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Simulative Design of a Load-Path Adapted Fibre Reinforced Composite (FRP) Transporter Rear Door

Saleem A.[1)], Damani V. R.[2)], Schreiter M.[1)], Emmrich J.[3)], Kroll L.[3)], Kaufmann J.[2)]

1) Systems and Technologies for Textile Structures (STEX), arham.saleem@iwu.fraunhofer.de, michael.schreiter@iwu.fraunhofer.de, Fraunhofer Institute for Machine Tools and Forming Technologies IWU, Reichenhainer Straße 88, 09126 Chemnitz, Germany

2) Department of Textile Technologies, viraj-rajivbhai.damani@mb.tu-chemnitz.de, joerg.kaufmann@mb.tu-chemnitz.de, Chemnitz University of Technology, Reichenhainer Straße 31/33, 09126 Chemnitz, Germany

3) Department of Lightweight Structures and Polymer Technology, jens.emmrich@mb.tu-chemnitz.de, slk@mb.tu-chemnitz.de, Chemnitz University of Technology, Reichenhainer Straße 31/33, 09126 Chemnitz, Germany

Keywords

Fibre-Reinforced Composites, Loadpath, Multi-Material, Resource Efficiency

Abstract

The demand for weight reduction in the automotive, aerospace, and railway industries is at an all-time high. Fibre-reinforced composites (FRC) have proved their suitability with their excellent combination of strength and weight. The only limiting factor in adapting FRC for mass-production in industries is the high costs of composite materials like carbon fibre reinforced plastics. A design workflow, suitable for FRC's and their available manufacturing technologies has been proposed by adopting a progressive approach. A multi-material component design has been optimized using Altair Hyperworks and OptiStruct to reduce weight and maintain stiffness and strength as compared to its conventional metallic version. The layup of the substrate laminate has been optimized using special optimization tools in OptiStruct in three stages. The determination of load-paths is followed by the optimization of the base laminate under given load cases. Subsequently, the geometry of injection-moulded stiffeners was determined by employing topology optimization considering the composite layup, obtained in previous steps.

1 Introduction

The recent revolution of alternative fuels has brought great developments in the automotive, aerospace, and railway industries, with a major focus on the reduction of weight using lightweight materials like fibre reinforced composites. With the innovation of multi-material component design, there is finally a solution to the expensive manufacturing costs attached to composites. The multi-material component design focuses on a load-path adapted model using cheaper composite materials like glass fibre reinforced plastics (GFRP) with expensive composite materials like carbon fibre reinforced plastics (CFRP) only where it is required i.e., under high tensile stress paths. Therefore, making composite structures economical by using maximum efficiency of carbon fibres along the tensile load-path.

The determination of these load-paths, especially in complicated design spaces and under a combination of different loads, is even more difficult with FRC's than the unreinforced plastics or metals. A variety of analysis and optimization techniques are available in commercial Finite Element Method (FEM) analysis tools. One of the most robust techniques of optimization is topology optimization. With this technique, the material inside a given design space is optimized under given loads, boundary conditions, and executes the objectives of the framework. During the topology optimization, the density of each element is varied as a design variable and penalized to achieve such a material distribution,

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which can still hold the structure under given loading conditions. The topology results in the conceptional plan aggregating into load-paths. This FEM-based optimization technique is very useful for structures with isotropic materials where each element of the model has the same stiffness and strength in all directions. For FRC's with a layered structure, mechanical properties are oriented differently in each shell element, depending on the layup definition. Topology optimization with a fixed layup can certainly save some ply area, but a load-path with fibres oriented along with it cannot be achieved with this approach.

An FEM-based optimization tool with Nastran/Patran has been previously developed to optimize the load-paths for manufacturing with the tailored fibre placement (TFP) technology [1]. This tool utilizes the computer-aided internal optimization approach (CAIO). In another study, the continuous fibre angle optimization (CFAO) approach based on topology optimization was employed in the context of additive manufacturing with short fibre reinforced plastics [2]. Tamijani et al. achieved an optimized distribution of the material by two different methods: a density-based method and a level-set method for orthotropic materials [3]. Hereby, the fibre orientation of each element or the fibre path is considered as the design variable.

