COMPUTING METHODOLOGY FOR SMC STRUCTURES REINFORCED BY CONTINUOUS FIBER REINFORCEMENTS

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ABSTRACT

The demand for fuel efficient aircraft and vehicles led to the development of innovative lightweight constructions and the use of lightweight materials, such as carbon fiber reinforced plastics (CFRP). In the same manner competences in new production technologies have been built up in the aerospace industry. However, current processes for developing and producing composites with an excellent mechanical performance cause high costs and long process cycles in comparison to approved metal processes. Furthermore, the used raw materials, such as carbon fibers and resin, are very expensive. In contrast to these technologies sheet molding compound is characterized by a very high productivity, excellent part reproducibility, cost efficiency and the possibility to realize complex components with integrated functions. The biggest disadvantage of sheet molding compound parts is a low level of stiffness and strength because of a low fiber-volume fraction and a short fiber length. In this context the combination of sheet molding compound (SMC) and pre-impregnated continuous fiber reinforcements in an in-situ compression molding and curing process merges the advantages of both materials to create load-bearing and autoclave-quality parts without an autoclave.

The intention of the present work is the development of a finite element based simulation and optimization method for a new hybrid composite technology for aerospace applications which includes innovative material combinations and an efficient production process in equal measure. The whole development process for the technology is guided efficiently by implementing different numerical optimization methods. Modern simulation methods are applied for validating robust material models, design, dimensioning and calculation of composite or hybrid aircraft components which should be produced with this new technology. This includes a complete structural FEM-analysis, regarding to stresses, strains and rupture of the composite material component. Tools for optimization of topology and laminate will be implemented in order to design load-orientated structures with a minimum of material usage. In addition, the study is based on reference parts from aircraft interior for which functional patterns are designed and manufactured. Prototype testing is performed in order to validate the technology and the virtual optimization as well as simulation methodologies.

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1. INTRODUCTION

Within the framework of a funded project a new composite technology for aerospace applications was focused which is called “Hybrid SMC” and which has been developed from the aircraft manufacturer Airbus. This technology is characterized by the combination of chopped fiber SMC fabrics with pre-impregnated continuous fiber reinforcements, which is processed in a single-stage pressing and curing process. Hence, the time-saving as well as cost-efficient production of geometrically complex and load-path-optimized components can be realized.

As reference component for the project and its investigations an aircraft cargo footstep made out of titanium was used. The new reference part was designed to be manufactured by the “Hybrid SMC” technology. That was necessary to validate the developed simulation and computing methods for the new material combination within the project. [1, 2, 3]

However, a detailed preparation of a requirements and a functional specification for the aircraft cargo footstep were required. In order to design such a reference part, it is necessary to know the loads to be expected in practice. These loads did not exist at the beginning of the project, so that they had to be determined. For this purpose, a partial and true-to-scale replica of the cargo compartment of an Airbus A330 with installed cargo footsteps was constructed. With the help of the cargo footstep test rig, called “step clinic”, tests were carried out by test persons to measure the loads occurring on the steps in reality. Here, the original titanium steps and the matching attachment panel were used. The “step clinic” simulates the real cargo compartment space in a loaded state, which is realized by an additional wall.

Into the next step a suitable material specification for appropriate SMC fabrics qualified for aircraft cargo applications was prepared. The materials investigated are SMC materials consisting of a thermoset matrix system based on unsaturated polyester resin, reinforced by glass fibers and filled with flame retardants. To determine the needed material data a large number of characteristic values are required for the most precise modelling of materials in FEM. Hence, quasi-static and cyclic material tests are carried out. The experimentally determined characteristic values of the material behavior are transferred into the appropriate programs for the execution of the linear and non-linear calculations. Consequently, the numerical calculations and especially numerical optimization can be realized. [4, 5]

The validation and comparison through testing of functional samples is performed by using a drop tower test setup and a quasi-static test facility to evaluate the functional models. Finally, the validation and evaluation of the cargo footstep followed. For realizing this, various field tests and application-oriented component tests are used. In addition, the results from these tests were used for optimization and performing technical adaptations.

This paper deals with the whole development procedure for a finite element based simulation as well as optimization method related to the “Hybrid SMC” material and process technology for aerospace applications. Hence, the present work reflects the development steps as well as results in the framework of the previously mentioned project.

2. SMC AND HYBRID SMC TECHNOLOGY

On the basis of the facts described into the introduction a new technology called “Hybrid SMC” was focused for the current work. This new material as well as process technology is a compression molding of a component-related combination of chopped fiber SMC fabrics and pre-impregnated continuous fiber reinforcements. The schematic technology approach is illustrated in Figure 1. In the framework of the project a chopped glass fiber reinforced SMC and continuous carbon fiber reinforcements are investigated.

In contrast to the compression molding of regular chopped fiber SMC materials a part-specific preforming procedure is required. This preform shall comply with the major surface of the mold cavity up to 95 percent. On the one hand this allows the required flowability of the SMC during the compression molding to fill the whole cavity, reach the needed consolidation and an appropriate part surface. On the other this fact limits the movement and disorientation of the continuous fiber reinforcements during the pressing procedure. In addition, various fixation mechanisms for the continuous fiber fabric such as special clamping or needle systems can be applied within the compression mold and related to the geometry as well as requirements of the component. [1, 2]

In both cases, the thermoset matrix systems have the same chemical basis. The matrix is based on unsaturated polyester, although the glass fiber SMC fabric is additionally filled with flame retardants such as aluminum hydroxide (ATH). This fact allows that the combination of the different fabrics meets the strict fire, smoke density and toxicity (FST) requirement of aircraft interior applications. It has to be taken into consideration that the continuous fiber reinforcements must be surrounded by the SMC within the produced component. Otherwise, the FST requirements cannot be fulfilled. Due to the use of high-reactive SMC formulations the curing cycle for aircraft cabin and cargo parts is no longer than 180 seconds. [1, 2]

