Lightweight design approach of an LFT-metal multi-material vehicle door concept

Danshi Li1 · Xiangfan Fang1

Received: 24 January 2022 / Accepted: 13 September 2022 / Published online: 20 October 2022
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Abstract
This work presents a new approach to design and validate an economical lightweight multi-material roof-integrated vehicle door concept made of long-fiber thermoplastics (LFT) and metals with the consideration of package constrain, critical static and crash loading cases. A novel “two-ring” door structure is introduced, which consists of a major load-bearing region and a minor load-bearing but highly function-integrated region. This concept design concentrates on using cost-efficient lightweight materials, such as aluminum, LFTs and uni-directional tapes (UD-Tapes), as well as corresponding mass-production methods. Using the topology and parameter optimization along with the load anisotropy analysis, the rib structure on the door concept is optimized and the effective usage of UD-Tapes is guaranteed. In comparison to the steel reference, the final LFT-metal multi-material door concept achieves 20% weight reduction with a comparable or improved mechanical performance.

Keywords Vehicle door · Lightweight design · Multi-material construction · Long-fiber thermoplastics · Structural optimization · Finite-element analysis

Abbreviations
BIW Body-in-white
CAD Computer-aided design
CFRP Carbon fiber-reinforced plastic
DIW Door-in-white
D-LFT Direct long-fiber thermoplastic compression molding process
FE Finite element
FEA Finite-element analysis
FRP Fiber-reinforced plastic
FRTP Fiber-reinforced thermoplastic
GFxx Glass fiber weight percent xx%
IMA In-mold assembly
LFT Long-fiber thermoplastic
LGFxx Long glass fiber weight percent xx%
MDB Moving deformable barrier
NVH Noise, vibration, harshness
OEM Original equipment manufacturer
PA Polyamide
PP Polypropylene
SDS Sub-design space

UD Unidirectional
UHSS Ultra-high-strength steel

1 Introduction and motivation

The lightweight potential of vehicle doors has received much attention in the past decade due to the trend of E-mobility and the increasingly stringent legislation requirements on the CO2 emission. Many attempts have been made by different automotive OEMs and suppliers to reduce the weight of door structures on serial products in last decades [16, 19, 25], Porsche [28–30]. They revealed not only the lightweight potential with steel and light alloys on door structures, but also corresponding limitations. The work by [16, 25] shows that a steel-intensive door structure can reach ca. 10% weight saving using either advanced lightweight materials (e.g., ultra-high strength steel and tailored blank) or innovative structural approach (two-part inner panel design with the functional integration). However, it could be hard to reach further weight reduction (e.g. > 20%) on door structures with a steel-only design. The work by [30] and [29] shows the huge lightweight potential of aluminum alloys on door structures (up to ca. 40%), which represents the state of the art of automotive OEMs. But the concomitant formability restriction and possible performance sacrifice should not be
neglected, such as the depth constraint on the deep-drawn inner panel made of aluminum sheets and the stiffness deficiency on the window frame made of aluminum extrusion profiles.

To achieve an even further weight reduction on door structures, fiber-reinforced materials are being investigated increasingly in advanced industrial and academic research projects. In the industrial project of [2, 31], a carbon-fiber-reinforced-plastic (CFRP) door concept was developed for the mass production, which features the inner panel and window frame made of CFRP. The complete Door-in-white (DIW) can be achieved by joining the metal outer panel module (including multiple reinforcements and the side impact beam) to the CFRP inner panel with bolts. In comparison to steel and aluminum reference, 55% and 35% weight reduction can be achieved, respectively. However, its high lightweight cost (21€/kg) is inacceptable in any series application.

In the research project of [17], a frameless fiber-reinforced-plastic (FRP) door concept was developed with the typical design principle of metal doors. Specifically, the typical metal sheets are replaced with fiber-reinforced thermoplastic (FRTP) organo sheets and rib reinforcements in the major load-bearing areas on the inner panel. Steel sheet inserts are placed in the hinge and latch area as load-introducing elements. Direct long-fiber thermoplastic (D-LFT) compression molding process is used to manufacture prototypes, which enables the overmolding of organo sheets and pre-formed steel inserts to the inner panel in one process. Due to the extensive use of organo sheets (almost the complete inner panel), this concept is likely to have a good structural performance (not specified) but with a relatively high cost (not specified). Its lightweight potential (15% weight reduction compared to an unspecified reference) was eventually limited by the use of the typical design principle of metal doors.

Based on the above-mentioned examples of lightweight doors from existing industrial applications and research approaches, it can be concluded that using the lightweight approach “material substitution with the traditional design principle of metal doors” is a feasible way to reduce the weight of door structures, but hard to achieve a cost-neutral lightweight design due to the high material cost, especially for FRPs. The material cost is a sensitive and crucial “game changer” for automotive OEMs since the conflict between the weight saving and the hard-to-ignore cost raising is always a central issue for the series application.

For this reason, the multi-material design method has drawn more attention since the end of last century. Many existing applications with the multi-material design method on structural and semi-structural Body-In-White (BIW) components, such as the front-end carrier [4, 5, 21–23, 27], the roof cross member [18], and the instrument panel carrier (ElringKlinger [7]), have proved that the multi-material design method is able to achieve weight reduction and deliver comparable structural performance with an acceptable lightweight cost. The continuous developing material- and process combination and the In-Mold-Assembly (IMA) techniques (e.g., adhesive bonding with adhesion promoter and mechanical connection with optimized shapes) for manufacturing multi-material components expand the application scenario of multi-material design in a fast pace [11, 14, Sheyyab et al. [32]).