Apart from the advantages of the above-stated methods, they all often result in a discontinued fibre path (e.g., fibre angles change abruptly between adjacent elements). Therefore, leading to stress concentration and manufacturing difficulties in the optimized structure [4]. A method has been made by Nomura et al. [5] and Lee et al. [6] to simultaneously optimize the topology and material orientation by extension of design variables in the topology optimization method. This method could optimize the topology and fibre volume fraction, as well as discrete fibre orientation angles. The strength aspects were not considered in these studies.

In this work, the design of a structure made of continuous glass fibre reinforced thermoplastic (GFRTP) tapes with hybrid carbon fibre roving reinforcements is under consideration. The main challenge here, has been to consider unconventional laminate construction for FEM-based composite optimization to achieve an integrated load-path adapted laminate design with an optimum amount of hybrid rovings. An automotive part is the subject of this study, which exists currently as a sheet metal part. Under the restrictions of fixed topology and space for peripheral parts, a lighter design with an innovative material combination was set as the aim of this work. The FEM analysis and optimizations were done using a commercially available FEM software tool from Altair Engineering i.e., Altair OptiStruct.

Altair Optistruct offers a three-fold optimization of composite laminates. This begins with optimizing the proportion of different angle plies in a laminate. In this step, so-called free-size optimization (FSO), Optistruct uses smear technology to cancel out the effects of stacking sequence on the laminate properties, and thus only the effects of ply angle and ply thickness are taken into account for the determination of laminate properties. The optimization done in this step is on element basis. The second step is size optimization (SO), detailed design optimization is carried out to ensure continuity of ply shapes with consideration of manufacturing constraints. The third step of this workflow, called shuffle optimization (SHO), finally optimizes the stacking sequence of the plies [7]. Several different additional optimization options such as manufacturing constraints highly influence the ply shapes and need to be applied very carefully.

2 Design Methodology

2.1 FEM-Modeling of the effiLOAD Structure

2.1.1 Geometry and Mesh

To develop and demonstrate the application of effiLOAD material (see section "Materials"), the rear door geometry of a transporter was selected. This structural part was selected due to challenges of design space and load transmission which had to be accounted for, using fibre reinforcements. Further, the part itself consists of two main subparts i.e., the inner part whose main function is to bear the loads and to contain auxiliary functions like a loudspeaker, wiper motor, etc. Whereas the outer part serves the function of aesthetics and protection against outdoor weather conditions.

Linear shell elements were used for the outer and inner shells. The arrestor hook was also realized with a shell mesh. Other hinges, due to their complicated topology, were meshed by using solid elements.

Different support geometries have been considered including the hinges and arrester hook. The consideration of the support geometries enables the consideration of realistic stress concentrations at the load transmission points.

