DEFINITION ALTERNATIVER RUMPFBAUSWEISEN VON VERKEHRSFLUGZEUGEN ÜBER MODELLBASIERTE ENTWURFSOPTIMIERUNG (ALTERNATIVE FUSELAGE CONCEPTS)

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SUMMARY

Alternative concepts of aircraft fuselage structures are discussed. These are based on modified topology and arrangement of the stiffeners or stiffener frames, the use of steered fiber reinforcements in case of fiber composite fuselages, and also possible increase of window sizes to enhance passenger comfort. Results indicate that such improvements look feasible in the future and allow reduced weight or increased performance.

1. INTRODUCTION AND OVERVIEW

Fuselage structures of commercial aircraft only have mildly changed in recent years in their topology and their global geometry of stiffeners and stiffener arrangement. This also holds for the shift from Al-alloys to CFRP materials, as can be seen from figure 1. Though there are some good engineering reasons for this similarity, some parametric design and optimization investigations as presented in the following shall indicate possible tendencies – and not so much detailed design proposals - for further improvements and mass savings. The focus is mainly on structural behavior, while other criteria as those e.g. related to production, scalability, maintenance etc. are considered only qualitatively, or are neglected by intention to highlight the different effects. These concept modifications also partly based on specific structural optimization studies are

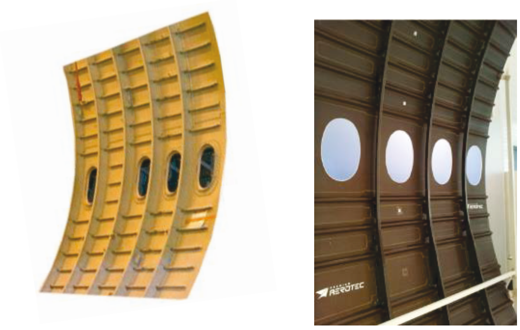

Fig. 1: Fuselage mock-ups for an Al- based (left) and CFRP based (right) design concept

- Structurally "ideal" positioning of stiffeners, and geodesic stiffener arrangement (chapter 2)
- Structural investigations and design optimization studies of fuselage panels to be mounted in between the stiffener framework. This also includes panels using steered reinforcing carbon fibers (chapter 3)
- Increase of window sizes, mainly based on future optically transparent load carrying materials (chapter 4)

Several of the results are primarily valid for Al-fuselages or those with isotropic skin, while extensions to fiber reinforced structures are discussed in chapter 3.

2. STIFFENER ARRANGEMENT

Starting point for the investigations is a "conventional" generic single aisle fuselage structure used also as a reference. Load cases taken into account are those given in figure 2, plus internal pressure [1]. Unless otherwise stated, this then also holds for the investigations given in the other chapters.

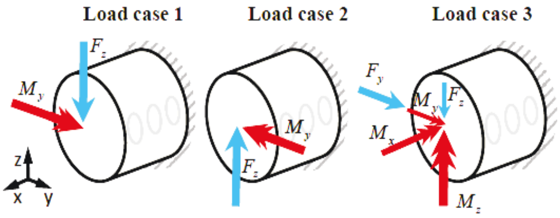

Fig. 2: Considered loads cases (plus internal pressure)

In a first step, topology optimization of the stiffeners of such a fuselage segment is performed under stress constraints without specific consideration of manufacturing and integration aspects, and also with shell's skin geometry kept fixed. For that purpose, Altair OptiStruct [2] is used with two types of meshes used simultaneously. One of these represents the (fixed) shell's skin structure, while in the other one consisting of volume or pixel elements being attached to the shell model the density or modulus respectively are taken as optimization variable to finally represent the stiffener topology. The achieved result for mass minimization under stress constraints is shown in figure 3.

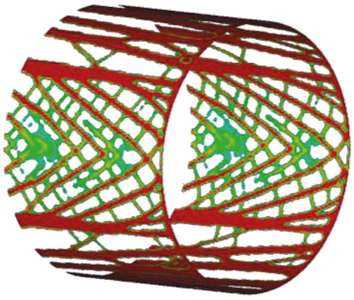

Fig. 3: Stiffening topology optimization result [1]

Primarily longitudinal stiffeners on the top and bottom parts take the applied vertical bending. The lateral sides are dominated by shear, which results into a more or less around +/- 45 degree stiffener arrangement. Though e.g. window cutouts or the effort of intersecting and joining of the stiffeners have not be taken into account, this result looks rather appealing.

