Structural Optimisation of a Composite Aircraft Frame Applying a Particle Swarm Algorithm

Lennart Weiß, Hardy Köke and Christian Hühne
Institute of Composite Structures and Adaptive Systems
DLR German Aerospace Center, Braunschweig, Germany
Email: lennart.weiss@dlr.de

Abstract—In this paper a heuristic optimisation technique for the maximisation of weight specific elastic deformation energy of CFRP z-frames used in aerospace applications is investigated. Therein, the focus was on the simultaneous consideration of mixed discrete and continuous variables. For that purpose a parametric finite element model was established. In that discrete laminate stacks and continuous geometry parameters were used for structural optimisation. In order to solve the non-linear unconstrained optimisation task, a particle swarm optimiser was selected and applied. Convergence was achieved after a reasonable number of function evaluations, within the solution space, a structural layout of the z-frame was identified being the best solution with respect to the optimisation objective. While the deformation energy appeared to be flange width dependent, the corresponding frame weight showed a strong relation to the applied laminate stacks. The majority of the suggested solutions exhibited similar response with respect to the overall deformation. Prior to structural failure, flexural-torsional buckling was the governing deformation mode.

I. INTRODUCTION

Research and technology projects on aircraft fuselage pursue the application of lightweight materials to achieve improved structural efficiency. Especially thermoset carbon fibre reinforced plastics (CFRPs) comply with the designer’s need for excellent specific material properties. Structural designs applying such composite materials need to satisfy the authorities airworthiness code for an "equivalent level of safety" [1] compared to current metallic fuselage designs.

Due to plastic deformation capacity of state-of-the-art metallic fuselage designs, those certification requirements are achieved almost naturally by the design’s intrinsic energy absorption capabilities. In contrast to metallic materials, thermoset CFRPs exhibit brittle fracture behaviour when loaded beyond their elastic limits. Thus, energy absorption by large deformation of structural elements is unsatisfactory limited. A current countermeasure is to attach energy absorption elements to the structural elements. Since the attached elements only act in crash landing scenarios, they are considered dead weight in standard aircraft operation scenarios. Thus, they negatively affect the mass balance. However, integrating the energy absorption functionality into the structural elements appears beneficial with respect to the mass balance. When considering CFRP, energy absorption principles such as fibre breakage and matrix cracking are utilisable.

In order to load those structural elements in a beneficial manner during crash landing conditions, the deformation kinematics of those elements in the sub-floor area of a composite fuselage are of special interest. Heimbs et al. [2] and Weiß et al. [3] highlight the significance of the frame deformations in a crash landing scenario. Since the frame is the circumferential stiffener, its deformation characteristics are determining the overall deformation kinematics. Moreover, the elastic deformation prior to structural failure is a decisive parameter for the distribution of elastic energy within the entire fuselage barrel. In order to favourably manipulate the overall deformation kinematics of the sub-floor area under crash load conditions, the elastic deformation energy is subject to maximisation.

Consequently, an optimisation technique for the maximisation of weight specific elastic deformation energy of CFRP z-frames used in aerospace applications is investigated. Therein, the focus is on the simultaneous consideration of mixed variables for discrete laminate stacks and continuous geometry parameters. For that purpose, the z-frame was extracted from a stiffened panel fuselage design studied previously by Weiß et al. [3], see figure 1. Due to the fuselage design concept, it is considered feasible to investigate the frame individually. The frame is not directly bonded to the skin or stringers. Instead, there is a generous clearance to those parts. Within the design concept, the frame is connected to the fuselage skin via clip elements, see figure 1. Thus, it is elastically restrained allowing large frame deformations before parts are getting in contact under load. Admittedly, investigating the extracted frame by itself is a simplification. Once a solution has been identified, the underlying parameter set should therefore be verified within the more complex fuselage assembly. Nevertheless, this paper rather intends to provide an optimisation technique based on a conveniently simplified model than suggesting one particular solution.

