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Cost and weight efficient partitioning of composite automotive structures

Per Mårtensson^{*1,2}, Dan Zenkert¹, Malin Åkermo¹

¹ Department of Aeronautical and Vehicle Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

² Volvo Car Group

* Corresponding author (per.martensson@volvocars.com)

Abstract

To make carbon fiber composites not only weight but also cost effective in high volume production the different cost drivers need to be addressed and new design philosophies considered. This study analyzes integral and differential design approaches when portioning large complex composite structures. The influence of different partition philosophies are investigated based on a framework of composites manufacturing cost modelling and structural optimization and the effects are exemplified by a case study. The results shows that depending on how the partitioning is made the structural performance and the manufacturing cost is affected. More particularly, if the portioning is made with the most beneficial philosophy differential designs can improve both these parameters.

Introduction

Cost sensitivity in the automotive industry is continuously increasing due to greater industrial maturity and consolidation [1]. Parallel to this process, requirements imposed on vehicle construction and performance have gradually become more demanding. Cars must be more energy efficient, provide greater safety, include advanced electronic systems and offer greater comfort. This implicitly means that an automotive body structure must be lighter while offering improved performance and safety at a minimum cost increase. Carbon fiber composites are currently the only real alternative to steel in order to succeed in this essential weight body structure decrease.

Composites have several advantages over metallic structures, advantages such as unsurpassed weight-specific mechanical properties and the ability to be manufactured in large complex and integral structures. However, carbon fiber composites are expensive so all potential cost cutting

measures must be explored and cost drivers defined concurrent with this overall weight pursuit. Further, when moving into high volume composite manufacturing, new conditions and prerequisites govern. Design and manufacturing approaches that are competitive in low volume scenarios might not be as cost efficient in high volume manufacturing. As an example, the advantages of integral design solutions where large structures are manufactured as one single complex component, with benefits such as limited number of tools, minimized structural weight and no assembly process, need to be assessed.

The potential cost gains from dividing a composite structure, i.e. moving from integral to differential design, have been studied previously. Apostolopoulos et al [2] evaluated the total manufacturing and assembly cost when dividing a composite fuselage for the aerospace industry. The authors chose to seek the ideal manufacturing part size without including geometrical complexity, industrial investment or the impact on structural weight. Mårtensson et al [3], [4] examined the influence of partition on resulting cost and weight of an automotive body structure by proposing a framework including material selection methodologies and partition analysis. The framework focused solely on carbon fiber composites and it was observed that the partitioning of a composite structure could be beneficial for the cost of the composite body structure; this since the main cost driver for high volume composite manufacturing [4]–[6] is material cost. The key to cost efficiency was to achieve improved material utilization by dividing the structure and decreasing material scrap. It was shown that, due to the automotive industry's high level of cost sensitivity and the 50-80% weight reduction potential of carbon fiber composites as compared to steel [7], small additional weight increases due to partitioning could be accepted if they resulted in cost benefits.

However, by introducing joints in a structure, several crucial issues that influence both performance and cost must be answered. Usually a joint is designed for either mechanical or adhesive joining [8]. Adhesive bonding is considered by many to be the ideal bonding method for composite structures [9]. However, common adhesives are more than 10 times less stiff and possess even lower strength than the carbon fiber composite adherents [2]. So, despite financial benefits when dividing a structure, performance disadvantages might occur that influences both the final cost and the weight of the structure. The effects of the partition are also extremely dependent on where the joints are placed. The common recommendation is to position the joint so that stresses and complex multiple loads are limited and shear loads are favored [10]–[12]. Hart-Smith [13], [14] argues that the adhesive joint should be designed so it does not become the weakest link and the strength of the joint should be superior to the adherents beside the joint. Furthermore, the joint must be designed to obtain well-balanced stiffness and avoid uniform loading in order to reduce peel loads [10] and creep, respectively. The cost-effective approach instead is focused on limiting the residual complexity of the parts after the partitioning, i.e. making a split to reduce geometric complexity and not to conform to the structurally ideal

approach. Consequently the two approaches for positioning the joints will result in two different designs with different effects on cost and performance.

This study is based on the conceptual work outlined in [3] but develops it towards a more realistic breakdown of integral and differential composite design solutions. Two different approaches for positioning of joints are studied; either following the suggestions for the most cost effective production by minimizing the geometric complexity or following common joint design philosophies and thereby positioning the joints in areas with low stresses and strains. The results for the integral design and the two different partitioning philosophies are discussed on the basis of the robustness of joint design as well cost-effective composite manufacturing.

Method

In this paper, partition analysis based on cost estimations is combined with structural design optimization to improve the comprehension of the effects on structural and cost performance of a composite structure when divided. The routine for analysis, output and evaluation is described in Figure 1.

