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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.

1. 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

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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 analyze 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.

2. 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 analyze 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

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

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.

3. Influence of manufacturing constraints on the optimal composite floor structure

The method developed in this paper is visualized on a composite automotive floor structure, shown in Fig. 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.

3.1. 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

$$C_f = A_c/A_p \tag{2}$$

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], were 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,

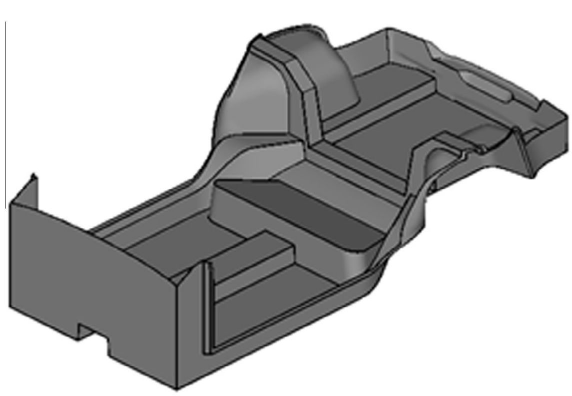

Fig. 1. Initial geometric definition or structural area suitable for RTM process with carbon fibre epoxy material system.