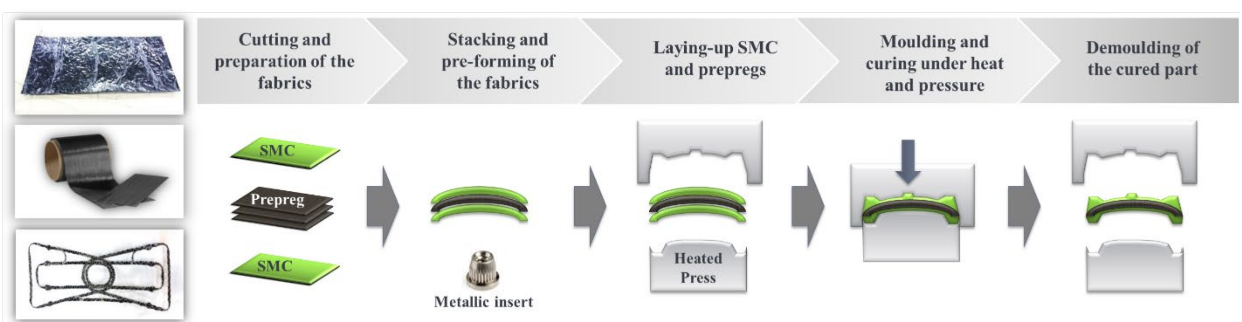


Figure 1: Schematic illustration of the “Hybrid SMC” process for aviation industry [1]

Short curing cycles, highly functional integration, comparatively high material utilization of over 90 percent and the opportunity for full automation are making this technology extremely time-efficient and highly economical. In addition, it offers the possibility of integrating various functional elements such as metallic inserts or complex rib structures directly. Due to the high degree of component complexity and functional integration the effort required for reworking, assembly and finishing can be decreased extremely in comparison the established composite technologies in aerospace industry. [2, 3]

The problem of mechanical properties in general and the dispersion of parameters in the case of the discontinuously oriented long fiber reinforcements of the SMC material can be addressed by a targeted design as well as the direct implementation of continuous fiber reinforcements according to the load paths of the components. Consequently, the lightweight potential can be increased significantly. [4, 5]

With conventional SMC technology the cargo footstep as reference part cannot be manufactured with the required stiffness, strength and impact properties by taking weight targets into account. For this reason, a cost-intensive metallic solution (titanium) is currently being used. Compared to the titanium cargo footstep currently used, the “Hybrid SMC“-variant is intended to reduce costs and weight compared to comparable technologies. This hybrid material combination and technology opens up new possibilities for the fast and highly efficient production of lightweight structures not only in aviation industry, but also for the automotive and transportation sector. [4]

3. DEVELOPMENT OF THE SIMULATION METHOD

The methodic approach for the simulation of fiber-reinforced-plastics is divided into four phases (see Figure 2). These phases are structured in such a way that each of them contains essential aspects that lead to a validated FEA model.

Phase 1: Collecting data

First, the occurring loads and boundary conditions are determined. Here it is important to identify all critical loads that can affect the component to be examined. Load cases caused by human errors should be also considered, as long as they result in high loads or are aimed at possible weak points. In this the load cases are determined with the “step clinic” test rig. On the basis of the results of the “step clinic”, substitute load cases are defined, which are integrated into the simulation. Furthermore, the mounting should be clarified and whether any friction between the components could be significant. The exact nature of the component's mounting is essential for accurate simulation. Fiber-reinforced-plastic material is anisotropic, therefor several types of stress (tensile, compressive, shear, bending) must be investigated during characterization. Due to the manufacturing conditions, in the production of fiber-reinforced components, a wider range of material behavior should be expected. In addition to the experimentally determined characteristic values, hardening parameters must be determined for the material law mat 25 CRASURV used for the Solver Radioss. These are determined iteratively on the basis of the respective direction-dependent stress / strain diagram by means of an algorithm. For validation, the material tests are simulated with an FEA model and compared with the investigations.

Phase 2: Simulation

With the material card, loads, constraints and geometry of the component the FEA model can be built. The aim of this FEA is to be able to make a validated statement about the behavior of the component. In the process, a 2D mesh is derived from the geometry and the material card is assigned. Subsequently, the boundary conditions (fasteners, contacts etc.) are set and the loads are applied. It is necessary to distinguish between an implicit and an explicit calculation. In this work, an implicit calculation with the solver Optistruct is used for the stiffness optimization and an explicit calculation with the solver Radioss for dynamic load cases and impact optimization. The following parameters are considered for the optimization process: layer structure, layer thickness, layer orientation, topology and topography.

Phase 3: Testing

Due to the dispersion of the material characteristics, which results from the manufacturing conditions of the SMC process and the production of the material, it is necessary to check the simulation results by appropriate tests. The test setup must be as accurate as possible, so that a comparison to the FEA model is possible. It is essential that the test provides reproducible results, since otherwise it can lead to errors in the evaluation. The validation of the results is done by comparing certain data from trial and simulation. In this work, the occurring force and axial deformation of the component are measured during a drop tower test. The measurement data are projected into a force / displacement diagram and compared with the diagrams from the simulation.

Phase 4: Validation of the results

If a sufficient correlation of the experimental data can be found in comparison to the simulation, a validated model is available. Based on the FEA model a decision can be made with regard to the component evaluation. Furthermore, the FEA Model can be used for similar load cases.

