CHARACTERIZATION OF FIBER-REINFORCED STIFFENER PROFILES FOR AIRCRAFT FUSELAGE PRELIMINARY STRUCTURAL DESIGN

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Abstract
This paper presents a characterization module for stiffener profiles. It is part of a modeling and analysis tool for stiffened structures in aircraft fuselage design. The module offers options to determine mechanical characteristics of a given section such as mass, stiffness, and failure loads for strength and local stability. For the characterization, analytical approaches and the Finite Element Method (FEM) are used. Both ways are presented and the results are compared as part of the verification of the module. Furthermore, how the module can be used for a basic comparison of design concepts is described.

Symbols

A	*mm²*	*area*	*l*	*mm*	*beam length*
E	*N/mm²*	*Young's modulus*	*m*	*kg/mm*	*mass per length*
F	*N*	*force*	*r*	*mm*	*perpend. distance to ce*
G	*N/mm²*	*shear modulus*	*rot*	*rad*	*rotational displacement*
M	*Nmm*	*moment*	*s*	*mm*	*length of profile section*
EA	*N*	*extensional stiffness*	*u*	*mm*	*translational displacement*
GA	*N*	*shear stiffness*	*y*	*mm*	*coordinate (ce system)*
GI	*Nmm²*	*torsional stiffness*	*z*	*mm*	*coordinate (ce system)*
EI	*Nmm²*	*bending stiffness*	*η*	*mm*	*coordinate (origin system)*
ES	*Nmm*	*elastic moment*	*ζ*	*mm*	*coordinate (origin system)*
			ρ	*kg/mm³*	*density*

Indices

0	*initial condition*		*crit*	*critical*
cg	*center of gravity*		*ana*	*analytical*
ce	*center of elasticity*		*sim*	*simulation*
cs	*shear center*		*stab*	*stability*
i	*iteration variable*		*stren*	*strength*
x,y,z	*x-,y-,z- axis of coordinate system*			

1. Introduction

1.1 High Performance Production of CFRP-Structures (HP CFK)

In the research project *HP CFK*, an interdisciplinary group of scientists from three universities, Technische Universität Braunschweig, Technische Universität Clausthal, and Leibniz Universität Hannover, develops structures out of carbon-fiber-reinforced plastics (CFRP) for aerospace industries with respect to lightweight requirements as well as efficient production. The project focuses on aircraft fuselage structures.

1.2 Motivation

In structural design of large aircraft, aluminum alloys have been substituted by composite materials in many airframe components during the last decades. Among the group of composite materials, CFRP is predominantly used since it offers excellent characteristics in terms of specific stiffness and specific strength. In recent aircraft, the mass percentage of composites in airframe structure exceeds 50 percent. Whereas mass reductions were achieved compared to aluminum designs, production cost is higher and future research needs to focus on efficiency of production [1]. Development towards more CFRP-specific designs and production processes allows for further improvement. In design the variability of anisotropic laminates can be used to locally adopt characteristics to requirements. The introduction of production technologies that have not yet been applied in this field, e.g. infusion processes, can offer potential for cost savings, but also provides more variability in component shapes [2]. The use of foam cores as form-generating elements even increases load capacity [3].

Using stiffener profiles as an example, it can be demonstrated how development processes get more sophisticated for composite structures. For the interaction of design and production planning this is described in [4]. CFRP-specific design approaches can lead to inhomogeneous stiffener sections with strongly curved shapes, which are more complicated to analyze. The presented characterization module extends available solutions for this purpose.