In this work, different to existing applications, a lightweight LFT-metal door concept is developed with the “economic” multi-material design approach, which considers the cost-effective material substitution, innovative structural approach, and mass-production-ready manufacturing methods at the same time.

2 Design principle and materials

The multi-material lightweight door concept in this work was developed according to the design principle shown in Fig. 1a [9]. The basic idea of this design principle is to divide the door structure into two regions: (1) the major load-bearing region and (2) the minor load-bearing but function-relevant region. The major load-bearing region is able to provide the primary stiffness and strength for the entire door structure. The materials used in this region could be steel, aluminum or FRP with high E-modulus. As for the minor load-bearing but function-relevant regions, it acts as a shear web and should be able to integrate all necessary functional components, such as the latch, door stopper, window regulation system and loudspeaker. Materials with medium or relatively low stiffness and strength, such as PP-GF or PA-GF, are suitable for this second region. In addition, the raw material cost for PP-GF is even much lower than aluminum, and only slightly higher than steel. The outer panel of this design principle (not shown in Fig. 1a) is still made of steel or aluminum sheet, which should be attached to the inner panel by hemming and gluing. It provides additional stiffness and strength to the entire door structure since it may contribute as a shear web as well. Overall, maximized lightweight can be achieved with this design principle, as each component is loaded according to the mechanical properties of its material.

The major load-bearing region is built by a “two-ring” structure (Fig. 1a). The first ring structure includes the
window frame and belt reinforcements. The second ring structure includes hinge reinforcements, side impact beam, latch reinforcements and belt reinforcements. Here, the side impact beam is always the lowest point of the two-ring structure and should be made of metals considering the structure integrity during the crash, which is generally required by OEMs. The preliminary study on this design principle shows up to 30% weight saving potential comparing to a steel reference and ca. 20% material cost saving comparing to an aluminum reference.

To validate and further develop the above-mentioned design principle, a serial vehicle door made of steel was chosen as the reference in this work (Fig. 1b). Besides door structural components, all important functional components and necessary surrounding BIW components on this reference door were provided by the cooperative automotive OEM. Thus, the maximal available design space could be precisely defined, which had a significant influence on the rib structures with LFTs. In this work, considering the in-practice requirements from OEMs in the product development, two challenging design restrictions were set up: (1) the design space of original sheet-constructed reference door should be possibly kept without major changes/expansions; (2) the new concept door must be installed to the original vehicle without changing surrounding BIW components.

Based on the above-mentioned design principle, reference door and design restrictions, a new LFT-metal multi-material door concept (Fig. 1c) was sketched, which featured a roof-integrated “inner panel” made of LFT with steel sheet...
inserts in the major load-bearing region and a LFT “belt reinforcement outer”. Besides structural responsibilities, this “inner panel” can integrate many door functional components. The outer panel (not shown in Fig. 1c) was made of aluminum sheet. Comparing to the reference, almost all components were redesigned. Only the original side impact beam made of the ultra-high strength steel (UHSS) was kept on this new concept due to its importance for the side impact safety.

To balance the structural performance and the additional material cost, the “compression-molded Direct-LFT PP-GF40” (abbreviated as PP-LGF40 in this work) was chosen for components “inner panel” and “belt reinforcement outer” because its longer average fiber length in comparison to the “injection-molded Granulate-LFT PP-GF40”. Thus, higher strength and energy absorption could be expected [20]. In addition, PP-GF-based UD-Tapes were used as local reinforcements on the concept door. Due to the roof-integrated design and the material switching from steel to PP-LGF40 in the window frame area, the foreseeable challenge on this concept was reaching the aimed frame stiffness with the narrow cross-sections.

The major joining techniques on this concept are: (1) adhesive bonding using adhesion promoters between PP-LGF40 and steel sheet inserts; (2) spot welding between the side impact beam (steel) and steel sheet inserts; (3) threaded metal inserts and bolts between “belt reinforcement outer” and “inner panel”. Note that the concept sketch could only be regarded as a starting point. During the concept development, based on the practical available design space and loading situations, the specific material usage and joining techniques could be adjusted accordingly.

### 2.1 Material properties

The anisotropy material mechanical properties of PP-LGF40 used in this work were measured with the quasi-static tensile tests. The tensile specimens were cut from the sample

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**Fig. 2** a PP-LGF40 sample plate and tensile specimens; b PP-LGF40 quasi-static tensile test results in the flow and cross-directions

![PP-LGF40 sample plate and tensile specimens](image)

![Quasi-static tensile test](image)
plates manufactured with the compression molding process [14]. Specifically, melted PP-LGF40 extrudates were put in the sealed mold and pressed as the plates. Since the anisotropy behavior of PP-LGF40 depends majorly on the fiber direction, specimens were taken in the flow (0°) and cross direction (90°) from the area far from where the extrudate were placed (see Fig. 2a). Typically, the level of the fiber alignment elevates with the increasing of the flow distance in the flow direction.

According to the testing results (see Fig. 2b), the E-modulus of PP-LGF40 in the 0° and 90° directions was 9500 MPa and 4300 Mpa, respectively. Its tensile strength in these two directions was 118 MPa and 30 Mpa, respectively. To avoid a far-from-reality optimum design, the E-modulus of PP-LGF40 was defined as 6500 MPa in the topology optimizations with OptiStruct software, since an isotropic material model was applied (details see Sect. 4.2). This value is lower than the average E-modulus of PP-LGF40 in flow and cross-directions (6900 MPa). Correspondingly, 70 MPa was defined as its tensile strength in all simulations.