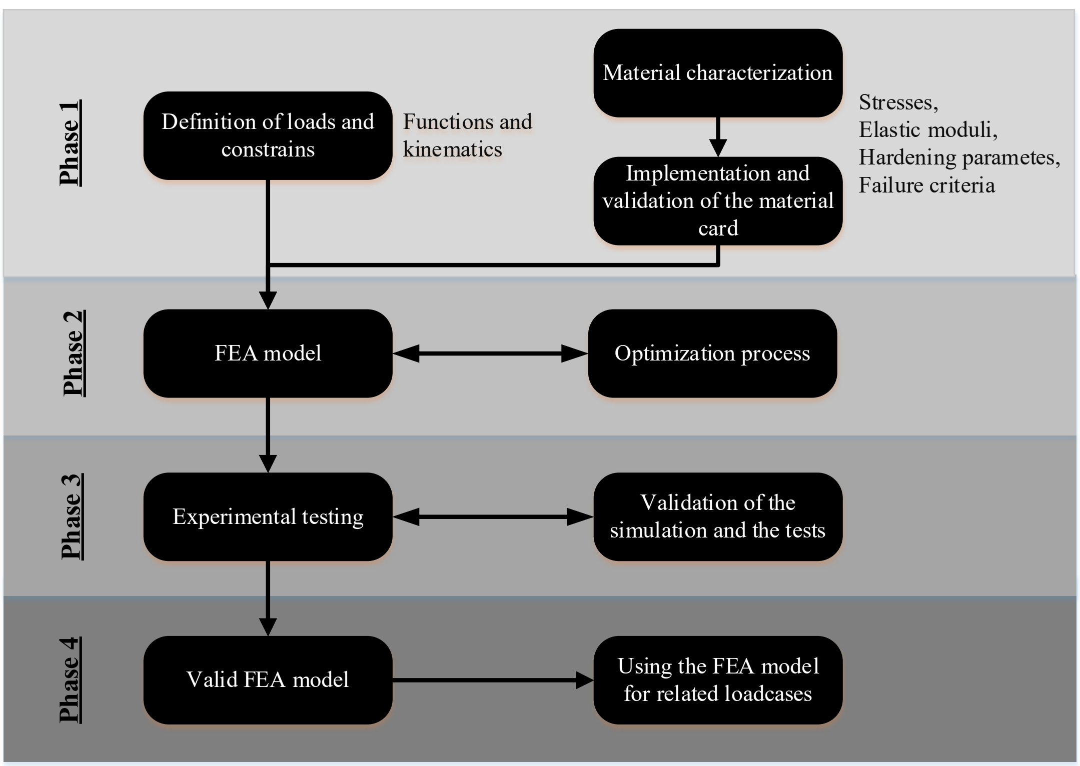


Figure 2: Methodic approach for the Simulation of fiber-reinforced-plastics

4. DETERMINATION OF LOADS FOR REFERENCE PARTS

In order to reach a robust design of the step reference part, the knowledge of the expected loads in real life situations is necessary. As these loads were not available at the beginning of the project, they had to be determined first. For this purpose, a partial and true-to-scale replica of the installation situation in the aircraft cargo compartment is built with two reference treads under consideration of the available space for walking for aircraft stuff members. Figure 3, left shows the real cargo compartment of an Airbus A330 in the empty state. The picture in the middle shows the created replica, which is referred to the "step clinic". This device is used for investigations with volunteers in order to measure real life loads on the steps. The width of the “step clinic” is 500 mm, the height is measured from the step surface with 1,650 mm. These narrow dimensions lead to a, in most people, stooped posture when crossing the cargo hold. There is thus an increased risk of tripping to be expected, whereby a shock load by means of the toe on the side wall of the tread is a common load case.

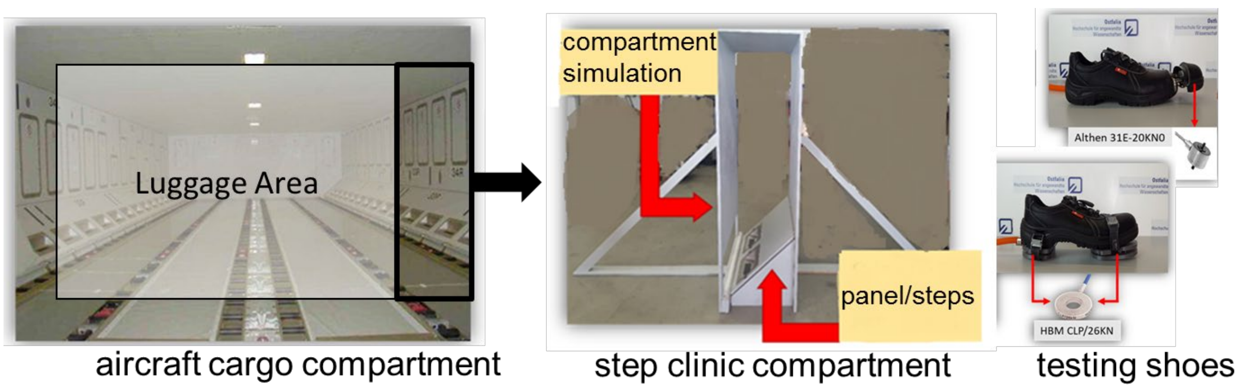
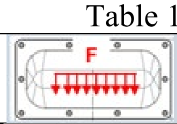
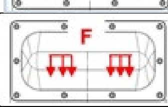
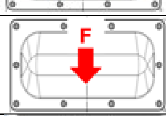
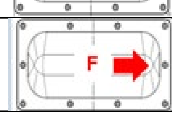


Figure 3: Determination of loads by using the “step clinic” test rig

To measure the forces during the volunteer test series, two trial shoes are used as shown in the right pictures in Figure 3. As shown, the trial shoes are equipped with load cells. For the load case of a foot hit in the side and back walls of the step, a sensor Althen 31E - 20KNO designed for a maximum dynamic force measurement of 20 kN is installed on the toe. The second trial shoe is intended for the load cases in normal foot loading. For this purpose, two sensors of the type CLP / 26KN HBM are used, which are installed in a plastic holder and secured by straps on the hoe and the ball of the foot.

Table 1: Derived loads from voluntary tests

Loadcase 1		central foot load	1000 N
Loadcase 2		footstep load left/right	1350 N
Loadcase 3		foot hit load back	1000 N
Loadcase 4		foot hit load side	850 N

The recording frequency of both sensors is set to 10 kHz. Finally, the load cases shown in Table 1 are determined based on the results of the subject trials and taking into account safety factors as design load cases.