Aircraft preliminary design uses large finite element models of fuselage structures to apply loads, analyze global phenomena, and extract local loads for more detailed models. Due to the large amount of structural elements involved, usually a simplified representation of skin and stiffener as shell and beam/truss elements is chosen. Many design requirements can be expressed in terms of beam stiffness, load limits, and mass [5]. During sizing processes, quick access to stiffener profile characteristics is needed. For isotropic structures it is common practice to store this information in a database or describe the dependencies in analytic functions to determine design parameters for the needed stiffener characteristics on demand during the sizing process. For simple sections the computation of geometric profile characteristics, e.g. area moments of inertia, is implemented in common FE-software. The results can be used to define the respective beam elements. Assuming the use of a homogeneous material, beam stiffness is calculated [6]. This is usually not available for inhomogeneous sections, for geometries with strongly curved segments, or designs that use core materials. Whereas analytical models for isotropic structures are available for various purposes, e.g. stability analyses, those for laminates are often limited to common configurations. Most stability models are defined for flat plates and cannot be expected to produce correct results when applied to geometries with strong curvature or support conditions different from ideal assumptions.

2. Characterization module

The module offers analytical approaches to determine profile characteristics. Additionally, FE-approaches are implemented, which are used to cover those cases that are described as problematic in the last paragraph, particularly considerations of local stability. Furthermore, they are run to validate the analytical approaches before using the module. As part of the modelling framework developed in HP CFK, both ways are implemented in Python. For the FE-integration Abaqus® is used. In the following discussion an omega-stiffener section is assumed. Figure 1 shows a parametric definition of the geometry and its division in sections for layup definitions.
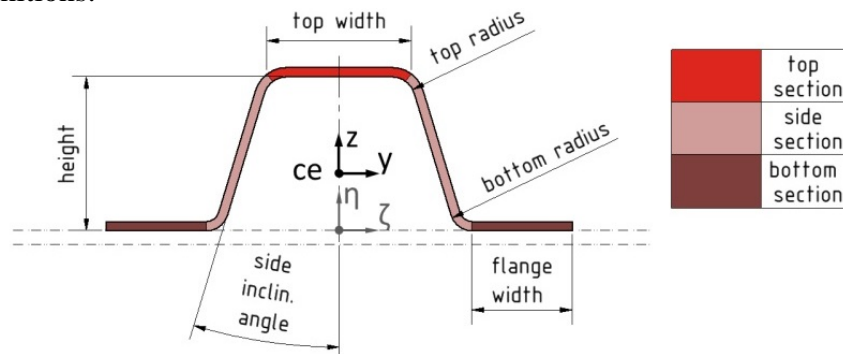

Figure 1. Parametric definition of an omega-stiffener section. The geometry is divided into three sections for layup definitions.

2.1 Analytical approaches

Mechanical beam characteristics are described based on a geometrical term and a material parameter. For beam stiffness these are second moment of inertia and modulus of elasticity. In homogeneous profiles material characteristics are constant for the whole section and can therefore be excluded from geometrical considerations at first. For inhomogeneous sections however, this is not the case and each segment has to be analyzed with the respective material properties. For each layup of the profile laminate properties are calculated with the classical laminate theory and a set of property definitions of the unidirectional layer [7]. To be accessible for analytical approaches, the profile geometry is discretized into small elements which are characterized geometrically. For designs with core material the integral area of each laminate element with the z-axis defines an additional unit for the core. Looping through the sequence of these elementary units, profile characteristics and material properties are processed according to the approaches from [8] presented in Table 1.

2.2 FE approaches

Most of the beam characteristics can also be determined through FEA by processing beam deflections under a specified load (Figure 2).
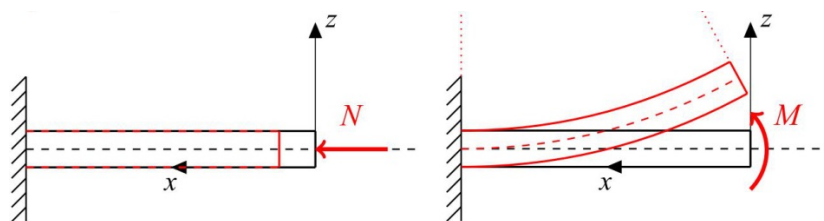

Figure 2. Beam deflections as a reaction on loads [9]

A shell model of a stiffener is built based on the definition of the profile's geometry and laminates. While one end of the stiffener is fixed, the other one is loaded and a static analysis is performed. Stiffness is calculated from the magnitude of the load and the respective deflections of the force application point. Further, reserve factors are determined with the use of failure criteria. Eigenvalue analyses are accomplished as an assessment of local stability failure load. This method can be applied to strongly curved geometries or profiles that use core material as well.