Since the optimisation model is based on mixed discrete and continuous variables, an evolutionary algorithm is suggested to solve the optimisation task. Kicinger et al. [4] survey the use of evolutionary computation in structural design. Therein, the implication of discrete structural parameters on the optimisation task as well as the structural model are discussed. A more general perspective on multiobjective evolutionary algorithms is provided by Zhou et al. [5], who examine evolutionary algorithms, as for example particle swarm optimisation, and their typical fields of application.
II. METHODOLOGY

A. Numerical Calculation

Essentially, non-linear explicit finite element analyses were performed using LS-Dyna as a solver with double precision arithmetic. The z-section frame was meshed using shell elements of type Belytschko-Lin-Tsay including the corresponding warping stiffness algorithm. To control possible hourglass effects, the stiffness form of type 2 was used to define the hourglass viscosity. The hourglass coefficient was set to 0.1. All other control options were set to default, following the suggestions of the LS-Dyna manual [6]. A more detailed examination of modelling parameters and computational settings is provided by Weiß et al. [7].

Figure 2 depicts the cross section view of the z-frame under investigation. Therein, the major dimensions as well as the three constituting segments are shown. The overall height $h$, the flange widths $w_{1,2}$ and the segment thicknesses $t_{1,2,3}$ as functions of the segment laminate stacks $s_{1,2,3}$ are provided. The laminate stacks and the flange widths will be used as variables within the optimisation outlined below.

A side view of the curved frame showing the boundary conditions, the angular velocity $\varphi$, the length $l$ as well as the initial curvature $\kappa$. The dashed line indicates the deformed state at 6° rotation, which is about the value obtained from the best solution.

Figure 3. Side view of the curved frame showing the boundary conditions, the angular velocity $\varphi$, the length $l$ as well as the initial curvature $\kappa$. The dashed line indicates the deformed state at 6° rotation, which is about the value obtained from the best solution.

The material properties summarised in table I were assigned to the shell elements using LS-Dyna Mat54. The properties provided by Feraboli et al. [8] are specified for a mesh size of 2.54 mm edge length. Explicit FEA codes are known to be particular mesh-sensitive when progressing failure such as composite material crushing is computed. For the current study, the onset of compressive failure marks critical load bearing behaviour. Feraboli et al. [8] points out that even the onset of failure is mesh-sensitive. Thus, a mesh density study was executed in order to determine a reasonable element size at acceptable calculation time. Considering the result quality as well as the analysis duration, a 10 mm edge length was selected as a compromise. Furthermore, the aspect ratio of the finite elements was specified approximately one for mesh construction. However, Mat54 allows to adjust the compressive failure load by parameter adoption. Parameter adjustment is only reasonable when numerical simulations are compared against experimentally obtained data. Since this research is

\[ \varphi, l, \kappa = \text{const.} \]

Figure 3. Side view of the curved frame showing the boundary conditions, the angular velocity $\varphi$, the length $l$ as well as the initial curvature $\kappa$. The dashed line indicates the deformed state at 6° rotation, which is about the value obtained from the best solution.

Figure 4. Angular rotation $\varphi$ versus time curve used as boundary condition.
Table I. CFRP material properties according to Feraboli et al. [8]. Subscripts T and C denote tension and compression respectively.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>1.52 g/cm$^3$</td>
</tr>
<tr>
<td>Modulus in 1-direction</td>
<td>$E_1$</td>
<td>127.00 GPa</td>
</tr>
<tr>
<td>Modulus in 2-direction</td>
<td>$E_2$</td>
<td>8.41 GPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>$G_{12}$</td>
<td>4.21 GPa</td>
</tr>
<tr>
<td>Minor Poisson’s ratio</td>
<td>$\nu_{21}$</td>
<td>0.02049 -</td>
</tr>
<tr>
<td>Strength in 1-direction</td>
<td>$Y_T$</td>
<td>2200.00 MPa</td>
</tr>
<tr>
<td>Strength in 1-direction</td>
<td>$X_C$</td>
<td>1470.00 MPa</td>
</tr>
<tr>
<td>Strength in 2-direction</td>
<td>$Y_T$</td>
<td>48.9 MPa</td>
</tr>
<tr>
<td>Strength in 2-direction</td>
<td>$X_C$</td>
<td>199.0 MPa</td>
</tr>
<tr>
<td>Shear strength</td>
<td>$\tau_{12}$</td>
<td>154.0 MPa</td>
</tr>
<tr>
<td>Cured ply thickness</td>
<td>$t$</td>
<td>0.1667 mm</td>
</tr>
</tbody>
</table>

a purely numerical study, the material properties suggested by Feraboli et al. [8] are directly employed. Although highly recommended by Rohwer [9], an experimental validation is not the goal of this paper.