As for local reinforcements, a type of PP-GF-based UD-Tape was used, which had an E-modulus of ca. 50 GPa in the fiber direction (mechanical properties provided by the manufacturer). Meanwhile, the mild steel CR3 was used as steel sheet inserts.

![Fig. 3 Overview of design and optimization process](image)
3 Development overview

Figure 3 illustrates the overview of the design and optimization processes for the concept door. In comparison to the steel reference door, reaching 20% weight saving and achieving comparable structural performance under defined static and critical crash loading cases are the major design goals for the concept door. More than that, the concept door should be installed on the original BIW without any changes on the surrounding components.

The finite-element analysis (FEA) on the reference door points out the required stiffness and strength on the concept door, which are used as the requirements for the topology optimization, parameter optimization and performance validations of the new concept.

Clearly, the challenge during the development is how to reach the design goals with the existing design space of the reference door without major changes. The proper use of the topology optimization could accelerate this design process, which requires a clear-defined maximal allowable design space. In this work, this design space was carefully extracted from the reference door with the consideration of all important door functional components. Considering the challenging material usage “PP-LGF40+UD-Tapes” in the window frame area, a feasibility analysis was done for the window frame based on the newly defined design space.

The design of the preliminary door concept in this work, especially the rib construction, was guided with the material distributions from topology optimizations. To reach the lightweight and performance goals, the parameter optimization was also used to help optimize the thickness distribution of the door structure. The optimized door design was achieved after the performance validations under defined static and crash loading cases.

In this work, several state-of-art commercial FEA solvers were used during the development (see Fig. 3). Besides, two self-developed methods (yellow boxes in Fig. 3), “anisotropy analysis” [10] and “component development method” (Fang et al. [13]; [24], were integrated in the workflow. The “anisotropy analysis” could help to find areas with a high loading anisotropy (see Fig. 10a), which are suitable for the efficient use of UD-Tapes. The “component development method” was applied due to the limited available BIW data (details see Sect. 4.3).
4 FEA modeling description

In this work, static simulation, topology optimization and crash simulation were used intensively. The corresponding important FEA modeling techniques are described in this section.

4.1 Static simulation (reference door)

The finite-element (FE) simulations with the static loading cases on the reference door were done with Abaqus 6.13. As illustrated in Fig. 4, its FE model was made of solid and shell elements. Door hinges were considered in this simulation for its significant influence on the door stiffness and meshed with Hex8 solid elements only (typical Tetra4 solid element behaviors too stiff in this case). The sheet metal components were meshed with shell elements, which had an average element length of ca. 5 mm and followed the state-of-art FE modeling requirements in the automotive industry. To match the real testing circumstance, actual hinge pillar was replaced with a steel plate (“hinge pillar substitution” in Fig. 4) in this simulation.

This reference door included four major joining techniques: (1) spot welding, (2) adhesive, (3) bolt and (4) hemming. The first two types of joining techniques were realized with standard “RBE3+Hex8” elements (1 and 2 in Fig. 4). The hemming (4 in Fig. 4) was realized by joining the outer and inner panel with “node equivalence” and giving the thickness of “2 × outer panel + 1 × inner panel” on the flange areas. All bolt connections were realized with “RBE2” elements. Boundary conditions and forces were also applied through the “RBE2” elements by constraining related nodes.

The non-linear material behaviors of different steel types were also considered in this simulation by giving corresponding stress–strain curves in the material models. In this way, the minor plastic deformation on steel components under certain static loading cases could be simulated accurately.

4.2 Topology, parameter optimization and validation of static performance (concept door)

The topology, parameter optimization and static performance validation on the concept door were done with the commercial software “OptiStruct”. To make the comparison of simulation results convincing, many modeling techniques were oriented on the static simulation in Sect. 4.1. This section focuses only on the specialties.

In this work, like typical topology optimizations, the model was separated into “design spaces” and “non-designs” (see Figs. 5 and 9). The “design spaces” were the opportunity spaces for the optimization of rib structures. They were meshed with 5 mm solid elements (Tetra4). The “non-designs” included typically the base surface of PP-LGF40 and local reinforcements, such as UD-Tapes, sheet/threaded metal inserts. They were meshed with 5 mm shell elements (Quad4/Tria3). The joining between the “design space” and the “non-design” was achieved with the “node-to-node” connection (black nodes in Fig. 5).

As for the material models in the topology optimization, metals and PP-LGF40 were defined with the MAT1 in OptiStruct, which is a type of isotropic and linear elastic material model (important material properties see Sect. 2.1). Since the lay-up suggestion of UD-Tapes was achieved at this phase (detail see Sect. 6.1 and Fig. 10), MAT8 was applied on UD-Tapes with defined fiber orientations, which is a type of anisotropic material model in OptiStruct.

Since different stiffnesses were required under different loading cases (detail see Sect. 5), the “minimal weighted compliance” was set as the unified objective for all topology optimizations in this work (Altair [1]). Different “weight coefficients” were given onto different loading cases and furtherly adjusted depending on the reactions/outputs (e.g., displacement at force point) of the topology optimizations. Besides, to reach the weight saving goal, the volume fraction of “design spaces” was constrained to a certain value, such as V%. This value means that only V% of the “design spaces” could be used to generate the material distribution for the rib structures. The design constraints on PP-LGF40 components, such as the draw direction, minimal and maximal dimensions, were also considered in the topology optimizations according to the specific LFT manufacturing method, such as the compression molding. Further modeling details are illustrated in Sect. 6 correspondingly.

