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NUMERICAL ASSESSMENT OF DAMAGE TOLERANCE ALLOWABLES FOR NEW DESIGN CONCEPTS OF STIFFENED COMPOSITE PANELS

Tobias Bach
German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems

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Abstract

Within an automated framework, a structural design process is built that increases the number of design concepts applicable during the optimization of composite wings. Because Damage Tolerance allowables are determined by expensive tests for each structural concept, only one concept is usually available for the optimization. To overcome this problem, a procedure based on detailed Finite Element models has been developed, where the design concepts are modelled as super-stringers. Strain fields are evaluated to assess the capability of structural concepts the bear higher strains at a steady load level. The process is demonstrated on an I-stiffened panel with a wide range of material combinations.

1 Introduction

In order to increase the efficiency and environmental friendliness of aircrafts, various approaches are investigated. An obvious approach is the reduction of the primary mass of the aircraft structure. Besides strength and stability criteria of composite structures, he Damage Tolerance (DT) has a significant impact on the design and structural weight of composite aircraft components. Therefore, several research programs have been undertaken to increase the Damage Tolerance of aircraft structures. Furthermore, a lot of research has been done to understand the general failure behavior of composites after an impact. In this paper, the focus is on the influence of the structural design concept on weight and Damage Tolerance.

1.1 Studies on Damage Tolerance of Structural Design Concepts

A study conducted in the 1980s by McCarthy and Roesler in the United States is the LCPAS study [1]. LCPAS stands for Large Composite Primary Aircraft Structure. Aim of the study was the development of a structural design that could replace a metallic structure with a composite one by keeping the structural performance and reducing the weight by ~ 30%.

During the study, I-, T- and J-stiffened panels were investigated. All designs had specific material combinations in skin and stringer. Also, detailed design features like pad-ups were considered. With all configurations, high strain values could be reached. In a test program, coupons, super-stringer and three stringer panels were tested. The test program revealed the high potential of laminates with high share of ±45° layers for a high Damage Tolerance allowable. The numerical results of the panel design study at the beginning of the investigations were confirmed with the test program. It has to be mentioned, that no investigations on edge impact, especially on the open edge of the T-stringer have been performed.

For a final optimization of the investigated structure, an I-stiffened panel with a skin laminate with high shear stiffness a stringer with high longitudinal stiffness was used. The concept is depicted in Fig. 1

In Europe, several GARTEUR Action Groups have dealt with Damage Tolerance of composites.

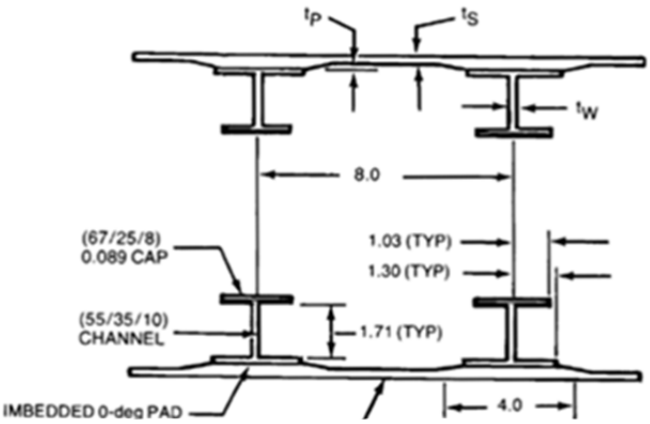

Fig. 1 LCPAS final design [1]

In Action Group 16 a so called “flushed skin concept” was developed by Wiggenraad et al [2]. In comparison to a soft-skin concept, the load carrying 0° plies are not placed in a pad up in the skin, but in the stringer foot. This foot however is embedded in the skin, see Fig. 2.