Nevertheless, MAT54 is used for the current study. Developed by Chang and Chang [10], the material model MAT54 enables anisotropic linear elastic material behaviour when undamaged. Non-linearities are incorporated by means of a non-linear shear stress - shear strain relation and a progressive damage model. Material failure detection follows the criteria stated by Chang and Chang [10], which is based on the criteria initially developed by Hashin [11]. As a major difference, the Chang-Chang model neglects shear for the tensile fibre failure mode. MAT54 allows for visco-plastic material behaviour by parameter adoption. However, visco-plasticity was not considered for this investigation.

After establishing a suitable modelling technique, a framework for automated analysis and data processing was configured using Python [12]. It consists of the three parts: pre-processing, solving (LS-Dyna), and post-processing, which allowed automated structural analysis with different input parameters. With respect to the optimisation task, the deformation energy was extracted in the post-processing part. Since explicit analyses with a time stepping scheme were executed, the post-processing involved the identification of a unique critical time step. Therein, the critical time step marked the onset of structural failure. However, structural failure was related to the occurrence of element deletion. Element deletion is an artificial numerical procedure, triggered as soon as each laminate layer or integration point of the stacked shell indicates material failure. From a material model point of view, failure is computationally achieved by stiffness degradation.

Figure 5 shows a typical structural response of the investigated z-frames. The bending moment and the corresponding deformation energy are plotted versus the rotation. While the bending moment was obtained at the frame centre ($l/2$), the rotation was recorded at the free ends. The black vertical line indicates the detection of structural failure (element deletion). At this stage, both the deformation energy as well as the bending moment are stored and forwarded to the optimisation framework. The computations were not automatically terminated after failure detection. The dotted part of the curves indicate post failure response.

However, this methodology allows the compilation of an unconstrained optimisation task. Typically, structural optimisation is subject to strength and buckling constraints. However, the present study does not intend to neglect solutions by the occurrence of certain strength or buckling related failure types. The approach outlined here, rather considers a global energy based measure. This measure implies the retrieval of an appropriate failure mode without prior determination. Therefore, the energy based measure is used as the optimisation objective.

### B. Particle Swarm Optimisation

The optimisation task is to maximise the weight specific elastic deformation energy. Thereby, elastic deformation denotes deformation before the occurrence of structural failure. Typically, structural failure is defined as a constraint to exclude invalid solutions from the solution space. Since the detection of structural failure is a necessary feature of the current methodology, it is not defined as a constraint here. Instead, structural failure was defined a desired feature of all the computations. Therefore, the optimisation task remained unconstrained. With the deformation energy at structural failure being used as the optimisation objective, failure occurrence was mandatory for the evaluation of the solution’s feasibility.

In order to achieve weight specific maximisation, deformation energy was related to the overall weight of the z-frame. Hence, the initial optimisation task was defined as:

$$\text{max} \quad \frac{\text{Energy}}{\text{Weight}}$$

s.t.: -

To assist convergence, the optimisation task was converted to a minimisation task. Consequently, the final optimisation task was rewritten to:
To solve this unconstrained non-linear mixed-discrete optimisation task, the pyOpt library [13] was utilised. Therein, the augmented Lagrange multiplier particle swarm optimizer (ALPSO) [14] was selected and applied. Besides the ability to solve non-linear non-smooth constrained problems, the algorithm allows to specify mixed-discrete variable sets. Within the current version (1.2.0) of the pyOpt library, ALPSO is the only algorithm able to handle discrete parameters. The algorithm parameters were set to default values with a swarm size of 40 particles, a maximum of 200 outer iterations, and a maximum of 6 inner iterations. Moreover, table II provides an overview on the various optimisation parameters as well as their according types and boundaries, which were related to the structural model.