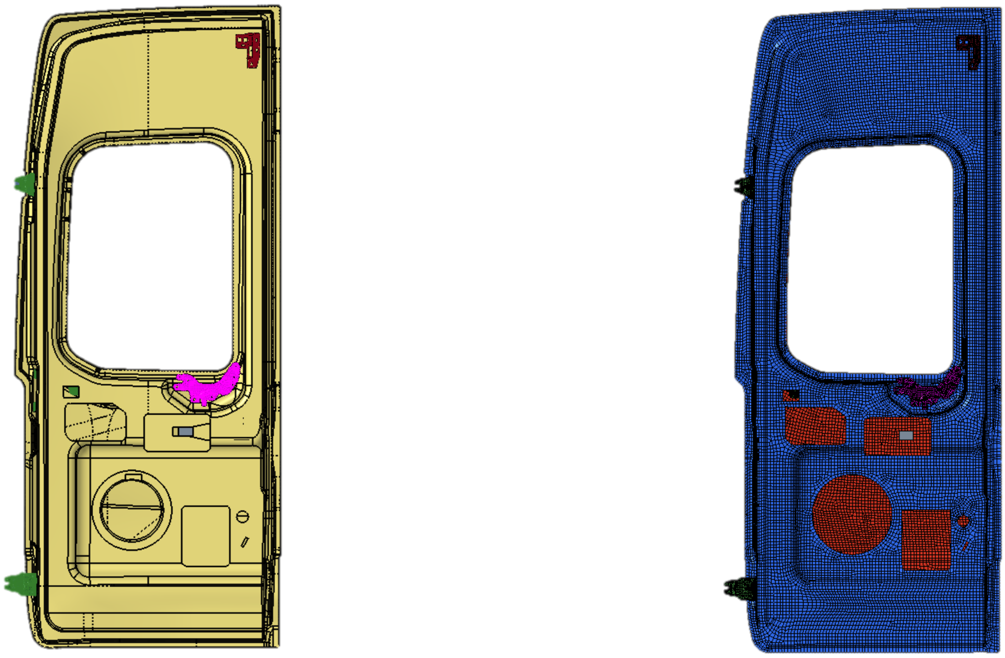

Figure 1: Rear door geometry (left), meshed geometry of the rear door (right)

2.1.2 Material Definition

The focus of this study is to use a multi-material fibre reinforced composite with local reinforcements. EffiLOAD material, which has been developed at the Technical University of Chemnitz, defines the substrate of glass fibre mat carrying glass fibre reinforced Polyamide6 (GF/PA6) thermoplastic tapes with approx. 47% fibre volume fraction. Using tape laying technology, the base laminate will be built up by using various layers of different fibre angles. This laminate will then be reinforced using hybrid rovings consisting of carbon fibres and matrix filaments mixed in a certain ratio, so that a volume fraction of around 50% can be achieved.

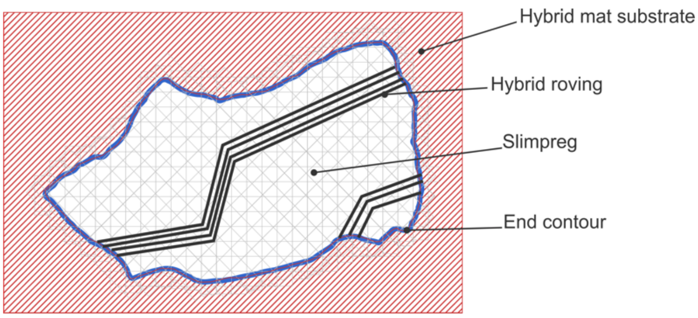

Figure 2: Illustration of an effiLOAD material

For certain thin-walled structures, additional stiffening might be necessary using injection moulded ribs. A wide variety of injection moulding materials are available. For the current study, commercial short glass fibre reinforced polyamide6 (PA6) with 30%wt. fill has been chosen. The inner shell has been defined as the fibre reinforced composite part and thus the main object to be optimized in this study. The outer shell consists mainly of a mineral reinforced polypropylene.

2.1.3 Load Cases

Four main load cases have been identified as relevant to the stiffness and strength of the door geometry. These are:

1. Wind force acting on the rear door while the door remains fixed at hinges
2. Wind force acting on the rear door while the door is allowed to rotate on hinges; motion normal to the door surface is being blocked by arrester hook
3. Downwards force acting on the door while it is fixed on supports
4. The door is fixed on supports and locks, while a force is acting outwards on the bottom corner of the gate

The load cases and the points of load introduction were defined by a project partner.