For the parameter optimization and static performance validation, most of the modeling techniques from the topology optimization were kept. One of the major differences was that the “design spaces” were replaced with
rib structures in the parameter optimization and validation phases. Parameter optimization was used to “fine tuning” the static structural performance and the weight of the concept door. Here, the rib thickness was optimized within a defined range (details see Sect. 7). Meanwhile, since the goal of this work is to reach weight saving without losing the mechanical performance, the optimization objective was set as “minimize mass” and the maximal allowable displacements at force points under different static loading cases were constrained in the parameter optimizations.

4.3 Crash simulation (reference and concept door)

Commercial explicit solver “Ls-Dyna R10.1.0” was used in this work for all crash simulations with the reference and concept door. To accelerate the whole development and validation process, the shell meshes from the reference and concept door in the static simulations were furtherly used in the crash simulations (without the solid-meshed hinge-pillar substitution and hinges). Here, the FEA modeling techniques, such element size/type, material models, and joining, followed the state-of-art requirements of the full-vehicle crash simulations in the automotive industry.

Specifically, shell elements with an average element length of 5 mm were used to mesh door and surrounding BIW components. Mat_24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) in Ls-Dyna [26] was used to describe the material behavior of metals and PP-LGF40. For metals, strain rate dependency was considered by defining multiple “flow curves” in the Mat_24. For the anisotropic material PP-LGF40, as mentioned in Sect. 2.1, it was simplified in the crash simulation as an isotropic material with Mat_24, where the E-modulus and the flow curve were conservatively defined (ca. average value in the flow and cross-directions). According to the work of [33], this simplification on PP-LGF40 can provide acceptable accuracy in the crash simulations with shell elements. This statement was approved at first by specimen level tests, such as tensile tests under different strain rates, notched tensile, shear, puncture and compression tests. In addition, this material simplification was further approved on simulation an airbag case. What should also be noticed here was that describing the anisotropic material behavior of PP-LGF40 relied on the filling simulation, which is typically unavailable at this phase of the concept development and also unfeasible with the middle-surface CAD model. The anisotropic material model Mat_54 (*MAT_ENHANCED_COMPOSITE_DAMAGE) in Ls-Dyna [26] was used to model UD-Tapes. No failure criteria for PP-LGF40 and UD-Tapes were considered in the crash simulations, since the investigation on the modeling of material failure was out of the scope of this concept development phase.

As mentioned in Sect. 3, due to the limited available BIW data, the “component development method” was used in this work. This method was developed for the design and validation of BIW side structures (e.g., door modules and B-pillar) on different vehicle classes, which used very limited BIW components to build the FE model and execute the crash simulation. For the model, only door rings including A-, B- and C-pillars, rocker and roof frame as well as small portion of floor panel are needed. The major benefit of using this method is that a comparable accuracy to the full-vehicle crash simulation could be achieved (Fang et al. 2005) under side impacts using only partial BIW data, since the reduced/unavailable BIW components were replaced by universal boundary conditions (BC) in simulations. These BCs are also implementable on a real test bench [24]. In this way, a reliable “close-to-full-vehicle-situation” crash behavior could be achieved for both the door structure and important surrounding components, which is crucial for the concept development in this work.

5 Structure mechanical requirements

Vehicle doors, as one of the most important closures, have huge influence on the NVH performance and passive safety of one vehicle. For the concept development in this work, several important static loading cases and one critical crash loading case were considered, which are described in the following sections.

5.1 Static loading case

In the automotive industry, there is no common standards for stiffness requirements on door structures. In this work, six representative static loading cases (Fig. 6) were defined according to the benchmarking from [15], Porsche [28]: (1) frame stiffness B-pillar; (2) frame stiffness middle; (3) door sag; (4) over opening; (5) belt stiffness outer; (6) belt stiffness inner. These six static loading cases are able to measure the stiffness of the most important door areas, such as frame, hinge, latch and belt.

Door stiffness goals under the six static loading cases above were defined based on the static simulation results with the reference door (FE model see Sect. 4.1). Here, the maximal displacement at force point on the reference door under every loading case (see Table 1) was set as the constraint/limit for the concept door. In this way, comparable or improved stiffness can be achieved on the concept door with FE optimizations. The accuracy of the static simulation
on the reference door was furtherly validated with the door hardware tests, which proved the reliability of the FEA modeling technique in Sect. 4.1, since the maximal deviation between the simulation and testing was less than 10%.

5.2 Crash loading case

The reference vehicle was launched only in the European market, which means that the reference door must properly fulfill the EuroNCAP side impact tests (much more severe than ECE R95) with the moving deformable barrier (MDB) and the rigid pole barrier. The rating scores of NCAP are usually translated into structural performance targets for BIW and door developments. For doors, the door velocities and intrusion as well as deformation patterns are the structural performance targets. In this work, the more critical side impact scenario with rigid pole barrier (version 2001) [8] was chosen to validate the concept door due to its higher intrusion value than the side impact with MDB [34] and higher strength requirements on the door structure. Specifically, in this test, the driver’s side of the vehicle will crash to a rigid pole barrier at the speed of 29 km/h with a 90° impact angle.