	Characteristic	Symbol	Unit	Analytical approach	FE-approach
Characteristic points	Mass	m	kg/mm	$\sum_i \rho_i\, A_i$	Output
	Center of gravity	y_{cg}	mm	$\dfrac{\sum_i \rho_i\, A_i\, \zeta_{cg,i}}{m}$	Output
		z_{cg}	mm	$\dfrac{\sum_i \rho_i\, A_i\, \eta_{cg,i}}{m}$	Output
	Center of elasticity	y_{ce}	mm	$\dfrac{\sum_i E_{x,i}\, A_i\, \zeta_{ce,i}}{EA_x}$	$rot_{z,F_x} = 0$
		z_{ce}	mm	$\dfrac{\sum_i E_{x,i}\, A_i\, \eta_{ce,i}}{EA_x}$	$rot_{y,F_x} = 0$
	Shear center (profile only, no skin)	y_{cs}	mm	$\dfrac{\sum_i ES_{z,i}\, r_i\, s_i}{EI_z}$	$rot_{x,F_z} = 0$
		z_{cs}	mm	$\dfrac{\sum_i ES_{y,i}\, r_i\, s_i}{EI_y}$	$rot_{x,F_y} = 0$
Stiffness	Extensional stiffness along x-axis	EA_x	N	$\sum_i E_{x,i}\, A_i$	$\dfrac{F_x}{u_x}\, l_0$
	Shear stiffness along y-axis	GA_y	N	$\dfrac{EI_z{}^2}{\sum_i \dfrac{ES_{z,i}{}^2}{G_i t_i} s_i}$	-
	Shear stiffness along z-axis	GA_z	N	$\dfrac{EI_y{}^2}{\sum_i \dfrac{ES_{y,i}{}^2}{G_i t_i} s_i}$	-
	Torsional stiffness along x-axis (closed section)	GI_x	Nmm²	$\dfrac{4\,A^2}{\sum_i \dfrac{s_i}{G_i t_i}}$	$\dfrac{M_x}{rot_x}\, l_0$
	Bending stiffness along y-axis	EI_y	Nmm²	$\sum_i E_{x,i}\left(I_{y,i} + A_i z_i{}^2\right)$	$\dfrac{M_y}{rot_y}\, l_0$
	Bending stiffness along z-axis	EI_z	Nmm²	$\sum_i E_{x,i}\left(I_{z,i} + A_i y_i{}^2\right)$	$\dfrac{M_z}{rot_z}\, l_0$
Crit. loads	Stability	$F_{crit,stab}$	N	Flat buckling plate for each segment [10]	Eigenvalue analysis
	Strength	$F_{crit,stren}$	N	Allowable strain according to failure criteria	Static analysis