A design concept close to this is to use a geodetically stiffened shell structure possibly together with some top and bottom girders.

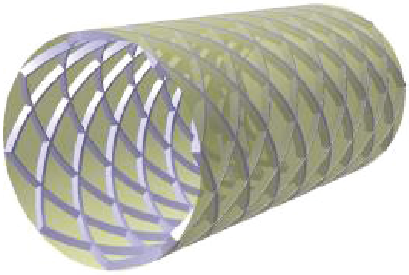

Fig. 4: Geodesically stiffened cylindrical shell

Though the basic principle of geodesic stiffening as outlined in figure 4 has already been used e.g. for the Wellington aircraft in the 1940s, it gets its revival under the view of CFRP structures such as in the design and production studies done e.g. in [3, 4]. Their structural benefit can be deduced from the results under compression load given in figure 5: the area of the shell´s skin rhombus is tensioned by the deformed stiffeners which then for buckling constraints allows (slightly) larger stiffener spacing or reduced skin thicknesses. This is also confirmed by the first buckling mode of a skin between geodesic stiffeners with two buckling waves as if a “virtual stringer” is placed onto such a skin section, see figure 5.

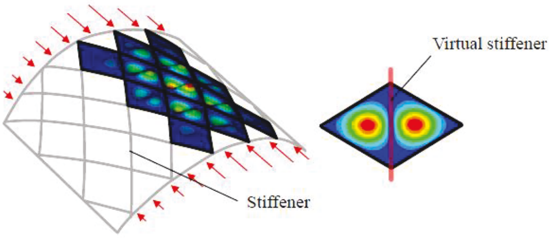

Fig. 5: Geodesic stiffening improves buckling resistance

The buckling load factor is also influenced by the helix angle and the bending and torsional stiffness of the stiffeners. While three-dimensionally curved Al-stringers can be produced via special extrusion processes such as those investigated in [5], an efficient production method for such CFRP stringers would have to be established. Weight savings of around 10 % compared to an Al-based concept can be expected then [1].

3. STEERED FIBERS COMPOSITE FUSELAGE PANELS

CFRP Fuselage skins or panels are usually made out of in-plane straight (nevertheless curved) fiber patterns with fixed reinforcement angles at least over a wider area. Steered fiber paths e.g. manufactured by Automated Fiber Placement (AFP) techniques continuously vary the fiber angles already in-plane and thus lead to locally variable stiffness laminates and structures.

$$\theta(y) = T_0 + \frac{2|y|}{h}(T_1 - T_0)$$

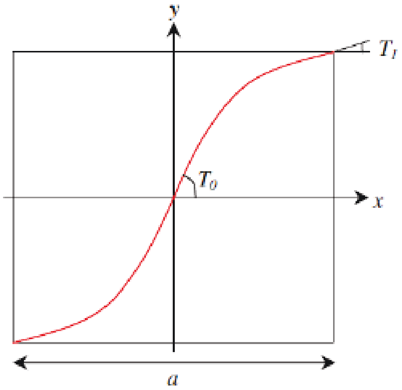

Fig. 6: In-plane variation of reinforcement angles of linear steered fibers

Because it can be assumed that this leads to improvements in load bearing, this has been investigated from different point of views by several authors, e.g. [6, 7]. So far this has found only little practical applications. There might be several reasons for this, such as possibly only smaller benefit for a large number of different relevant load cases, or the possible generation of overlapping or gaps between the fiber tows or rowings giving rise to possible local reduction in load carrying capability. This is going to be overcome by further improvement in production processes, such as providing a slight twist to the fibers during fiber placement.

Since the design of most fuselage skin areas is governed by stiffness and elasto-stability requirements, the effects of steering vs. straight fibers in that context are briefly outlined in the following. More details can be found e.g. in [8] and [9].