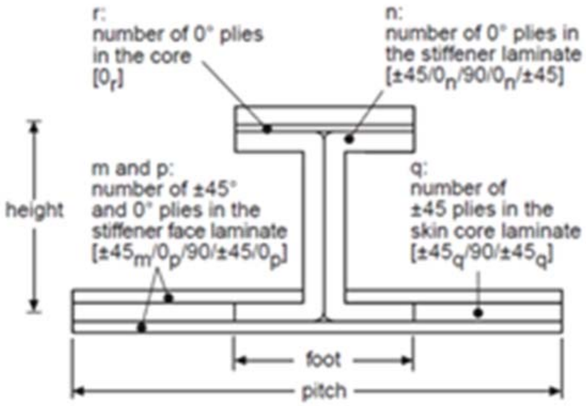

Fig. 2 Garteur concept of skin integrated stringer foot [2]

Here, T-, I- and Omega Stringers were used. In the end, all concepts reached a strain level of ~5200 microstrain. Again, no edge impact was considered, which usually is critical for T-stringers with open web edge. Like the LCPAS concept, the designs have a stiffness ratio (SR) above 0.6. The stiffness ratio is defined as ratio of longitudinal stringer stiffness to longitudinal panel stiffness, E represents the Young’s modulus and A is the cross section.

$$SR = \frac{(E * A)_{Stringer}}{(E * A)_{Stringer} + (E * A)_{Skin}} \quad (1)$$

In Action Group 22, I-stiffened panels were investigated intensively [3]. An enhancement of Damage Tolerance after skin and stringer foot impact was the goal of a work package of the group. The investigations lead to concepts with a SR below 0.3. Furthermore, the impacted panels failed between 1400 and 2700 microstrain. It has to be mentioned, that the panel loads and geometry were different compared to the other studies.

1.2 Conclusion of previous studies

Summarizing the presented studies, it can be stated, that groundwork for an increased Damage Tolerance of composite panels has been done. For the skin laminate, especially laminates with a high shear stiffness show very good performance. If it comes to the stringer, the results of the Garteur Groups point out, that both very stiff and more flexible concept can be used.

Nevertheless, a factor missed out is the edge impact on the stringer web. It can easily imagined, that an impact on an unprotected, open edge of a stringer web has an impact on the residual strength, and therefore on the Damage Tolerance allowables. Due to lack of experimental data, only concepts with a protected web are considered for the work presented afterwards in this paper.

2 Optimization Environment for new Design Concepts

In order to analyze various structural concepts regarding structural performance and Damage Tolerance, a fully parametrized and automated framework was built. Within the framework, detailed Finite Element Models (DFEM) of structural concepts are automatically created, analyzed and optimized as a super-stringer. A super-stringer consists of a stringer and its related left and right skin fields.

The model generation is based on a parametric description of the structure, were all geometrical information as well as material values, laminates and thicknesses are stored. The generation of the DFEM is done purely in Python 2. The DFEM is written to a MSC Nastran bdf-file.

2.1 Model generator & analysis capabilities

The overall process is shown in Fig. 3. Following, the key capabilities of the model generator are described. In Fig. 4, an exemplary I-stiffened super-stringer is shown. Each color represents a property.