Table 1. Approaches for omega profile characterization

3. Validation

For validation purposes profile geometries are created in random configurations and assigned random symmetric, balanced laminates independently for the bottom, side, and top section. The profiles are characterized with the analytical and the FE-approach and the results are compared. Figure 3 shows profile geometries (a), mass (b), and stiffness (c,d). Good agreement between the approaches can be observed for mass, extensional stiffness, and bending stiffness. The deviation is below ten percent. The values for torsional stiffness show slightly higher disparity. Besides the values shown in Figure 3 more results were compared. The locations of center of elasticity and shear center are consistent. For the determination of the center of gravity the Abaqus® response has to be questioned. While the z-coordinate's value is reasonable, the output for the y-coordinate is inexplicably high. For the critical loads good agreement can be observed for strength failure in axial tension or compression when maximum strain criterion is used. More sophisticated failure criteria have not been implemented in the analytical approach yet. Huge deviations of more than 100 percent can be observed for local stability failure depending on the geometrical configuration. In this case the FE-result can be seen as more realistic.
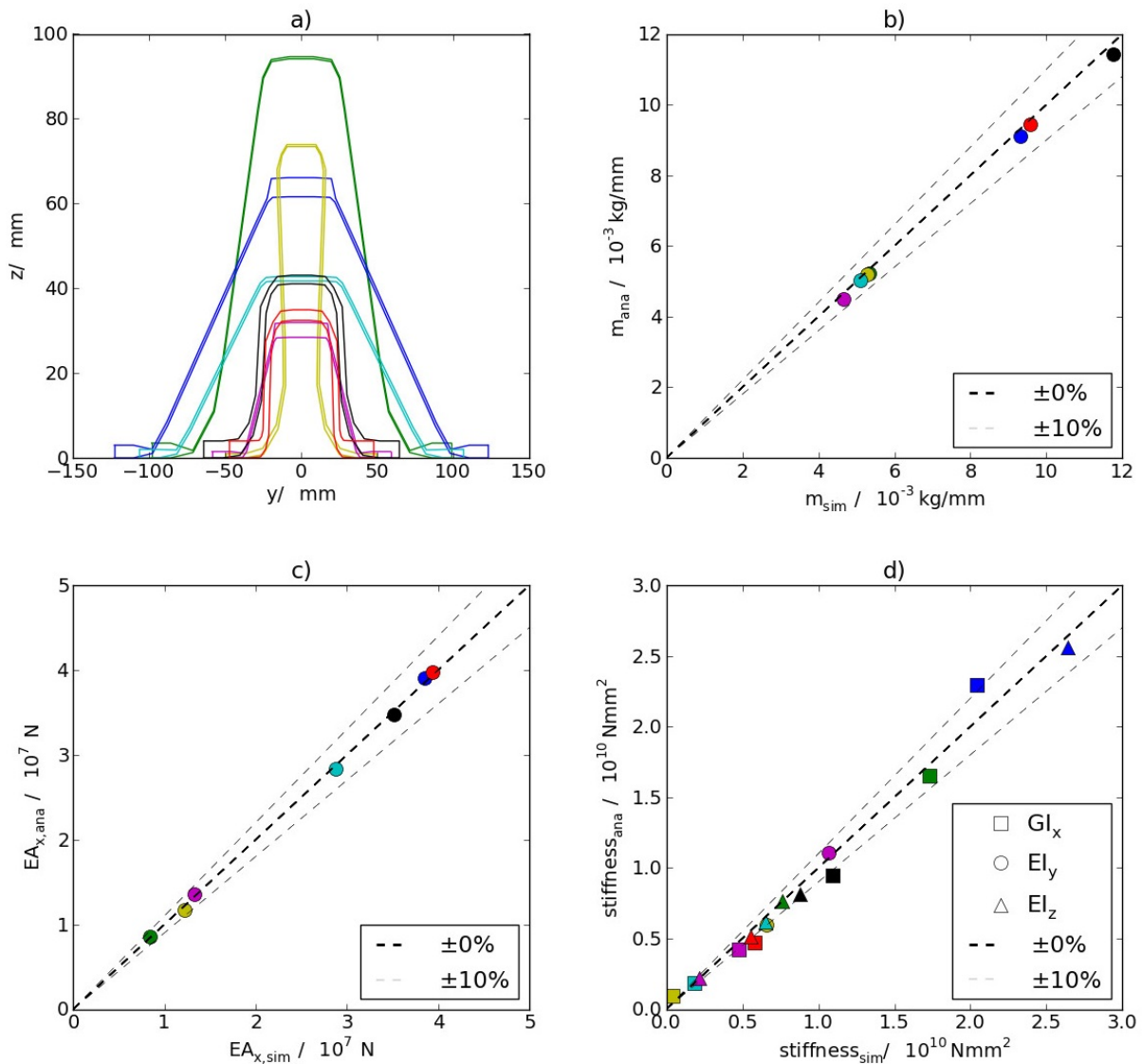

Figure 3. Comparison of analytical solutions and simulation results for mass (b), extensional stiffness (c) and rotational stiffness (d) of random profile geometries (a) with random balanced, symmetric laminates.