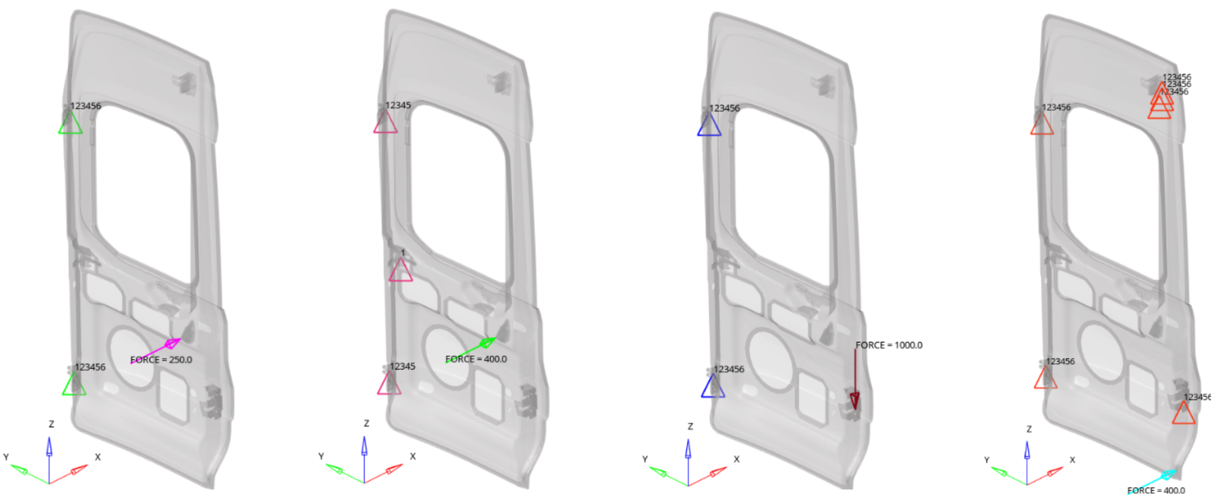

Figure 3: Overview of load case1 to 4 (from left to right)

2.1.4 Contact Definition

As mentioned in section 2.1.1, the door structure itself consists of two main parts – the outer shell and the inner shell. A contact definition for a proper load transmission was essential. This was realized by defining tied contacts between them, assuming an ideal bonding situation, and neglecting the additional effects due to adhesives. Furthermore, other essential smaller parts like arrester hook, hinges, and other loads relevant sheet metal parts were also attached to the inner shell using surface-to-surface tied contacts.

For the later stages of a rib structure optimization, also contacts were considered between the main shell structures and rib structure.

2.2 Optimization Workflow for a Load-Path Adapted Design

The main workflow of optimization consists of the following steps:

1. Identification of load-paths using topology optimization
2. Optimization of base laminate with consideration of reinforcement rovings
3. Optimization of reinforcement ribs

2.2.1 Loadpath Identification

As a first step, it was necessary to find the load-paths in the inner shell for given load cases. Different approaches have been trialled in this study. This starts from performing the topology optimization of the base geometry with the given load cases. An optimized topology with the isotropic material does not take specifically the orthotropy and better performance of composites under tensile loads into account. Thus, the resulting topology does not necessarily represent the load-paths for a fibre reinforced structure, where fibres have more strength in the longitudinal direction. Replacement of an orthotropic material with an isotropic material was also trialled, but no adequate load-paths have resulted here either, due to the very nature of the optimization algorithm and its dependency on element densities

In another approach, the topology optimization of the inner shell was done using isotropic material to find all regions of higher significance. These results were then overlayed upon by first principal stress vectors to further filter out the regions where tensile loads dominate. This also assured the elimination of regions under compressive or shear stresses.

After finalizing the load-paths, a manufacturable design of reinforcements was drafted and integrated into the unreinforced geometry. This included the consideration of tape width, minimum tape length, maximum angular deviation, etc.

Figure 4: Element density results overlayed by first principal stress vectors in load case 2 (left) and the final reinforcement geometry (right)

2.2.2 Laminate Design

To find out the optimum layup of door laminate using glass fibre tapes, the said material was defined ply-wise on the whole inner shell. Each ply in the initial layup covers the whole surface area of the part. Drapability of the effiLOAD material was not considered due to the missing data regarding this type of material.

For all steps of optimization i.e., FSO, SO and SHO, the objective was set to minimize the total mass of the design components. A maximum deformation constraint was defined for each load case. Another constraint was defined to make sure that no element of composite material undergoes a failure as per Tsai-Wu failure criteria. Manufacturing constraints of effiLOAD production were also considered while configuring the optimization model. These constraints were particularly the minimum tape length, tape width, tape thickness, maximum laminate thickness, and symmetry of plies.