5. MATERIAL CHARACTERIZATION AND VALIDATION

For the numerical calculations in this project the solver Radioss with the material law 25 is used. The Solver Radioss is designed for explicit calculations and is used for highly dynamic simulations in which the material behavior can be fully characterized. Here not only the elastic range is considered, but also the plasticizing and the failure of the material. There are two variants of the material law 25, which differ with regard to the calculation of plasticity. When assigning the value O or 1 to the variable I_{form}, it can be chosen between the Tsai-Wu model or the CRASURV model. With the CRASURV model, plasticization can be adjusted in all directions, so that this model is preferable for dynamic loadable arrangements. Figure 4 displays all parameters that influence the behavior of the material [6]. The parameters in line 2 describe the elastic behavior in three directions, such as the modulus of elasticity and the shear modulus. The parameters in line 4 describe the damage behavior of the material and the failure criteria for deleting elements. Lines 6 to 10 describe the directional behavior of the material in tensile-, compression- and shear directions. The parameters in line 5 and all c_i^j variables which describe the strain rate dependence and the parameters in line 11 which consider the delamination of the layers, are not considered in this project.

1	ρ											
2	E_{11}	E_{22}	E_{33}	υ_{12}	G_{12}	G_{23}	G_{31}					
3	I_{form}											
4	ε_{f1}	ε_{f2}	ε_{t1}	ε_{m1}	ε_{t2}	ε_{m2}	d_{max}	W_{pmax}	W_{pref}	I_{off}	$Ratio$	α
5	c	$\dot{\varepsilon}_0$	ICC_{global}	F_{smooth}	F_{cut}							
6	σ_{1y}^t	b_1^t	n_1^t	σ_{1max}^t	c_1^t	ε_1^{t1}	ε_2^{t1}	σ_{rs}^{t1}	W_{pmax}^{t1}			
7	σ_{2y}^t	b_2^t	n_2^t	σ_{2max}^t	c_2^t	ε_1^{t2}	ε_2^{t2}	σ_{rs}^{t2}	W_{pmax}^{t2}			
8	σ_{1y}^c	b_1^c	n_1^c	σ_{1max}^c	c_1^c	ε_1^{c1}	ε_1^{c2}	σ_{rs}^{c1}	W_{pmax}^{c1}			
9	σ_{2y}^c	b_2^c	n_2^c	σ_{2max}^c	c_2^c	ε_2^{c1}	ε_2^{c2}	σ_{rs}^{c2}	W_{pmax}^{c2}			
10	σ_{12y}	b_{12}	n_{12}	σ_{12max}	c_{12}	ε_1^{12}	ε_2^{12}	σ_{rs}^{12}	W_{pmax}^{12}			
11	γ_{ini}	γ_{max}	d_{3max}									

Specific test/valid method for each parameter set			
	Specific density test ISO 1183 A		Tensile test DIN EN ISO 527-1+4
	Shear test DIN EN 2377 or for continuous fibers tensile test with an orientation of ±45°		Validated by numerical calculation
	Not Considered		1-element-method
	Pressure test DIN EN 6036		Residual stresses set to 0

Figure 4: Radioss material law 25 CRASURV Parameters

In order to get a robust simulation result in a first step the mechanical material behavior from physical material testing must be implemented and validated in simulation models. In this context the result of tensile and compression tests in 0°, 90° and 45° for all considered fiber-matrix-combinations are used for modelling the mechanical properties (1-element-method) in the material model, see Figure 5. In the modelling process the tools Hypermesh and Hypercrash as well as Hyperview for visualization of the results were used. Further testing (e.g. bending, compression after impact) is planned in order to do a further validation of the material model. Nevertheless a main goal to achieve is to minimize the testing effort for validating the material model in order to increase the usability of the tool for the series development process.

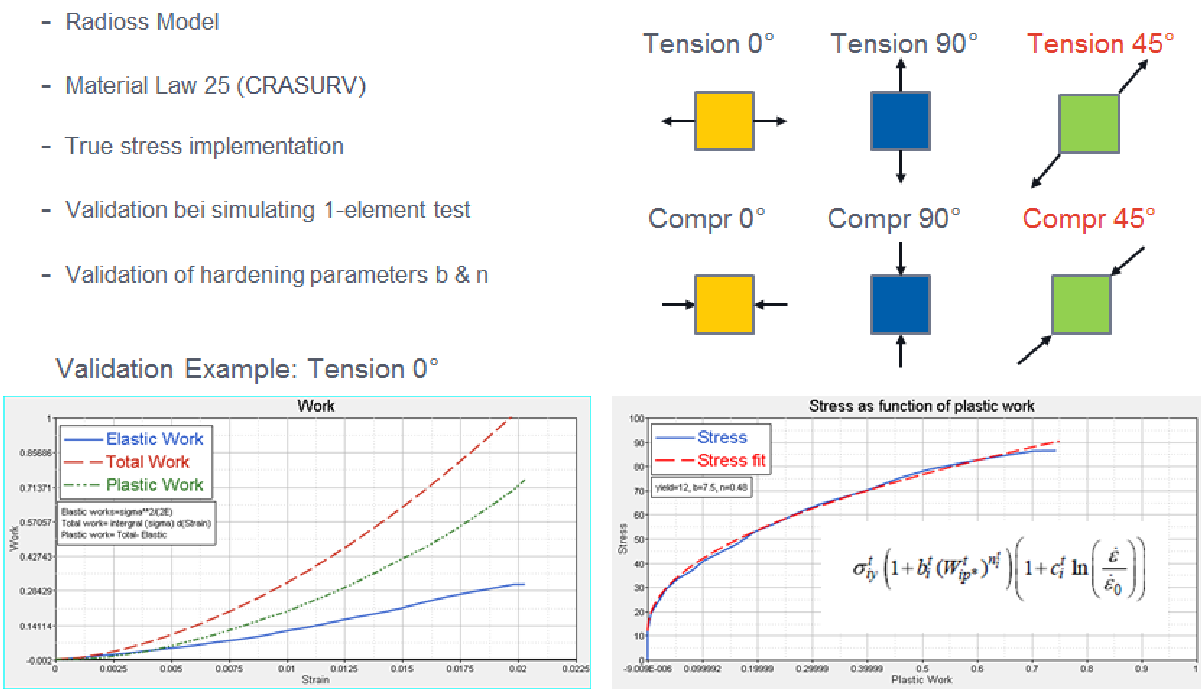


Figure 5: Material modelling (example tension 0°) [4]