Figure 1. Analytical approach for the evaluation of the method

Steps in the routine

1. Defined geometry

A defined structure with a pre-determined material system and manufacturing process is selected for partition analysis, here termed defined geometry.

2. Structural design optimization -Integral design

Using FE modelling, a weight-optimized structural design is made for the initial geometry based on the structural requirement for the part. The structural optimization provides material thickness, fiber angles and ply lay-up as well as a stress map over the part and structural weight for the integral solution. This integral solution provides input into the partition analysis and cost estimate and serves as baseline for the final evaluation.

3. Partitioning analysis

The partitioning analysis assesses if a more cost-efficient solution could be found by dividing a structure. The manufacturing and assembly cost for the integral and differential designs are given by the cost model developed in previous work [3]. The complexity of a structure in the cost model is based on the complexity factor C , defined as,

$$C=A_c/A_p \quad (1)$$

where A_c is the complete area of the structure and A_p the projected area of the same. Partition analysis follows the method presented [3] with the following exceptions:

- Division is made according to the adapted partition philosophy described later.
- Partition is allowed to result in two components of different size and complexity.
- The complexity factor C of each part is always calculated using Eqn 1.
- Each new part, in the event of a partition, is re-analyzed for further partition as the routine in Figure 2 shows.

Figure 2. a) Partitioning analysis routine with design loop, b) Exemplified partition analysis for a structure g1

Figure 2b exemplifies the iteration, where the initial geometry g1 is analyzed and a number of parts, n, are suggested (n=1 suggests an integral design). The initial geometry is divided and then a new partition analysis of the parts, g1.1→g1.n, is performed. This routine is repeated until no further partition is recommended. The reason for this design loop is that when dividing a structure in reality, it must not be assumed that two similar parts are created with lower complexity which is assumed in the conceptual model [3]. On the contrary, the result of a partitioning, depending on joint design philosophy used, might create parts with a higher complexity factor than the previous geometry. The positioning of the joints is made manually with the intention of following one of the given joint philosophies as accurately as possible. This is a subjective approach and multiple solutions are present even though they follow the same approach on joint position.

4. Structural design optimization (differential design)

Following the routine shown in Figure 1, structural weight optimization is carried out for the differential design solutions. The same structural requirements, material systems and manufacturing constraints are considered as for the initial optimization of the integral design.

Case study

The case study is performed on a structure consisting of front, rear floor and firewall of an automotive body structure shown in Figure 3. The structure is designed for stiffness and the overall geometrical properties are given in Table 1.

Figure 3, initial geometric definition or structural area suitable for RTM process with carbon fiber epoxy material system.

Table 1. Mechanical requirements, overall geometric and complexity properties

	Requirements Torsional Stiffness [kNm/deg]	Projected area [m ²]	Complete area [m ²]	Complexity factor[3]
Floor structure	1.39	5.49	10.7	1.94

Material and process

The manufacturing process considered in this study is Resin Transfer Molding, RTM and the material system epoxy resin together with carbon fiber non-crimp fabrics, NCF. An epoxy resin [15] suited for RTM and a standard high strength carbon fiber, Hexcel AS4 [16] are used with material properties as described in Table 2.

Table 2. Material data

Materials	Stiffness (E1) [GPa]	Stiffness (E2) [GPa]	Shear modulus [GPa]	Density [g/cm ³]	ν	Strain to failure
NCF CFRP[15,16]	140	10	3	1.5	-	-
Epoxy adhesive[21]	1.8	-	-	1.25	-	11%

Structural optimization

The Altair Hyper Works Optimization routine for composite structures [17] is used for finite element analysis and structural optimization. The laminates are modeled with shell elements and the adhesive bond line is modelled with solid elements. Table 3 shows the design constraints considered for the optimization and Table 2 shows the material data used. Furthermore, the laminate design is idealized in the sense that no overlapping plies due to complicated draping are considered.

Table 3. Design constraints for optimization routine

Design constraints	Data
Max laminate thickness	20 mm
Min laminate thickness	1 mm
Min ply thickness	0.1 mm
Number plies permitted per fiber angle	4
Fiber angles	0/90/45/-45
	Balanced layup
Adhesive thickness	1 mm
Stiffness	1.39 kNm/deg

The load case for torsional stiffness requirement in the case study are modeled as shown in Figure 4.

Figure 4. Floor structure with torsional load case applied.

Joining

Single overlap joints, as shown in Figure 5a, are considered in the FEM model as well as in the cost model. Moreover, for joining in close proximity to sharp angles, a single supported corner

joint design is used [3], [18], shown in Figure 5b. The cost model considers the same material addition and investments for both joint types.

Figure 5. a) Single overlap joint. b) Single supported corner joint

The same overlap length is used for both the single supported corner joint and the single overlap joint. In literature, the overlap length is often determined in relation to the laminate thickness [13], [19], but recommendations vary greatly. Kelly et al [19] conclude that the recommended overlap-length-to-lamina-thickness relationship varies between 8:1 for test samples, to 80:1 for some projects in the aerospace industry.