In side impact tests, the intrusion and intrusion velocity are decisive values to evaluate the performance of door structures [12]. As shown in the Fig. 7, to make the comparison between the reference and concept door quantitatively, several measuring points were defined on the door and surrounding BIW components. The position of measuring points considered almost all potential BIW areas which were related to or could be affected by the structural performance of door. Clearly, more measuring points could be found in the major pole impact areas, where the maximal intrusion could happen and were more crucial for the passive safety of passengers.
Specifically, in this work, the maximal intrusions and intrusion velocities on measuring points were used as the validation criteria for the concept door. Based on the crash simulation result of the reference door, its maximal intrusion happened at 70 ms when the “bounce back” starts (see Fig. 15a “reference door”). The values of maximal intrusions on corresponding measuring points can be found in the Appendix A (Table 4 under the column “reference door”). The important intrusion velocities in the critical passenger-related areas of the reference door are also given in Fig. 16 (red curves).
6 Structural development with topology optimization

6.1 Design space definition and feasibility analysis on window frame

The maximal allowable “design space” and “non-design” were defined at the beginning of the topology optimization, which used the original CAD data of the reference door as boundaries, such as steel sheet components and functional components. According to the new design principle (see Fig. 1), the total design space was furtherly separated into “major load-bearing” and “minor load-bearing” regions (Fig. 8a).

The spaces for original functional components, such as the side impact beam, loudspeakers, window regulation system and latch, were fully considered during the definition...
of the design spaces. Their mounting points were defined as non-designs. Most contours on the newly defined design space followed the original boundaries of sheet metal parts on the reference door, except for the window frame. As illustrated in the cross-section views of Fig. 8b and c, the design spaces were expanded to the inside surfaces of the original frame trim, which is reasonable for the window frame made of PP-LGF40 since the welding flange could be avoided. There are two major benefits by doing this: (1) expanded cross-sections increase the surface moment of inertia, which could compensate the loss of E-module due to the material switch from steel to PP-LGF40; (2) keep the same visual block area at A-pillar upper, which is required by OEMs for safety reasons. Clearly, the rubber sealing must be redesigned slightly in this situation, since the flange area remains unchanged for the primary sealing and the secondary sealing is installed on the surface of the inner side of the window frame with clips, as can be seen in Fig. 8b and c. These surfaces are the same for the original and new door. The sight obstruction for the driver will also not be affected since the maximal design space of concept door is within the original design space of the reference door.

After the definition of the total design space, a feasibility analysis on the material usage in the frame area was made with a simplified calculation method (detail see Appendix B). With this method, the thickness range/combinations of LFT and UD-Tapes was tested without the CAD design of the window frame. Instead, it used the relationship between deflections, E-modules and the moment of inertia of cross-sections.

To reach the same or even higher frame stiffness, the frame deflection on the concept door should be smaller than or at least the same as that of the reference. The area mass on the cross-section of the concept door should also be lower to ensure the weight reduction. Based on these requirements and results from the simplified calculation method, following conclusions can be made: (1) frame made of pure PP-LGF40 cannot reach the aimed stiffness in a manufacturable thickness range (typically 2–4 mm); and (2) a closing profile with the material combination “PP-LGF40 + UD-tapes” (see Appendix Fig. 17c) is a promising and practical solution for the frame area to reach the aimed stiffness and still achieve certain amount of weight saving (as can be seen later). Since the influence of possible rib structures cannot be considered in the simplified calculation (no CAD design was available at this moment), accurate thickness and region of UD-tapes and PP-LGF40 could only be achieved by further topology optimizations.

The total design space was separated into three sub-design spaces for different components, while considering the joining technique (method and geometry). Three different sub-design spaces (SDS) were: “SDS-belt reinforcement outer” (Fig. 9a), “SDS-hinge reinforcement” (Fig. 9b) and “SDS-inner panel major” (Fig. 9c). To achieve a clear material distribution, the sub-design space was specially assigned to have a non-design shell layer and a volume design space. Most SDSs used the −Y direction of the vehicle global coordinate as their demolding direction, except for “SDS-hinge reinforcement”. By setting its demolding direction in −X direction, the IMA of threaded metal inserts in the hinge holes and an optimal rib construction could be ensured.

Besides the above-mentioned sub-design spaces, the reinforcing closing plate (Fig. 9d) for the window frame was specially designed to increase the frame stiffness, based on the aforementioned feasibility analysis in the frame area. As illustrated in Fig. 9(A–A), due to the demolding direction constraint of “SDS-inner panel major”, only an open profile could be achieved in the frame area with the surfaces on the inner panel, making it very inefficient to carry bending moment even with the rib reinforcements. To solve this problem without adding too much extra weight, a reinforcing closing plate was added to achieve a closed cross-section together with existing frame surfaces on the inner panel.

Specifically, for the joining techniques, “SDS-belt reinforcement outer” and “SDS-inner panel major” were connected with threaded metal inserts and bolts. Threaded metal inserts were in-mold assembled into the PP-LGF40 inner panel during the compression molding process. The positions of bolt holes are defined in the sub-design space (Fig. 9c). Since “SDS-hinge reinforcement” and “SDS-inner panel major” belonged to the same component, no additional joining was needed here (node-to-node connection). The closing plate could be joined to the inner panel on the edges (Fig. 9d) using either the ultrasonic welding or infra-red welding depending on the final geometry.