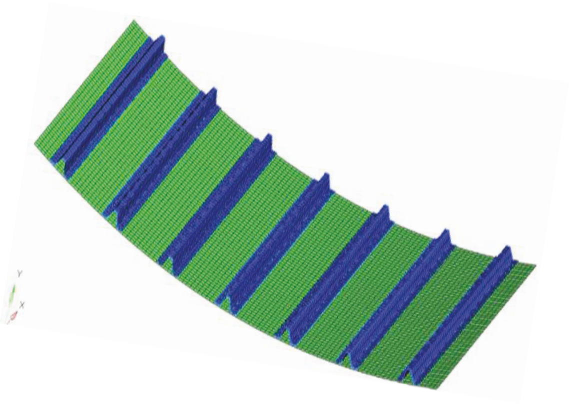

Fig. 7: Section of a stiffened curved panel

For that purpose, a stiffened panel as outlined in figure 7 is used as a reference example. Its curved edges are rigidly clamped but free in axial direction, while its straight edges were simply supported. It is loaded with a compression load twice as high as the linear critical buckling load, in order also to evaluate effects coming from exceedance of the linear buckling range. In such post-buckling regimes, the displacement amplitudes are still kept constrained in design optimization.

The following design optimization cases are investigated, each with constraints on linear critical buckling factor to exceed 0.5, but with limited displacement of 2.7 mm in the nonlinear post-buckling regime:

- Case 1: The straight fibers “reference design” with laminate thicknesses as design variable only, and mass to be minimized
- Case 2a: Straight fiber design, with lamina fiber angles used as optimization variables, and mass to be minimized
- Case 2b: Displacement in axial (stiffener longitudinal) direction to be minimized, with fiber angles as design variables and laminae thicknesses fixed (i.e. mass is fixed)
- Case 3a: same as case 2a, but steered fiber design
- Case 3b: same as case 2b, but steered fiber design

In the steered fiber cases 3 the fiber angles are varied in a plane according to figure 6

This nonlinear design optimization problem is solved via the process outlined in figure 8. Design variables updates are carried out via an SQP-algorithm with several automatically generated starting vectors as implemented in [2]. The post-buckling behavior is handled either via an implicit dynamic nonlinear analysis procedure with a series of generated load steps, or the Equivalent Force Method (EFM). Both implicit dynamic nonlinear analysis and EFM are actually utilized in the optimization procedure shown in Fig.8 for design variables **b.** With the aim to reduce number of expensive nonlinear structural analyses in the optimization, EFM is employed

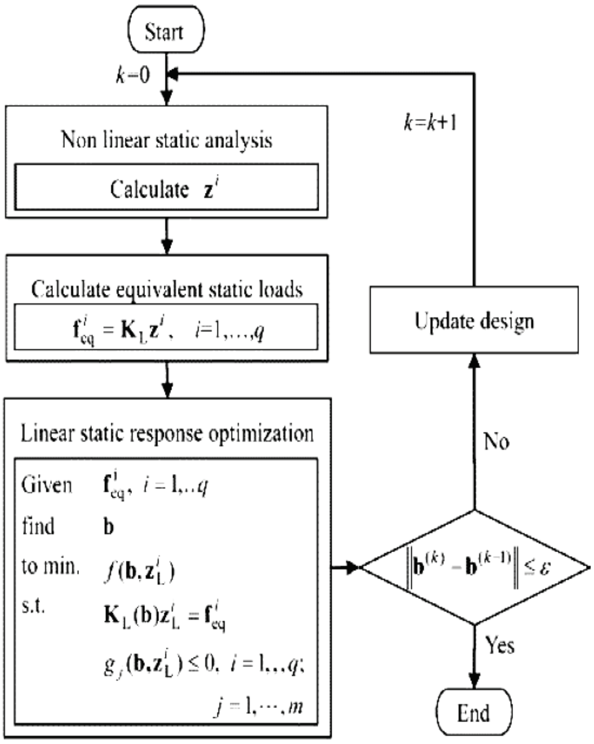

Fig. 8: Flowchart of the design optimization steps

to provide affordable gradients as the nonlinear response is now available by equivalent static loads. Conventional gradient-based optimization based on generated equivalent static loads is then conducted afterwards. In the new optimization iteration, full implicit dynamic analysis is done to check panel instability with updated design variables provided from the linear static optimization. A new set of equivalent forces is then generated and a new loop of linear static optimization is performed. The whole optimization procedure stops when relative change in objective values found from the nonlinear analysis is less than 0.5% for two consecutive iterations.

Though geometric nonlinearity is still quite moderate, some convergence problems during design optimization steps might arise. At the expense of possibly somewhat higher number of iteration steps, the introduction of move limits to the design variables helps to avoid this.