After setting the overlap length, a balanced joint with equal adherent thickness is designed to minimize peel loads and the bending at the joint ends [11], [20]. The laminate in an optimized design will most likely vary in thickness over the length of the joint for all partition philosophies analyzed here. This must also be addressed in the overlap length design. Hart-Smith [14] describes an approach utilized in the project Primarily Adhesively Bonded Structure Technology (PABST) where a universal overlap length was considered only related to the thin laminate and locally thicker areas were only tapered to reduce any induced peel loads. This approach is also adapted in this case study and the overlap length is considered for each joint based on the dominant laminate thickness in the structure. In this paper, a universal overlap length is considered based on the average laminate thickness of the optimized integral design. A relation of 30:1 is used according to industry standards, which is a reasonable reduction compared to the aerospace industry, where 1:60 is suggested [14] for single lap joints

The allowed strain in the adhesive is set to 1/10 of strain to failure [12] according to aerospace guidelines and an structural epoxy adhesive is assumed [21]. The surface ply orientation is considered optimal so the joint design does not experience any reduced strength due to surface effects [17].

Partition philosophies

Two different approaches to dividing the structure and positioning the joints are addressed. They are described as followed;

1. Minimum stress/strain and thin laminates in joint areas;
 - This approach is based on the design philosophy proposed by Hart-Smith, implying that the joint should not be the weakest link. Joints are therefore placed in areas of low stress and strain with the intention of avoiding joints positioned in areas of thick laminates since such areas increase risk of failure due to creep in the joint. This partition philosophy is below referred to as **MinStress**.
2. Minimize complexity;
 - This approach suggests that the structure should be divided in order to minimize complexity (and thereby cost). No consideration is given to the stiffness or stresses in the area of the joint. This partition philosophy is below referred to as **MinComp**.

Cost model

Figure 6. Cost model processes for RTM manufacturing and assembly cost

The cost model, detailed described in [3] and schematically shown in Figure 6, describes the steps of an industrialized RTM and assembly process. In brief the cost model addresses:

- Influence of geometrical features such as part size, part complexity and part thickness
- Volume dependency
- Investment costs, e.g. robots, presses, equipment etc.

- Labour cost
- Fixed costs, e.g. floor space, fix electrical cost etc.
- Running cost, e.g. electrical cost etc.

Table 4, 5 and 6 present the data used [22] for the cost estimates as well as partition analysis. All machines require certain floor space and energy consumption and the cost model adds a 10% installation augmentation for each machine. A complete investment in new machines and tools required and depreciation of 5 years is assumed.

Table 4. Data for initial scrap levels and cycle times for the process included in the parameter study, all figures should be treated as rough or approximations [22]

In-data	RTM
Cycle time [min]	5
Fiber volume fraction	0.55
Material cost	
Carbon fiber cost [€/kg]	20
Resin cost [€/kg]	5
Scrap levels	
Initial scrap fiber level	0.2
Initial scrap resin level	0.02
Initial scrap prepreg level	NA
Density (resin fiber mix) [g/cm ³]	1.5
Epoxy adhesive [€/m]	0.2

Table 5. General data for the model, all figures should be treated as rough or approximations [22]

In-data			
Annual workdays	200	d/y	
Shifts/day	3		
Working hours	24	H	
Operator dedication	0.5		
Operator salary	30	€/h	
Floor cost	160	€/m ²	
Electricity variable cost	0.008	€/kWh	

Table 6. Investment cost, excluding installation fee, all figures should be treated as rough or approximations [22]

Machine	Price		Operational speed	
CNC cutter	150 000	€	0.25	m/s
Post treatment machine	300 000	€	60	s/part
RTM equipment	300 000	€	NA	
Material handling robot	60 000	€	10	s/ply
Hydraulic press	See press cost section			
Tool cost	See tool cost section			
Hydraulic draping press	See press cost section			
Pre-shaping tool	See tool cost section			
Adhesive application robot	60 000	€	0.1	m/s

Results and discussions

The results of the case study are summarized in Table 7 and further commented on below. The laminate thickness for the optimized integral design working as baseline for the partitioning is seen in Figure 8. It can be observed that large parts of the structure are at the smallest thickness allowed, 1mm, while other parts of the structure, mainly in corners and flanges, have reached maximum thickness, 20 mm. It can also be observed that the thick areas are rather large, spreading out from the corners in order to achieve the required stiffness in the entire structure.