Results after each optimization step were checked for their feasibility and the optimization workflow was iteratively used to achieve a manufacturable design. After initial iterations, a rather discrete thickness map (see figure 5) was obtained according to the load cases. This thickness map, along with the thickness of each angle ply, was considered to identify two thickness zones. Zone 1 covered most of the area of the door, while zone 2 was limited to the supports region. This simplification resulted in manufacturable ply shapes and relatively uniform thickness regions.

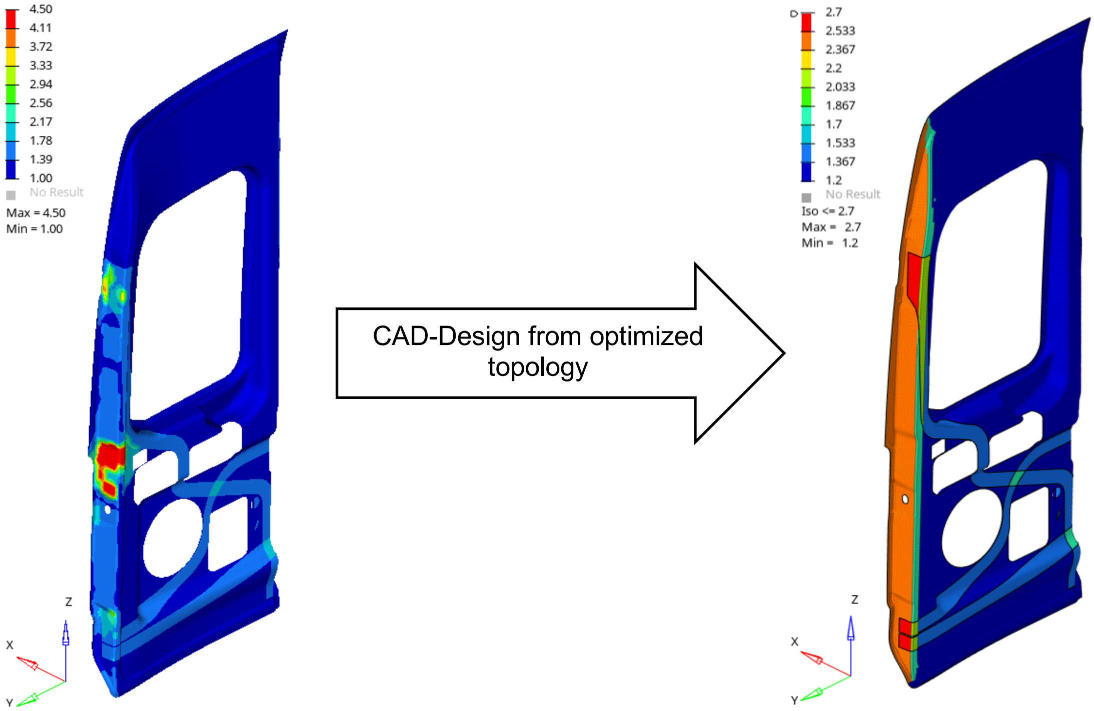

Figure 5: Thickness plots after laminate optimization (left) and ply shape refinement (right)

The percentage of different ply angles in each zone was then assessed to reach a final layup, ensuring symmetry and connectivity between both zones. Due to higher stresses in zone 2, optimized ply angles in this region were prioritized for the complete layup. To avoid drastic changes in laminate thickness over the boundary of zones, a transition was introduced between the two zones (see figure 6).

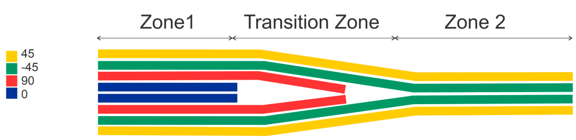

Figure 6: Suggested laminate with two thickness zones and ply drop-off region

2.2.3 Reinforcements Ribs

After achieving a global laminate design with two zones and 5 reinforcement rovings, the safety factors in certain local regions were still critical as can be seen in figure 6. These regions were particularly in contact with door supports i.e., hinges and arrestor hook. An additional increase in thickness was not in favour of manufacturing. Thus, a reinforcement on the backside of the inner shell was needed. This issue could be solved by employing stiffeners in form of injection moulded ribs on the critical regions.