4. Example

As a demonstration of its capabilities design concepts for omega stiffeners are compared in a simplified way using the module. Here, it is assumed that the requirements of stiffener profiles are determined by beam characteristics only. In fact skin and stiffener should be designed simultaneously and with their interaction taken into account in detail [11]. However, for a quick comparison of design concepts this simplified scenario is sufficient.
A generic stringer profile is chosen as a reference (Figure 4). It is assumed to be connected to a skin of three millimeter thickness and 240 millimeter width. Skin and stiffener laminate are quasi-isotropic and each of constant thickness. Their connection is not further defined and assumed to be rigid.
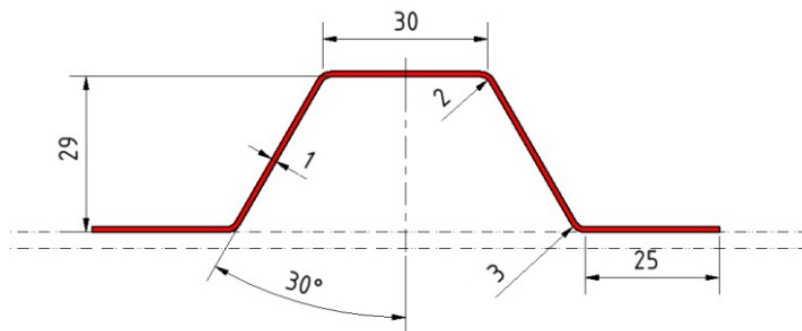

Figure 4. Generic reference stringer profile with quasi-isotropic layup.

The additional design concepts discussed are chosen as examples for the design capabilities of CFRP. The reference design is characterized again with an additional foam core. Another concept implements a balanced, symmetric laminate of equivalent thickness in side and bottom section, but with additional 0°-reinforcement straps in the top section. Again, the design is characterized with an additional foam core. Eventually, this concept is redesigned in order to demonstrate how the mass impact of the foam core can be reduced.
The compared stiffeners are equivalently connected to the same skin. Flange width is constant. As a requirement the profiles' stiffening effect to the skin has to be at least equal to the one of the reference design. For their sizing, an optimization problem is formulated:

> Minimize
> o   mass of stiffener
> with respect to
> o   extensional stiffness of stiffener,
> o   bending stiffness of skin and stiffener along y-axis,
> o   torsional stiffness of skin and stiffener,
> o   critical load for local stability failure of the stiffener in axial compression.