6. VALIDATION OF REFERENCE PARTS AND DAMAGE CRITERIA

The evaluation of the quality of the simulation models is performed by means of dynamic testing based on the load cases described in chapter 4. A drop tower test bench is set up for the experimental testing according to Figure 6. The investigated footstep is loaded by a spherical rigid impactor. For documentation of the testing results, force and travel are measured at the impactor. The detailed behavior during the test can be analyzed by using the pictures from high speed video capturing with a frequency of 4,000 Hz.

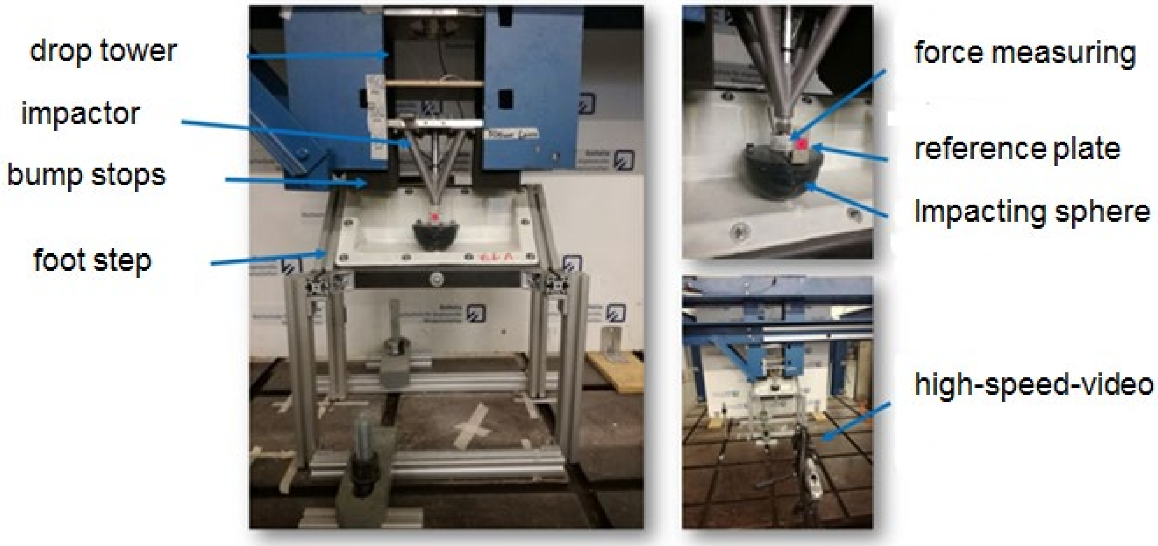


Figure 6: Experimental drop tower test set-up

The quality of the derived results is shown exemplary for the load case foot hit load in Figure 7. The measured force-deflection plots from six identical testing configurations are overlaid with the results from different simulation models. The main difference between the simulation models is the usage of different failure models for the endless reinforcement fiber models used. A rather simple deformation energy based model is compared to fiber rupture and cohesive rupture models from Hashin and Puck. All curves from the simulations are in the range of the scattering of the measured data, thus a good correlation can be achieved. In order to describe the validation quality, medium force and deflection from simulation are compared to the averaged testing curve with the following result:

- Failure after maximum energy: Force (88%), Deflection (97%)
- Hashin Failure: Force (91%), Deflection (97%)
- Puck Failure: Force (91%), Deflection (97%)

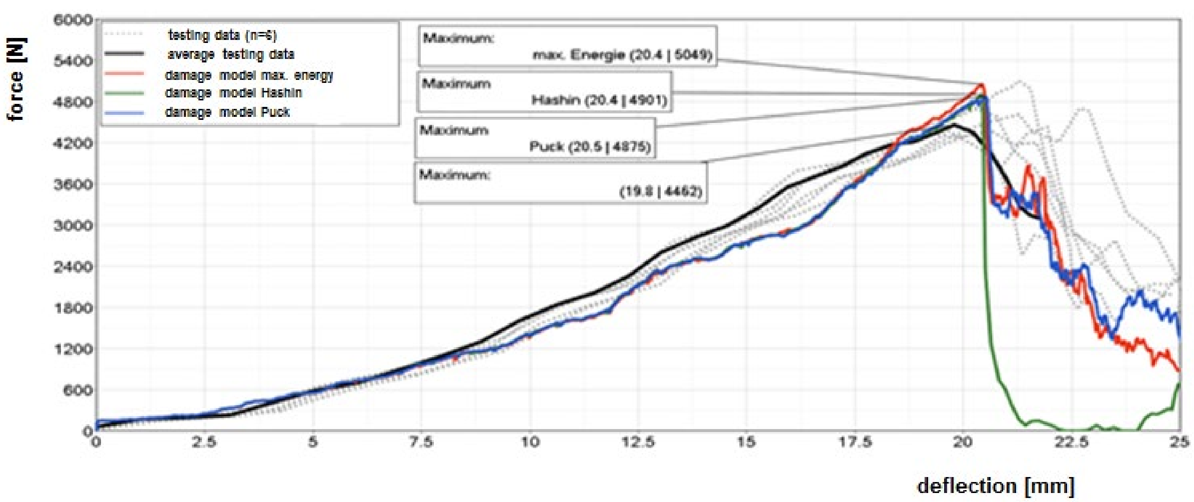


Figure 7: Validation by usage of different damage models (load case “foot hit load”)

7. METHODICAL OPTIMIZATION PROCEDURES

The numerical simulation and optimisation process for the part can be divided in a stiffness optimisation and an impact optimisation for the part as shown in Figure 8.