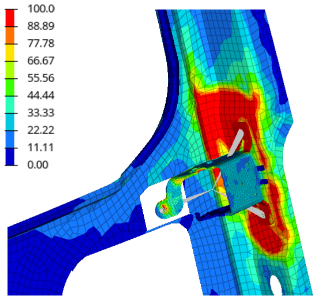

Figure 7: Critical stress region at the interface of arrestor hook and inner shell

The design of these ribs also needed to be as light as possible to maintain the weight advantage of the materials and manufacturing technologies. The design volume of the cavity between the inner and the outer shell was optimized using topology optimization in combination with the components, especially with the optimized effiLOAD laminate to consider the effects of mechanical behaviour of fibre reinforced composite and the roving reinforcements. The optimized rib design was then reworked in a CAD program to make the geometry manufacturable.

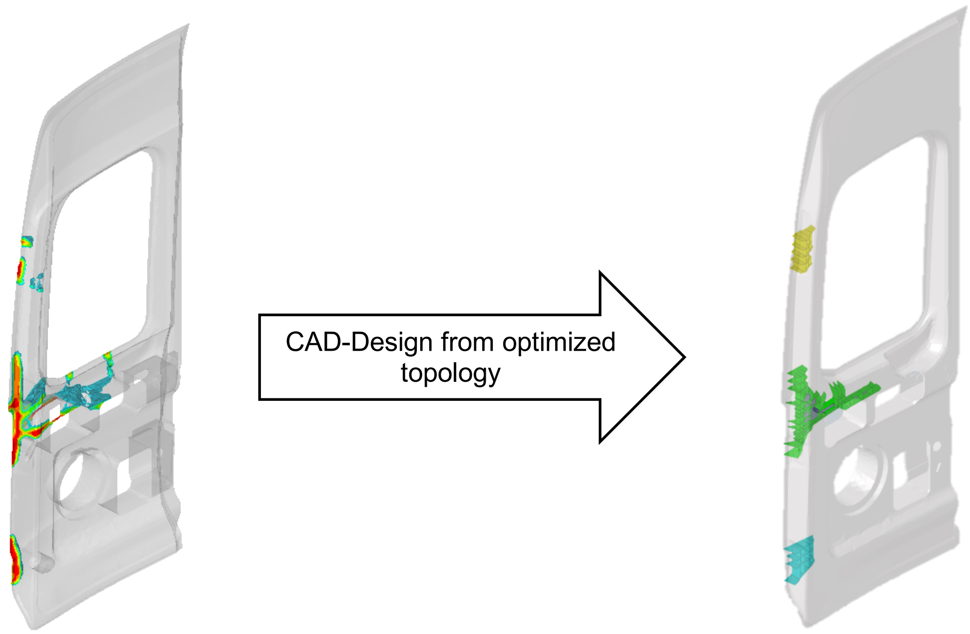

Figure 8: Optimized element densities for ribs (left) and CAD-Geometry of ribs (right)

3 Results and Discussion

After optimization of each component i.e., inner shell layup, roving path and ribs geometry, a final simulation was run with the complete model. Hereby, the ribs geometry was considered with the minimum possible manufacturable thickness, so that a possibility for the upscaling would be available if required. The laminate was also fine-tuned, so that a better compromise between strength and stiffness could be achieved.

In the graphs below (see figure 9 and figure 10), results after the finalization of each major step are illustrated. The load cases 1 and 2 are relatively more critical as compared to the load cases 3 and 4, since the structure is well supported in the latter ones.

An optimized effiLOAD laminate with discrete thicknesses shows promising results regarding the strength, stiffness, and mass characteristics. But, as indicated in this paper, a manufacturable design was only possible with larger regions of constant thickness. Therefore, the optimized thicknesses and angles have been spread onto a larger surface resulting in two zones of constant thickness. This distribution resulted in a sub-optimal resistance to failure in the locality of the supports and increased total deformation in all load cases. Also here, load cases 1 and 2 show higher sensitivity to the changes.