There is no strength criterion applied. Since valid designs will have at least the stiffness of the reference, for the assumed load conditions, an additional application of a strength criterion for maximum strain, as commonly used in aircraft industry, would be a redundant restriction. For the optimization an Evolutionary Algorithm is used. Choice and set-up of the optimization algorithm are not discussed here. Linearized material characteristics of unidirectional CFRP tape [12] and polymethacrylimide (PMI) foam [13] are used. A comparison of the results can be seen in Figure 5.
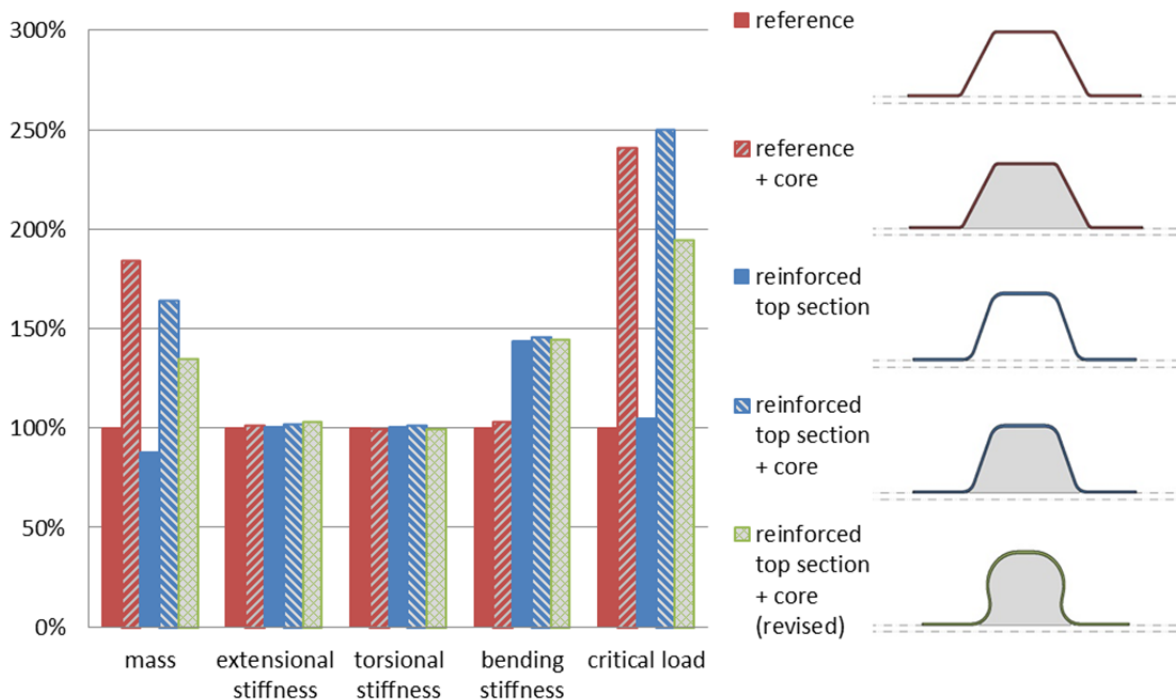
Figure 5. Comparison of investigated stiffener profiles

It is obvious that the additional foam core increases the mass of the stiffener considerably while beam stiffness is hardly improved. Critical axial compression load is increased by about 140 percent. The optimization of the inhomogeneous laminate design with reinforcement straps in the top section achieves twelve percent mass reduction. Except from bending stiffness this design approaches all the boundaries set to the design space by the restrictions.

In the revised design the additional mass of the foam core could be reduced by adopting the profile's dimensions. The optimization algorithm steered the new design to have a reduced integral area, which means reduced foam volume inside of the stiffener. Since torsional stiffness is strongly affected by this, stiffness of the layup was driven to higher values in shear.

5. Conclusion

The presented module extends available features of FE-software for the definition and characterization of beam sections so that CFRP-specific designs can be analyzed. Analytical and numerical approaches for the determination of characteristics are implemented and it is shown that, for most of them, solutions are in good agreement. For efficiency purposes it is recommendable to use the analytic option except for the calculation of critical local stability loads. These show high deviations from the numerical approximations. For more precise results non-linear stability analysis should be used to confirm the linear approximations.

The compared stiffener design concepts include examples for more CFRP-specific approaches. For foam cores a significant mass impact is obvious. It is shown that this drawback can be reduced by a revised design. However, the benefit from improved local stability of the stiffener cannot be highlighted in the presented scenario because stiffness requirements dominate the evolution of the designs during the optimization. The potential of foam cores should be further investigated with production cost taken into account. The locally reinforced design achieves twelve percent mass reduction, while the bending stiffness of skin and stiffener was increased by 44 percent. This demonstrates the potential of more CFRP-specific designs and encourages further investigations in more detail.

Acknowledgements

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