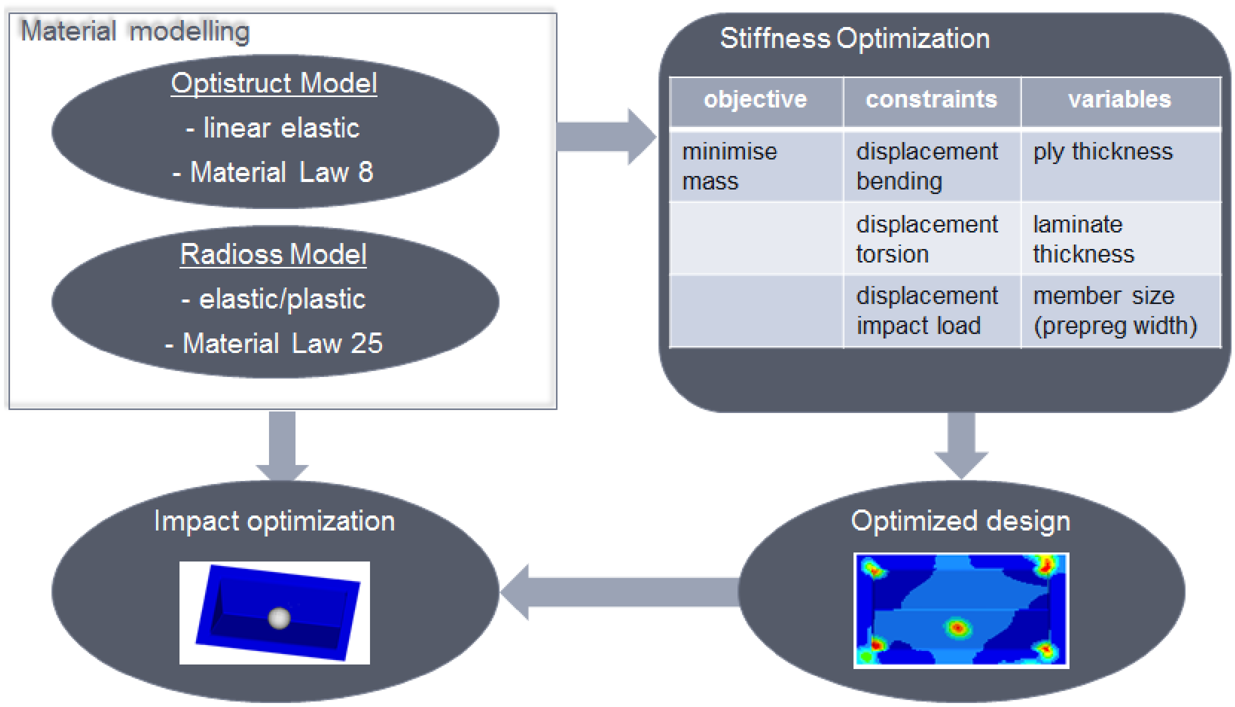


Figure 8: Optimization process for development of the reference part [4]

For the stiffness optimization a three step process is used, that is combined with a topology optimization in order to optimize the part with respect to the given package requirements. In the first step – a free-size optimization – areas for an efficient reinforcement with endless fibres in different directions were identified. The free-size optimization creates a design concept by variation of the thickness of each ply for every single finite element of the model. For this purpose the fiber angle and the thickness for each ply of the draft laminate are assigned to the model based on the results of the topology optimization according to Figure 9. The load case is a combined load based on stiffness and a substituted load representing the impact requirements (see chapter 4). The following parameters are considered during the set-up of single optimization runs. By variation of single parameters the result can be influenced with regard to production restrictions for the reference part and its geometry.

- Boundaries for the thickness of the whole laminate
- Boundaries for the thickness of the single plies
- Balanced thicknesses between the single plies

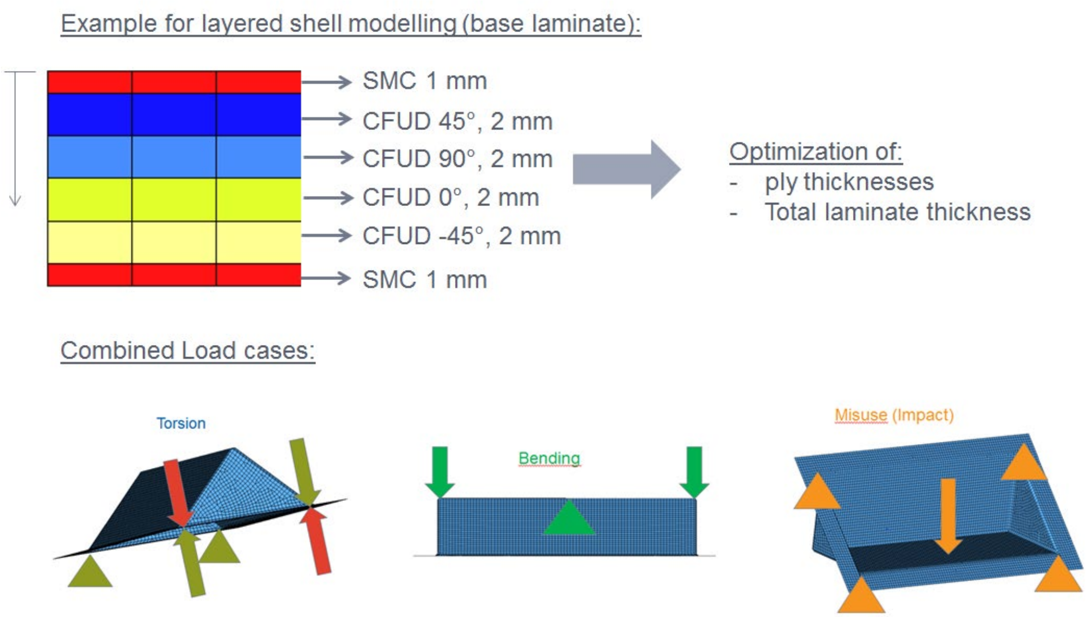


Figure 9: Base laminate and load cases for the free-size optimization

The result of this step is a design proposal for the orientation of fibre patches in the single areas of the cargo footstep. The main optimization with regard to the resulting part weight and stiffness is already reached after repeating this step for different design variants. Figure 10 shows an exemplary result from this optimization step with a design proposal for the thicknesses of different layers in the cargo footstep laminate.

