therefore results in a lower structural weight, which both MinStress and MinComp show. When comparing MC2 and MC4 it may be observed that MC4 has a greater variation in laminate thickness due to the greater number of plies and cutting patterns that enable a more tailored design. Compared to MC4, the thicker areas have grown in MC2 and the solution becomes irregular with greater leaps in thickness.

Figure 7. Manufacturing cost efficiency for structural designs influenced by the different manufacturing constraints.

The manufacturing costs show a slightly different trend compared to the weight optimization. Focusing initially on the manufacturing cost effectiveness, which is often measured in the cost of one kilo final structure,[19] is the ratio between capital input and material output. Shown in Figure 7, the changes in manufacturing cost effectiveness dependent on manufacturing constraints show a continuous improvement with increased constraints. MC1 shows the lowest cost per kilo final structure and the same improvement is seen with the Integral design as well as the differential designs. However, the final part manufacturing cost, shown in Figure 8, is the only relevant measurement in this context. MC2 displays the least expensive solution, closely followed by MC4. MC1, which is commonly thought to provide the most cost-effective production method, results in by far the greatest final part cost. The limitations provided by the strict MC1 constraints result in a heavy, but still structurally optimized, design and since carbon fibre composites are such expensive materials the final cost becomes high.

Figure 8. Final part manufacturing cost breakdown for the structural designs a) Integral, b) MinComp, c) MinStress.

This effect becomes apparent when examining the trade-off between part cost and weight, solving the penalty function (1). As seen in Figure 9, MC2 provided the best trade-off between weight and cost for all designs and MinComp is the overall most favourable design solution. However, the improvement from MC4 to MC2, related to manufacturing cost and the improved manufacturability of the part by reducing the complexity of the pre-stacking and forming, is small. The Integral design experienced a great improvement when releasing the manufacturing constraints since the handling of large ply shapes for the entire structure is expensive. As the differential designs are already less complex and require that only smaller plies are handled in the pre-stacking, the improvement from MC4 to MC2 is also less significant.

Figure 9. Objective function based on Equation 1.

The value of weight is not a fixed number but is expected to increase in future automotive applications. When this happens, the design based on MC4 constraints would be the most beneficial. Though it is clear that MC1 could never be preferred over the other solutions since it is heavier and more expensive. It also shows that differential designs are less sensitive to manufacturing constraints. A design solution which could be regarded as an option to maintaining the most manufacturing effective constraints, MC1, while increasing the structural design freedom, would be to increase the number of parts. Though this was covered in previous work where, after defining the ideal number of parts, a continuous increase of both cost and weight was observed[6]. A composite structure should therefore only be divided as long as the desired balance between manufacturing advantages and optimized structural lay-up is maintained. This study considers the high volume manufacturing of an automotive floor structure with given structural demands. While the results obtained could be considered general to composite structures, changing to e.g. medium-volume manufacturing, lower structural demands or a cheaper material system will naturally change the break-even points or even turn the results around. One of the most important results of this study is that it demonstrates the importance of including manufacturing constraints in the structural optimization of a composite part as well as including cost analysis in the design framework to challenge the cost effectiveness of different design solutions. The proposed methodology is generic and can be used for any composite case.

Conclusions

The aim of this work was to investigate the influence of manufacturing constraints on the final cost and weight of a composite structure. The study focused on the structural design of an automotive floor structure aimed at high volume manufacturing. Three different design solutions were considered: one integral design, one partitioned design where joints were placed in order to reduce the complexity of inherent parts and a second differential design where the parts were partitioned with the aim of reducing stresses over the joints. Manufacturing constraints were provided focusing on the permitted number of plies during preform manufacturing. Restricting the number of plies allowed simplified preform stacking, but at the same time limited the freedom of design.

Structural design optimization was performed including the given manufacturing constraints. The results confirmed that it is more favourable to use a differential design, but also that this becomes even truer the more severe the manufacturing constraints applied. When limiting to allowing only one uniform thickness over the

entire component, differential design solutions offer increased freedom by permitting the use of different thicknesses in each sub-part, which drastically improve the weight and cost of the composite component. Releasing the design constraints improves the cost/weight balance for all the designs considered, however the differential design based on reduced part complexity always showed the best cost to weight trade-off.

The results presented show significant discrepancies between different designs depending on level of manufacturing constraints applied, thereby emphasizing the importance of including such constraints in the design of composite structures.

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