As mentioned in Sect. 3, the position and dimension of UD-Tapes on the concept door were determined based on the load anisotropy state in different door areas. Here, the anisotropy analysis was done with the method from the work of [10] on the reference door with the consideration of above-mentioned static loading cases. A dimensionless “anisotropy value” defined by [6] was used in this method to describe the level of load anisotropy. The load anisotropy values are shown in Fig. 10a. Four areas with high anisotropy value (ca. > 0.7) were identified. Based on that, four UD-Tape areas with different fiber directions were defined correspondingly (Fig. 10b: 1 UD frame; 2 UD belt inner; 3 UD belt outer; 4 UD closing plate).
To consider the side pole crash loading case at this phase, a substituted crash loading case (Fig. 11a) was added in the topology optimization. Its force values were derived from the side pole crash simulation with the reference door (see Sect. 5.2) by setting up two sections on the side impact beam (Fig. 11a) nearing the joining areas to the inner panel. The

![Fig. 10](image)

**Fig. 10**  
(a) Anisotropy analysis with reference door; (b) areas with UD-Tapes on the topology optimization model and fiber direction
peak section forces in X and Y directions were converted as static forces in the topology optimization.

The steel side impact beam was joined to the PP-LGF40 inner panel using the spot welding with the help of two steel sheet inserts (applied with adhesion promoter coating) (Fig. 11b), which are pre-formed and partially overmolded to the inner panel during the compression molding process. The application of the adhesion promoter could enable a strong bonding between steel sheet inserts and PP-LGF40, which makes it suitable for BIW components. Moreover, these steel sheet inserts also help to conduct the huge impact force from the side impact beam to the major load-bearing ring structure on the inner panel.

6.2 Topology optimization and preliminary design

The topology optimization for the new concept was done after the definition of all model details and necessary parameters in simulations (see Sect. 4.2). Specifically, to reach the 20% weight saving goal, the volume fraction of PP-LGF40 was constrained to ca. 10%.

Besides the topology optimization with all loading cases (e.g., Fig. 12a), one additional optimization was done with the substituted crash loading case only (e.g., Fig. 12b), which was used to achieve a clear material distribution in the crash-related joining areas between the side impact beam and the inner panel (e.g., black box in Fig. 12b). As example, the achieved material distributions of the component “inner panel” are illustrated in Fig. 12a and b.

Here, by considering the material distributions from both topology optimizations at the same time, the preliminary rib construction on the component “inner panel” was achieved (Fig. 12c). Meanwhile, all non-design surfaces, UD-Tapes and metal inserts (threaded inserts and sheet inserts) from the topology optimization model were kept on the preliminary door design (Fig. 12c) without major changes.

7 Parameter optimization and performance validation

The components “inner panel”, “closing plate”, and “belt reinforcement outer” from Sect. 6, together with the original side impact beam and the aluminum door outer panel were firstly assembled as the preliminary door concept, which was then simulated under the static loading cases with the same hinge and hinge-pillar substitution as the reference door static simulation (see Sects. 4.1 and 5.1). The static performance of preliminary door concept (see Table 3) fulfilled all pre-defined static stiffness requirements and some of them were even “over-engineered”, such as loading cases “frame stiffness B-pillar”, “door sag”, “over opening” and “belt stiffness outer”. However, the deficiency on the weight reduction was not negligible, which could be further optimized through the parameter optimization.
Based on the preliminary door concept, further optimizations were carried out:

1) Rib number reduction on components “belt reinforcement outer” and “inner panel” due to the manufacturing difficulties (small rib distance).

2) Rib thickness optimization on components “belt reinforcement outer” and “inner panel” to achieve more weight reduction and relieve the over-engineered situation. The optimization range was from 2 to 3.5 mm.

3) Local base surface thickness reduction on components “belt reinforcement outer” (light blue area in Fig. 13c) and “inner panel” (dark blue area in Fig. 13a). The chosen areas were either related to over-engineered loading cases or to a minor stress state. The thickness was reduced from 3.5 to 2.6 mm on “belt reinforcement outer” and to 3 mm on “inner panel”, respectively.

The optimized door concept (Fig. 13) was achieved after the parameter optimization and manual thickness fitting. Its
important design parameters and manufacturing methods are summarized in Table 2.

![Diagram of the door concept with component labels and manufacturing methods.

**Table 2** Optimized door concept: important design parameters with two dedicated LFT manufacturing methods

| Component              | Closing plate | Belt reinforcement outer | Inner panel                      |
|------------------------|---------------|--------------------------|----------------------------------|
| Manufacturing method    | Injection molding | Compression molding      |                                   |
| Surface thickness (Ts)  | 3.5 mm        | 2.6 mm                   | 3.5/3 mm                         |
| Rib thickness (Tr)      | No ribs       | 3.5 mm                   | Frame area: 3.5 mm Bottom area: 2–3.5 mm |
| Average rib distance (Dr-avg) | –            | 18.7 mm                  | 12.2 mm                          |
| Average rib height (Hr-avg) | –            | 27 mm                    | 40.5 mm                          |
| UD-Tape thickness (Tu)  | UD closing plate: 1.5 mm | UD belt outer: 1 mm | UD frame: 1.5 mm UD belt inner: 1.5 mm |

*Rib virtual thickness is considered

Compression molding and injection molding were applied on the optimized door concept. Compression molding was used on components "belt reinforcement outer" and "inner panel".
panel”, where a longer average fiber length was required for a better crash performance [3]. Injection molding process was chosen for the “closing plate” due to its complex UD-Tape lay-up.