However, the stacking sequences $s_{1,2,3}$ under investigation were quasi-isotropic, balanced and symmetric. Following best practice stacking rules, the stacks ranged from 8 plies (1.336 mm) up to 26 plies (4.342 mm). The stacks with the range specified were generic but of similar scale as reported in Woodson [15] and Heimbs et al. [2]. The individual layer orientations within the stacks were either 0°, 45°, 90° or 135°. Thus, the layer orientations within stacking sequence 0 were $[45,135,0,90]_l$, while for stacking sequence 26 they were $[45,135,0,90,0,45,135,0,90,0,45,135,0]_l$. The stacking sequences 0 and 26 acted as lower and upper boundary respectively. In between the two, the stack thickness increased gradually with increasing sequence number. The list of discrete stacking sequences was provided to the optimisation framework in an ascending order.

### Results and Discussion

#### A. Optimisation

Applying the optimisation algorithm and the outlined parameters, the following results were obtained. Figure 6 provides the evolution of the objective versus the number of function evaluations. Recalling the swarm size (see section II-B), the first function evaluations were governed by an initial random number seed. Thereafter, the swarm explored the parameter space based on the function response. Such it progressed towards a convergence zone at about 3.3 g/kJ. Occasionally, the algorithm tested parameter combinations being very different to the fittest known set. This, however, is a typical scenario for nature inspired heuristic optimisation algorithms. For the following plots, the red vertical line indicates the function evaluation 1099 at which the best solution was obtained.

In order to explicitly study the two major criteria constituting the objective, deformation energy and overall weight of the frame are plotted versus the number of function evaluations, see figure 7. Therein, the relation between the two becomes obvious. While the mass increased, the required energy to deform the present material increased as well. Hence, the curves show similar evolution with increasing numbers of function evaluations. From about 800 function evaluations onwards both, deformation energy and weight, steadily approached their convergence value. Whereas the deformation energy appeared to be flange width dependent, the corresponding frame weight showed a strong relation to the applied laminate stacks. Examining the progress towards convergence, the deformation energy moved in an continuous manner, while the weight converged step wise due to the discrete laminates.

The evolution of the five optimisation variables is provided in figures 8 and 9. While figure 8 contains the discrete type variables representing the laminate stacks, figure 9 depicts the continuous type variables denoting the flange widths. Initially, the entire parameter space was extensively explored. Considering the evolution of the three stacks applied to the respective z-frame sections, clear trends became obvious. While stacking $s_1$ quickly converged to the lower boundary, stacks $s_2$ and $s_3$ approached the upper boundary. With the optimisation progressing, stacking sequence $s_2$ remained at the upper boundary and stacking sequence $s_3$ converged towards stacking sequence 7. Recalling the evolution of the structural weight, stack $s_3$ appeared to be the decisive variable for weight convergence.

Similarly, the continuous variables converged at or close by the boundary values. While the flange width $w_2$ quickly approached the upper boundary (28.00 mm), various intermediate values were tested for the lower flange width $w_1$. After

### Table II. Geometric Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ (mm)</td>
<td>constant</td>
<td>80.00</td>
<td></td>
</tr>
<tr>
<td>$l$ (mm)</td>
<td>constant</td>
<td>1000.00</td>
<td></td>
</tr>
<tr>
<td>$w_1$ (mm)</td>
<td>continuous</td>
<td>14.00</td>
<td>28.00</td>
</tr>
<tr>
<td>$w_2$ (mm)</td>
<td>continuous</td>
<td>14.00</td>
<td>28.00</td>
</tr>
<tr>
<td>$s_1$</td>
<td>discrete</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>$s_2$</td>
<td>discrete</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>$s_3$</td>
<td>discrete</td>
<td>0</td>
<td>26</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{min} \quad & \frac{\text{Weight}}{\text{Energy}} \\
\text{s.t.} \quad & - \\
\end{align*}
\]
the approach of section $s_2$ towards stacking sequence 7 was confirmed, the lower flange width converged to 14.01 mm.