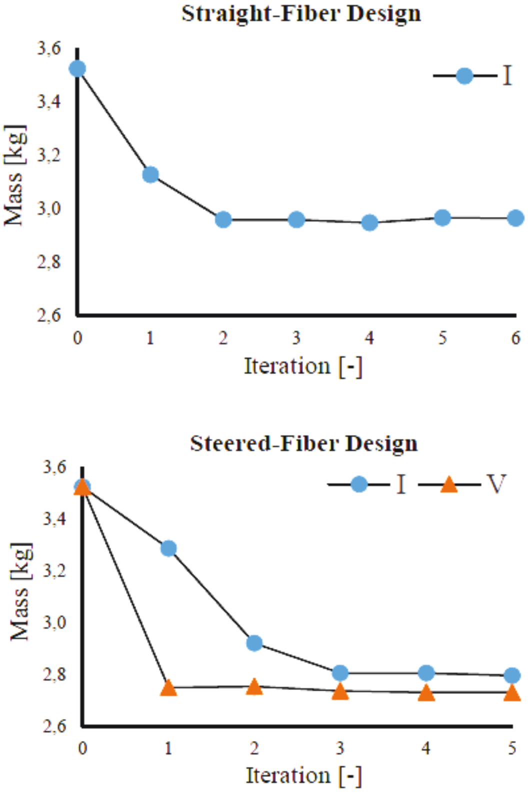

Fig. 9: Mass optimization results for the straight (case 2a) and steered (case 3a) fiber panel design with different starting vectors I and V [9]

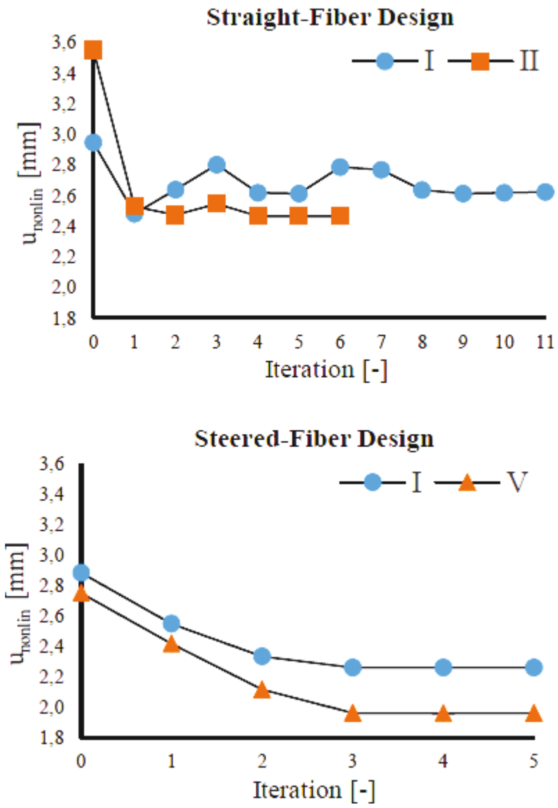

Fig. 10: Displacement minimization under compression load for design cases 2b and 3b obtained from different starting vectors I, II or V [9]

Results from such design optimization investigations are given in figures 9 and 10. From these, the benefits from steered fiber designs and from allowing a mild post buckling behavior can be seen. The results of these cases dominated by buckling behavior, where static failure criteria showed to be not binding under the assumption that there are no stress peaks due to gaps or overlapping. As stated above, the findings should be further substantiated by still more realistic design cases including several load conditions and possibly also further design and manufacturing constraints.

4. INCREASED WINDOW SIZES

Larger windows are expected to increase passenger comfort because of better view and illumination. Positive psychological effects also give the impression of more spaciousness and thus are reducing the typical uncomfortable feeling in passenger cabins.

Table 1: Materials with certain optical transparency and reasonable mechanical properties

	ρ [kg/m³]	σ_T [MPa]	E [GPa]	K_{Ic} [MPa√m]	Transp. [%]
PMMA	1170-1200	38-70	2.5-3.5	0.7-1.6	80-93
GFRP	1750	(375)	32.0		
Al_2O_3 (PCA)	3960	260	340.0-420.0	3.0-5.0	57
Al 2024 T6	2700	325	73.0	26.0-37.0	–

The advent of optically transparent load bearing materials such as those listed in table 1 has triggered investigations in enlarged windows, such as that reported in [10], or from Bauhaus Luffahrt in cooperation with LLB [11]. Among the candidates listed in table 1, density related strength and stiffness modulus properties are best for "transparent" GFRP, with E-modulus being relevant for buckling resistance and transparency still to be improved further [12]. Since for conventional windows the loads are nearly fully taken by the surrounding stiffeners and window frames, an important structural aspect is whether for enlarged windows also further stiffening is required. Some results from related investigations [11] are briefly summarized in the following.