Key manufacturing restrictions, such as the rib distance and height, were taken into account on the optimized door concept. Specifically: (1) minimal average rib distance was 10 mm; (2) maximal average rib height was 40 mm. As shown in Table 2, the average rib distance and rib height of the optimized door stays in the reasonable range, which proves its manufacturability in large extend.

Still, there are a small number of high ribs on the optimized door concept, which are hard to avoid due to the pre-defined package constraints, such as the fixed inner panel depth and the fixed position of door stopper. For instance, some top surfaces of high ribs are used as the important contact surfaces for the installation between “belt reinforcement outer” to “inner panel”. Meanwhile, some high ribs on the side wall of the door inner panel are installing surfaces for the door stopper. Without a local depth change on the inner panel, it is hard to reduce their heights.

However, in the typical product development, these problems can be solved easily when these package constraints are removed. Under this circumstance, rib height could be furtherly reduced by shifting the local inner panel surfaces to the middle of high ribs. This change may provide the space and possibility to build ribs on both sides of the inner panel surfaces, and thus reduce the rib height. In this way,
a negligible loss of structural performance could also be expected.

Besides the rib distance and height, the window frame structure made of PP-LGF40 and UD-Tapes was also a challenge for the D-LFT compression molding process due to the slim geometry and the long material filling distance. To achieve a reliable component, the placement location and number of PP-LGF40 extrudates must be optimized in practice by “trial and error” or with the help of filling simulation, which should be conducted in the next step.

As mentioned in Sect. 6.1, bolts together with IMA threaded metal inserts were used to join components “belt reinforcement outer” and “inner panel”. As an example, joining area J1 (highlighted in Fig. 13a with a black box) is illustrated in Fig. 14 in detail. The closing plate of the window frame (Fig. 13b) was joined to the frame area of the inner panel on the edges using either the ultrasonic welding or infra-red welding.

As can be seen in Table 3, the final optimized door concept meets the design goals related to the static performance and weight. The final weight of the optimized door concept, which includes all PP-LGF40, UD-Tapes, sheet- and threaded metal inserts except bolts, is 13.11 kg and thus ca. 20% lighter than the reference door.

The Von Mises stress level on all PP-LGF40 components in all static simulations are below 70 MPa, which is the middle value of the tensile strength of PP-LGF40 in flow and cross-directions (stress concentrations caused by RBE2 rigid elements are excluded). Tensile strength is used here as the criterion since no clear yield point for PP-LGF40 material can be identified.

Besides static loading cases, the optimized door concept was furtherly validated under the side pole impact with the FE model described in Sect. 4.3. The intrusion comparison between the optimized door concept and the reference door is illustrated in Fig. 15. The concept door shows a comparable deformation behavior to the reference (Fig. 15a), when the maximal intrusion happens and the “bounce back” starts (70 ms).

To evaluate the crash performance quantitatively, the maximal intrusion values on corresponding measuring points from the concept door and reference are compared (see Appendix A). Based on the percentage difference of maximal intrusions and the criteria given in Fig. 15b, the door and surrounding BIW components are separated into different areas. Clearly, as shown in Fig. 15b, most areas on the optimized door concept are either in “good (green)” or “ok (yellow)” area, which evidences a positive crash performance. Especially, almost all “good” is in the passenger-related areas, which is a big plus for the concept door.

As for the intrusion velocity, the concept door also shows comparable or even lower intrusion velocities on important measuring points to that of the reference. Here in Fig. 16, the intrusion velocity comparisons in the critical positions of the passenger (head, chest and abdomen) are given as example. Among them, the maximal intrusion velocity on the concept door is below 8.7 m/s, which is in the acceptable range [12]. Since no material failure criteria were applied for
both reference and concept door due to the character of this work, it can be approximately concluded that the optimized concept door shows a comparable crash performance as the reference door under the side pole impact scenario with the original BIW surrounding structures.

8 Conclusion and outlook

An innovative design approach and economical material concept for an LFT-metal multi-material lightweight concept door with a roof-integrated structure has been investigated and realized virtually in this work. Following the new door design principle, the “two-ring” load-bearing structure are majorly made of PP-LGF40 and reinforced with the rib structures, UD-Tapes and steel sheet inserts. The original steel side impact beam was kept and integrated into the tworing structure. All original door functional components from the OEM series production, such as latch, stopper, loudspeaker, window regulator and interior components, can be installed onto the concept door without any changes.

From the simulation level, the positive structural behavior on the concept door under typical static and critical crash loading cases (side pole impact) proves the feasibility and effectiveness of the new door design principle. Especially, the ideal window frame performance illustrates the potential of using cost-effective material combination “PP-LGF40+UD-Tapes (PP-GF-based)” in the stiffness-demanding window frame area. Further, a smart design has been
done by integrating the major load-bearing structure (two-ring) into the PP-LGF40 inner panel, which maximizes the lightweight potential and increases the component integration level. Thus, the inner panel on the concept door can work more than as a carrier for door functional components and also as a shear web to carry a minor part of load in the area out of the “two-ring” structure. Moreover, the state-of-art LFT Joining techniques and the IMA joining techniques for LFT-metal multi-material design were also considered during the concept development.

During the whole development, FEA simulations were intensively used. Topology optimization and parameter optimization were the “work horse” to help achieve the complex rib structure and reach the weight reduction goal. Two self-developed methods, “anisotropy analysis” and “component development method”, were integrated in the workflow to either help determine the UD-Tape areas or to bring higher simulation accuracy in the crash simulation with limited BIW components.