**B. Best Solution**

The best solution was found at function evaluation 1099. In order to discuss the solution obtained, it is examined in detail. The fittest parameter set is provided in table III. Therein, the worst solution is provided as well. Figure 10 provides the undeformed z-frame as well as the deformed section prior to failure. The colours of the undeformed section indicate the different sections with their individual laminate stacks and thicknesses. The lower flange (blue) features a width of 14.01 mm while the laminate uses stacking ID 0 with a thickness of 1.336 mm. Stacking ID 26 was assigned to the web section (yellow) with a resulting thickness of 4.342 mm. Stacking ID 7 was found for the upper flange (green) $[45, 135, 0, 90, 45, 135]_S$ with a thickness of 2.004 mm, and a corresponding flange width of 28.00 mm.

The contour plot of the deformed section indicates the deformation mode. The overall deformation was governed by flexural-torsional buckling. As expected, the open asymmetric section twisted under load. This, however, was the desired deformation mode as it allowed large deformation prior to failure. Thus, the deformation energy required to achieve such amount of deformation increased compared to non-twisting sections. In order to achieve maximum section twist prior to failure, the flange widths as well as the flange thicknesses of the best solution are at the respective parameter boundaries. Although the structural model is simplified with respect to
the complex fuselage assembly, the boundary values were selected based on the overall assembly dimensions and the subsequent part requirements. With that approach, all solutions were feasible for an immediate application within the fuselage assembly.

Figure 11 depicts the bending moment as well as the corresponding deformation energy. Following the moment versus rotation graph (green), the deformation history becomes apparent. Since the results were obtained from an explicit calculation with pulse loading, stress waves were propagating through the section. Moreover, the bending moment was obtained at \( l/2 \) which marked the section centre. Therefore, the bending moment was initially zero while the rotation, which was obtained the free end of the section, constantly increased. Due to inertia of the section and the consequent dynamics of the structural response, the bending moment became negative for the first degree of rotation. Up until the first peak at about 2.4° rotation, pure bending was the dominating deformation mode. From this point onwards, the central cross section of the z-frame started to rotate as the bending deformation increased. The flexural-torsional buckling behaviour was triggered. A second load peak formed at about 3.1° rotation. Afterwards, the load decreased until the onset of structural failure.

Comparing the best and the worst solution, the overall structural response was similar. Due to the applied parameter combination, the z-frame was less efficient with respect to the optimisation objective. Although being a lighter solution (−26.0%), the amount of deformation energy required to achieve structural failure was substantially lower (−73.7%). Moreover, a thinner laminate stack was applied to the upper flange which favoured structural failure to occur earlier compared to the best solution.

IV. CONCLUSIONS

In this paper a heuristic optimisation technique for the maximisation of weight specific elastic deformation energy of CFRP z-frames used in aerospace applications is proposed. Therein, the focus was on the simultaneous consideration of mixed discrete and continuous variables. For that purpose a parametric finite element model was established, where discrete laminate stacks and continuous geometry parameters were used for structural optimisation. In order to solve the non-linear unconstrained optimisation task, a particle swarm optimiser was selected and applied. Convergence was achieved after a reasonable number of function evaluations. Exploring the parameter space a structural layout of the z-frame was identified being the best solution with respect to the optimisation objective. While the deformation energy appeared to be flange width dependent, the corresponding frame weight showed a strong relation to the applied laminate stacks. The majority of the suggested solutions exhibited similar response with respect to the overall deformation. Prior to structural failure, flexural-torsional buckling was the governing deformation mode.

All in all, the application of a particle swarm optimisation algorithm for the optimisation of composite structures proved it’s worth. Especially using the open source programming language Python, with its optimisation library pyOpt, appeared beneficial with respect to the overall effort necessary to solve the given task.

ACKNOWLEDGEMENT

The authors would like to thank Daniel Stefaniak for the critical review of the manuscript.

REFERENCES