The addition of injection moulded ribs to the whole structure enables a regain in strength and stiffness close to the level of discrete thickness effiLOAD laminate. So that the goals for maximum deformation in each load case were met along with the satisfaction of composite failure criteria.

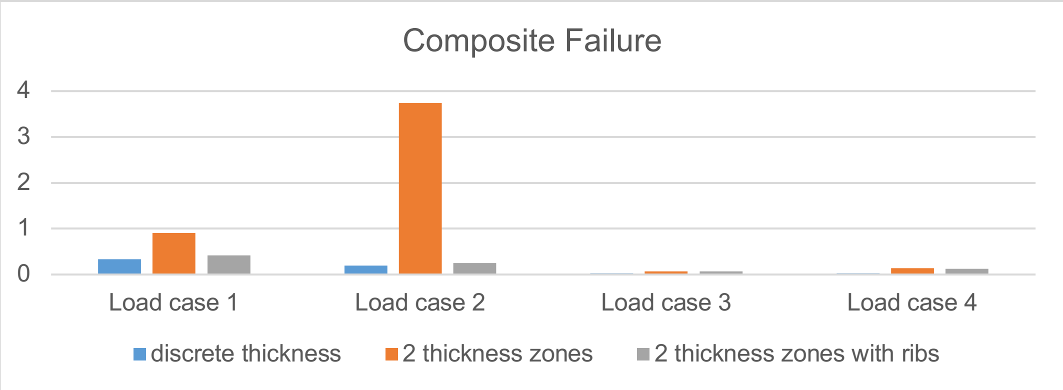

Figure 9: Comparison of composite failure results after each design step

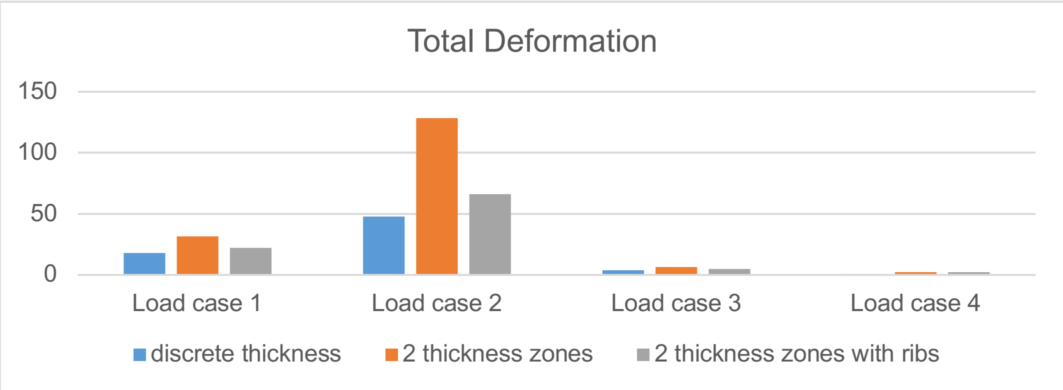

Figure 10: Comparison of total deformation results after each design step

4 Conclusion

4.1 Summary

A load-path adapted FRC door structure has been successfully optimized based on FEM-simulations. Due to geometrical constraints and material combinations in effiLOAD material, additional complexities were added to the model. Considering the lack of established practices for load-path optimization of fibre reinforced composites using commercially available FEM tools, the authors evaluated different modelling and optimization strategies, that could lead to a manufacturable load-path adapted design of FRC structures. Hence, a workflow with Altair Hypermesh and Optistruct solver has been developed, which could be applied to other similar structures in automotive industry.

With the final optimized design, a weight saving of approx. 43% was achieved as compared to the original sheet-metal part.

4.2 Outlook

The authors feel a need for further improvements in the workflow presented in this study to automate various steps, especially for the determination of load-path with fibre reinforced composites. Further the consideration of ply-draping in early steps has been identified as an important aspect to obtain a manufacturing process-friendly design after optimizations. This also helps in the division of the laminate area into various ply zones.

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