Overall, in comparison to the reference, the final door concept reaches the 20% weight reduction goal and shows a comparable mechanical performance. The positive result in this work not only offers a feasible door structure solution, but also shed the light on using the LFT-metal multi-material design to achieve the weight saving on other vehicle closures.

In the next step, process simulations for the compression- and injection-molded LFT components should be made to furtherly validate the manufacturability of this door concept, especially for the “inner panel” due to the foreseeable difficulties caused by the long filling distance and the slim window frame structure. Meanwhile, the manufacturability of LFT components could be furtherly enhanced by adjusting the structural dimensions, such as the rib direction, height and distance. Based on the results of process simulations, a more close-to-reality FE model can be built by integrating the process-dependent fiber orientation of LFT components and eventually the anisotropic material behavior into the static and crash simulations (also called as “mapping”). Thus, material failure models of the LFT and UD-Tape for the crash simulations could be adopted and validated.

Appendix A

See Tables 4, Fig. 17.

Appendix B

To realize this simplified calculation method, two frame-related loading cases (frame stiffness B-pillar and middle) were converted as partial frame models and furtherly

| Measuring point number | Reference door | Concept door | Dif% (%) | Dif% (mm) |
|------------------------|----------------|--------------|---------|----------|
| S1                     | 49.5           | 43.4         | −12     | −6.1     |
| S2                     | 62.6           | 55.3         | −12     | −7.3     |
| S3                     | 25.5           | 26.5         | 4       | 1        |
| S4                     | 22.4           | 20.8         | −7      | −1.6     |
| S5                     | 19.6           | 21.1         | 8       | 1.5      |
| S6                     | 20.6           | 21.6         | 5       | 1        |
| S7                     | 28.6           | 28.3         | −1      | −0.3     |
| S8                     | 29.1           | 28.5         | −2      | −0.6     |
| S9                     | 25.1           | 25.5         | 2       | 0.4      |
| S10                    | 51.5           | 51.5         | 0       | 0        |
| S11                    | 75.4           | 73           | −3      | −2.4     |
| S12                    | 142            | 135          | −5      | −7       |
| S13                    | 110            | 120          | 9       | 10       |
| S14                    | 81.3           | 95.4         | 17      | 14.1     |
| S15                    | 80             | 93           | 16      | 13       |
| S16                    | 74.1           | 87.5         | 18      | 13.4     |
| S17                    | 54.3           | 58.8         | 8       | 4.5      |
| D1                     | 67.9           | 71.4         | 5       | 3.5      |
| D2                     | 86             | 78.8         | −8      | −7.2     |
| D3                     | 52.3           | 52.6         | 1       | 0.3      |
| D4                     | 46             | 46.4         | 1       | 0.4      |
| D5                     | 43             | 41.9         | −3      | −1.1     |
| D6                     | 41.7           | 38.3         | −8      | −3.4     |
| D7                     | 40             | 40           | 0       | 0        |
| D8                     | 45.6           | 43.8         | −4      | −1.8     |
| D9                     | 52.1           | 49.6         | −5      | −2.5     |
| D10                    | 77             | 81.8         | 6       | 4.8      |
| D11                    | 159            | 165          | 4       | 6        |
| D12                    | 236            | 268          | 14      | 32       |
| D13                    | 177            | 196          | 11      | 19       |
| D14                    | 122            | 144          | 18      | 22       |
| D15                    | 120            | 136          | 13      | 16       |
| D16                    | 122            | 130          | 7       | 8        |
| D17                    | 75.4           | 85.1         | 13      | 9.7      |
| D18                    | 167            | 162          | −3      | −5       |
| D19                    | 168            | 176          | 5       | 8        |
| D20                    | 84             | 77.8         | −7      | −6.2     |
| DP1                    | 84.8           | 78.8         | −7      | −6       |
| DP2                    | 202            | 193          | −4      | −9       |
| DP3                    | 253            | 242          | −4      | −11      |
| DP4                    | 270            | 257          | −5      | −13      |
| DP5                    | 339            | 331          | −2      | −8       |
| DP6                    | 221            | 249          | 13      | 28       |
simplified as the cantilever beam problem. The simplification of the load case “frame stiffness B-pillar” is given in Appendix Fig. 17a as an example. Meanwhile, cross-sections of the reference door and the design space were simplified as rectangles as well (Appendix Fig. 17b and c). Since no CAD design was available at this moment, estimating the effect of rib structures on the frame stiffness was difficult. For this reason, the possible stiffness provided by rib structures on the frame of concept door was neglected in this simplified calculation, and an approximative approach was applied to determine the starting geometry of cross-sections.

To make this method easier to understand, the calculation based on “cross section A-A” is used here as an example. As can be seen in Appendix Fig. 17b and c, the “middle surface contour” of the reference and the “design space” contour of the new concept were converted into different “calculation rectangles” according to the force direction at first. What needs to be ensured here was that
the area of “calculation rectangle” should be equal to its original “middle surface contour” or “design space”. In this way, calculation results achieved from “calculation rectangles” are comparable to their original contours. Then, the moment of inertia “I,” of “calculation sections” can be easily determined by giving thickness on the “calculation rectangles”.

With this simplified calculation method, the thickness range/combination of the PP-LGF40 and UD-Tape was tested using the given parameters in Appendix Fig. 17b and c and the relationship between deflections, E-modules and the moment of inertia. For example, according to the calculation result, using 1.85 mm UD-Tape and 2 mm PP-LGF40 on the cross-section A–A can achieve comparable frame stiffness to the reference with ca. 26% weight saving.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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