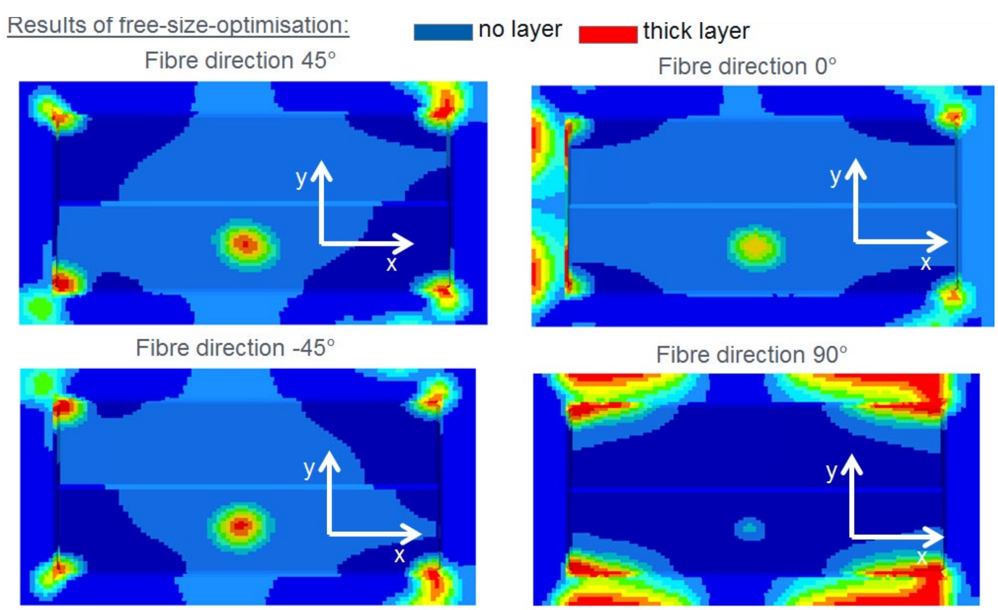


Figure 10: Design proposal as result from the free-size optimization

In the third optimisation step the manufacturing process limitations were considered, using a sizing optimisation. This step can be performed by automatically importing the result from the free-size optimization. Based on this, discrete thicknesses of the single patches and the number of layers could be designed according to manufacturing limitations. Figure 11 shows the change of the step design during this optimization step. Whereas the left design (as a result from the free-size optimization) is theoretical and not feasible, from the right design a feasible laminate can be derived from.

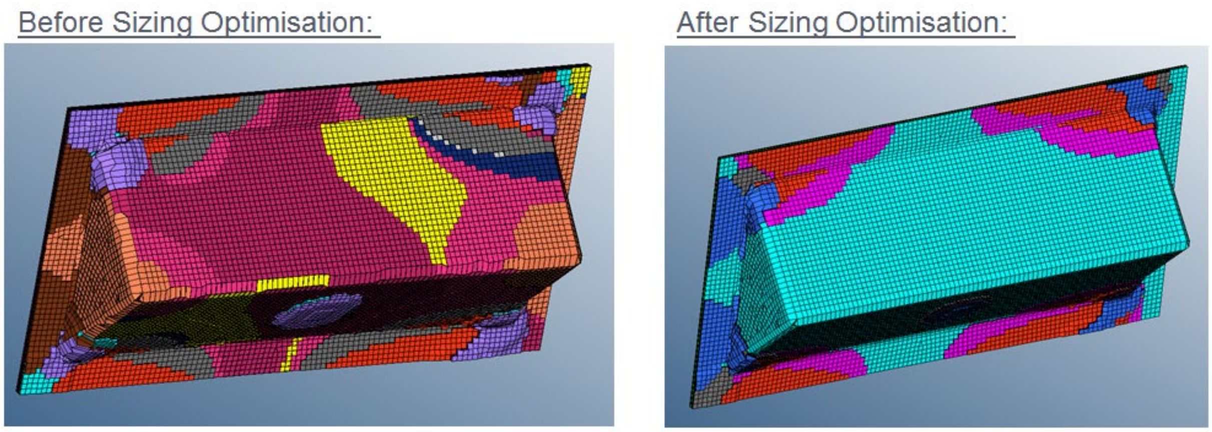


Figure 11: Generating a feasible laminate design by usage of sizing optimization

In the final optimisation step based on the result of the size optimization a shuffling optimisation was performed in order to optimise the order of the single layers in the laminate. During the project described in this paper this final optimization step was of minor importance as the number of layers is strongly restricted and the outer cover layers of the laminate must be from the fire-resistant base SMC material. Nevertheless in general the shuffle optimization is a strong tool for further optimizing the mechanical performance of the structure.

Finally, the optimized model was implemented in a crash simulation model for optimization of the impact and damage behaviour of the cargo footstep. With the same weight of the cargo footstep in whole a significant reduction of the occurring damage could be reached by the optimization process. Figure 12 shows the result from the Radioss crash simulation for one exemplary design and impact point.