Table 7. Results of cost and weight analysis of the different partition philosophies

	Integral	MinStress	MinComp
Number of parts [n]	1	5	4
Average complexity factor ⁴	1.95	1.68	1.42
COST [€]	2281	1480	1353
WEIGHT [kg]	57.8	61.2	53.7
COST DIF [€]	0	-102€	-191€
WEIGHT DIF [kg]	0	3.4kg	-4.3kg

Figure 7. Laminate thickness plot of integral design solution.

The final part geometry for each partition philosophy is shown in Figure 8a and b resulting from the partitioning approach outlined in Figure 2 and the results of the analysis of the integral design in Figure 7.

Figure 8. a) MinComp, b) MinStress

The initial difference observed between the two partition approaches MinStress and MinComp is the number of parts. This is a result of with which efficiency the partition philosophies enables to reduce the geometric complexity of the structure when dividing it. It becomes more obvious when comparing Figures 9a and 9b showing the thickness variations resulting from these two approaches. MinComp positions the joints in corners and sharp areas, striving to flatten out the geometry and reduce complexity. Following the MinStress approach, on the other hand, the joints are positioned in the middle of flat panels where stresses are low and the thin adherents are located. Consequently, the complexity reduction is lower, which is seen in the number of parts as well as in the resulting average complexity factor of parts included, Table 7.

Figure 9. Laminate thickness plot of a) MinComp design solution, and b) MinStress design solution

The results of the cost and weight study, seen in Table 7, show that MinStress became heavier compared to the integral design solution. A weight increase was expected since joining requires overlapping material and adhesives, both adding weight. However, the weight increase due to bonding is limited since the joints are placed in low stress areas and therefore the overlap is thin adding a limited amount of extra material. With the added weight it can be assumed that also the cost of the structure will increase due to additional material cost. However the cost is actually

reduced since the partitioning of the structure decreases the complexity of the parts lowering scrap levels and investments due to simplified pre-processing, despite a heavier structure and more tools being required.

MinComp, on the other hand, provides a reduced structural weight compared to the integral design despite the additional joints, see Table 7. The weight reduction is significant, almost 10% lighter than the integral design, which is a result of the positioning of the joints and the design constraints. As seen in Figure 9b, the joints are placed in the sharp angles to allow for reduction of geometric complexity according to the philosophy applied. As expected, the joint weakens the structure and requires thicker laminates over greater areas, as seen in Figure 9b, to maintain low strains in the adhesive. However, the advantage is that these joints coincide with the areas where the greatest structural stiffness is required and the additional material contributes to the global stiffness. So, while the integral design is limited to a laminate thickness of 20 mm, see Table 3, the MinComp is allowed to double the thickness of the joints (to 2 times 20 mm). Reduction in structural weight also affects the cost positively by decreasing the material cost. As seen in Table 7, the MinComp provides the least expensive solution with the lowest overall cost due to reductions in part complexity, scrap and material cost as well as investments.

These results show that dividing the structure can be a cost and weight-efficient approach, particularly if manufacturing constraints are present. The outcome of this case study is, of course, partially dependent on the geometry and load case chosen as well as on design constraints, but it emphasizes the potential of positioning the joints where they contribute to the global requirements and not purely strive to minimize complexity. In a further assessment of the opportunities of identifying more suitable partitioning strategies, the two approaches MinStress and MinComp were combined, i.e. selecting split lines in order to minimize part complexity, but only choosing areas with low strains and thin laminates. However, it was found that this did not improve either weight or cost.

Finally, it has been shown that the integral design does not provide either the cheapest or the lightest solution with the design constraints given here. These constraints can, of course, be questioned. However in high volume manufacturing there will be similar constraints stipulated by the manufacturing process which will most likely be tougher than these. Also the choice of overlap length would influence the results by increasing the structural weight for solutions placing the joint in areas requiring thick laminates and high stress. Guidance on overlap length often considers pure shear stress [23] and it has been noted that for bending loads, thicker laminates not requiring oversized overlap lengths are more effective [24]. The issue concerning the manufacturability of composite structures is relevant and manufacturing constraints will influence both differential and integral solutions. In this study, the thickness increased continuously instead of step wise as would be the case when using discrete layers with no

minimum ply area being adopted. Further, in reality an integral design will, in most cases, involve overlapping plies due to cuts and draping complications. However, since several of these manufacturing constraints are linked to part complexity, differential designs with low sub-part complexity is still anticipated as being the most promising solution. The influence of such manufacturing constraints will be further studied in future work.

Conclusions

This work shows that by using an appropriate design philosophy allowing partitioning of composite structures, great benefits both in regard to weight and cost can be found. Though, in order to capitalize on the advantages, the positioning of the joint should be made unconventionally and contrary to conventional composite joining guidelines. The key is to exploit the additional material required in the joining area so to contribute to the global performance of the structure. Even when applying a more conservative partitioning philosophy, cost benefits could still be gained compared to an integral design as long as the partitioning reduces complexity and improves material utilization, however with an increase in structural weight.

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