Different window sizes as shown in figure 11 have been used, with properly adjusted stiffener arrangement Strength and buckling of the windows together with their surrounding has been taken into account to be achieved with minimum mass penalty.

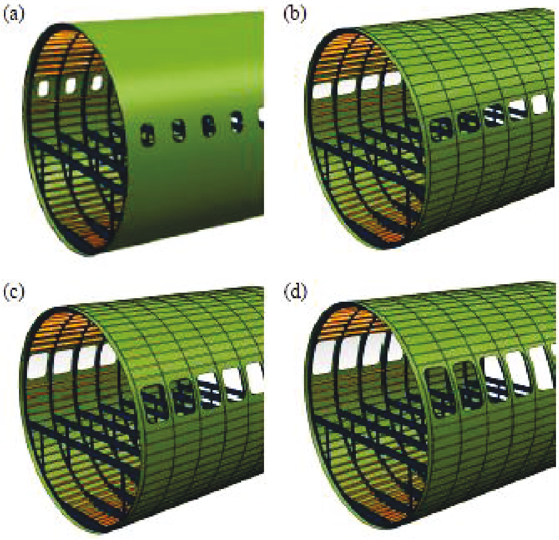

Fig. 11: Increased window sizes: starting case (a) to final case (d) [11]

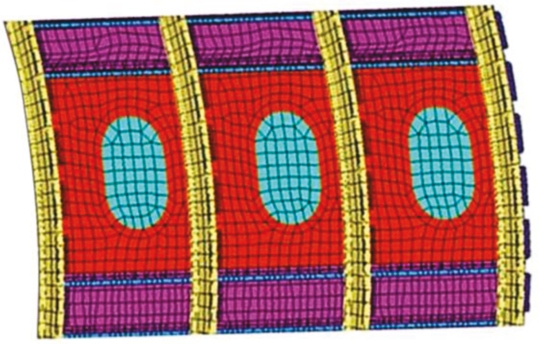

Fig. 12: Parametrized FEM for windows area

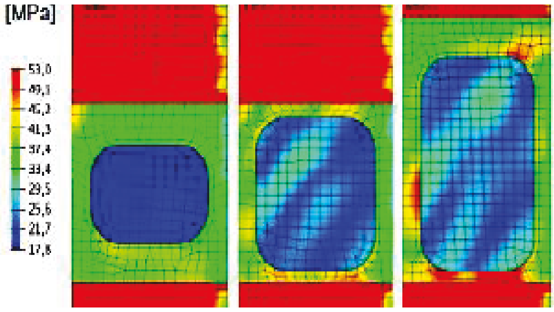

Fig. 13: Stress distribution in and around windows of different sizes [11]

Strength and stability behavior is obtained from the parameterized FEM as shown in figure 12, where also stiffener positions could be varied. Since such windows with a homogenous thickness of around 5 mm well match with the stiffness of the surrounding fuselage shell and the window material has reasonable strength, no window frames or further stiffeners are needed from a structural mechanics point of view. Mass balance analysis indicates a negligible mass penalty, if at all. Stress distributions in the GFRP windows are quite homogenous. Minor locally increased stress levels at the window rim for size D as shown in figure 13 are likely reducible by further detailed design measures.

Improvements in optical properties, further stiffening of the window material and also the establishment of proper integration concepts might lead to technically feasible solutions. Thermal control can be managed in combination with thermally isolating coatings which are optically transparent but nontransparent for infrared wave lengths.

5. CONCLUSION

Different modifications of fuselage structures have been discussed which indicate that further improvement in mass reduction or increase in structural performance or of passenger comfort are feasible. For that purpose, more in-depth design optimization investigations also including improved and efficient production steps should be carried out. Further progress in optically transparent and load carrying materials for large windows are to be expected. A synthesis of the different concepts and design modification might bring alternative and possibly better fuselage concepts close to technical reality, even if for the time being some of these concepts advocated in literature might still look somewhat artificial.

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