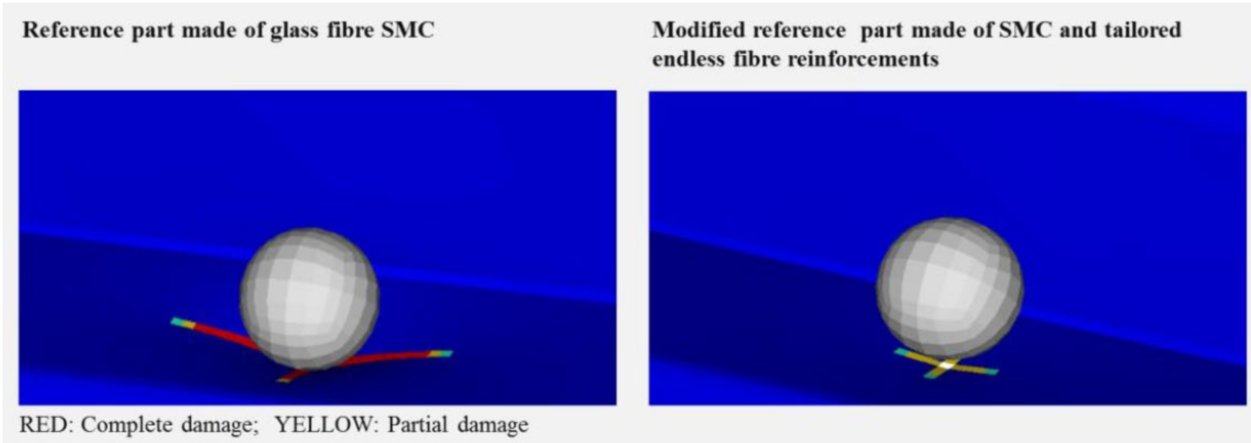


Figure 12: Exemplary results of the Radioss crash simulation for one impact point (left: reference part made out of glass fibre SMC; right: reference part made out of "Hybrid SMC")

In addition, Figure 13 shows one exemplary resulting layout for the cargo footstep. The results for the final design of the step are compared to a reference part (standard SMC without reinforcements) which is not suitable to fulfil the load case performance required (see chapter 4).

- Final design fulfils all requirements from impact load cases.
- Weight of final design is reduced by 13% (from 515g to 447g) to the standard SMC reference part.

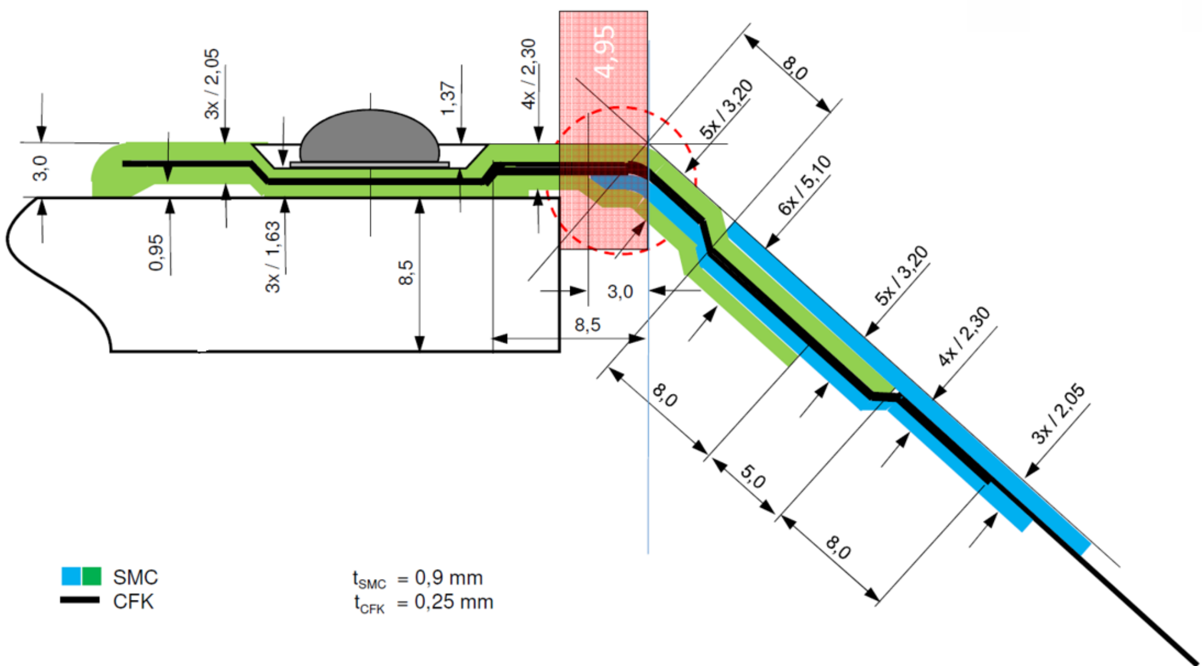


Figure 13: Derived layout for the outer step area

8. CONCLUSIONS

By using the developed finite element based simulation and optimization method for the "Hybrid SMC" technology used for aircraft applications the lightweight potential as well as the opportunities for applying it can be increased significantly. The goals for component stiffness, strength and wall thickness formulated for the project were achieved.

The quantitative objectives formulated for the exemplary aircraft cargo application for achieving the desired technical functionalities were fully achieved during processing, particularly with regard to the criteria of prediction quality of the computing tool, fire protection, component thickness, strength and rigidity. Nevertheless, the quantitative weight target was slightly exceeded while maintaining the surface of the cargo footstep.

However, this work analyzed the potentials and evaluated that the advantages of the new "Hybrid SMC" technology can be better exploited by optimizing the component geometry with a smaller tread area, so that the weight disadvantage is reduced. A weight increase of 47g compared to the reference step made of titanium occurred due to production restrictions for the minimum thickness of the chosen SMC material.

All in all, the "Hybrid SMC" technology obtains various potentials for being used for load-carrying aircraft applications, too. In the context, it is necessary to develop and use reliable simulation and optimization methods to predict the material behavior and increase the lightweight potential to realize its industrial application.

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