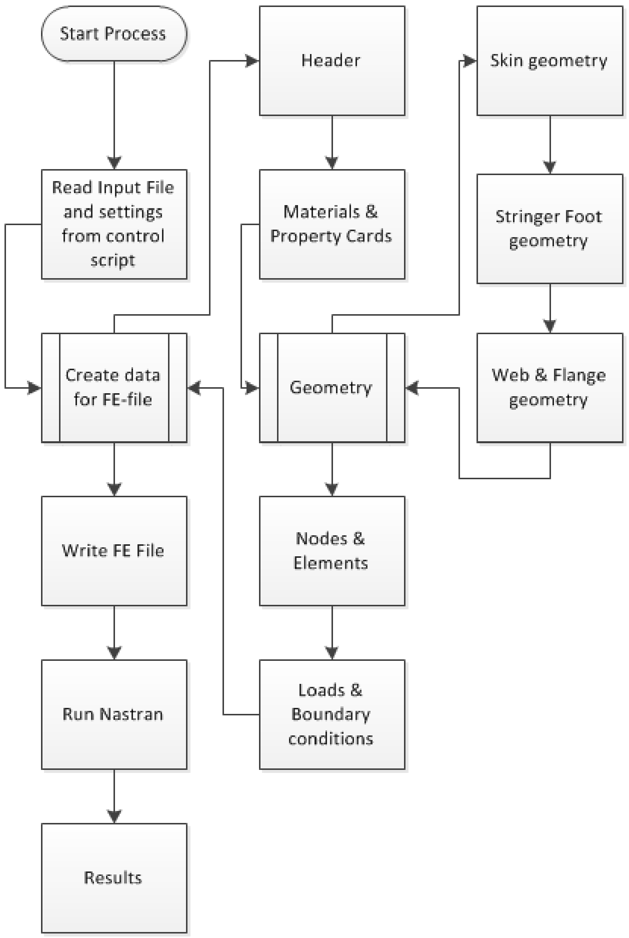

Fig. 3 Model generation & analysis process

2.1.1 Representation of geometry

The geometry is represented with the necessary details. This means, that the skin and all stringer objects like foot, web and flange are modelled with shell elements. The stringer elements are provided with an offset to the skin elements in order to consider the different materials and thicknesses in skin and stringer foot. The skin and stringer foot nodes of the finite element meshes are connected with RBE2 elements. Therefore, the two meshes must be congruent. Furthermore, all changes in thickness and geometry in the direction of the stringer are represented in the model. For this purpose, properties, element offsets and simply the outer geometry itself are modified. The skin field is not limited to rectangular fields. Skew fields can be considered, in case a stringer is placed near a spar or a run-out area. Furthermore, the stringer foot is placed to the skin with an offset. The offset $\Delta_{SkinFoot}$ is calculated using the skin thickness t_{Skin} and stringer foot thickness t_{Foot}:

$$\Delta_{SkinFoot} = 0.5*(t_{Skin}+t_{Foot}) \qquad (2)$$

The offset is varied along the length due to possible changes in stringer foot thickness. The height of the stringer and the foot & flange width can be varied as well. At the upper edge of the stringer web, bar elements with a cross section and longitudinal stiffness near zero are modelled. They will be used to evaluate the strain of the stringer during the optimization. For each load case, a linear static (Nastran SOL101) and an eigenvalue calculation (Nastran SOL105) are performed. The SOL101 run calculates displacements and strains, while the SOL105 run calculates the eigenvalues and the corresponding eigenvectors of the super-stringer.

2.1.2 Materials

The composite materials can be modelled in different ways. The most accurate consideration is the usage of PCOMP cards [4], where each layer is placed into a stacking. The layer entry links to an orthotropic material card (Nastran MAT8). For the optimization, a "smeared PCOMP" is used. Hereby, also a PCOMP is used as property card, but not every layer is written to the property card. Instead, an eight layer stacking with $[45/-45/90/0]_s$ is used, where the layer thicknesses can be varied. With this approach, the material distribution is modelled adequately. An error in the bending stiffness calculation is made, but limited due to the chosen stacking sequence.

2.1.3 Structural concepts, loads and boundary conditions

The tension and compression loads are applied at node introduction points, which are located at the center of each stringer side. Using RBE2 elements, the load is distributed into the structure from these points. Only displacements in the direction of the applied loads are transferred into the structure, other displacements are constraint. At these nodes, also bending and twist moments can be applied. The shear load is applied at the skin edge nodes as nodal force. To consider internal pressure, i.e. from fuel, a pressure can be applied on the skin elements using the Nastran PLOAD4 card.

For the analysis it is assumed, that a simply supported boundary condition of the structures direction are applied at the complete edge, while x-direction (1) and y-direction (2) are only applied at nodes in the middle of the panel (1) and the short edges (2).

The structural concepts that can be modelled: are T-stiffened, I-stiffened and Omega stiffened panel.

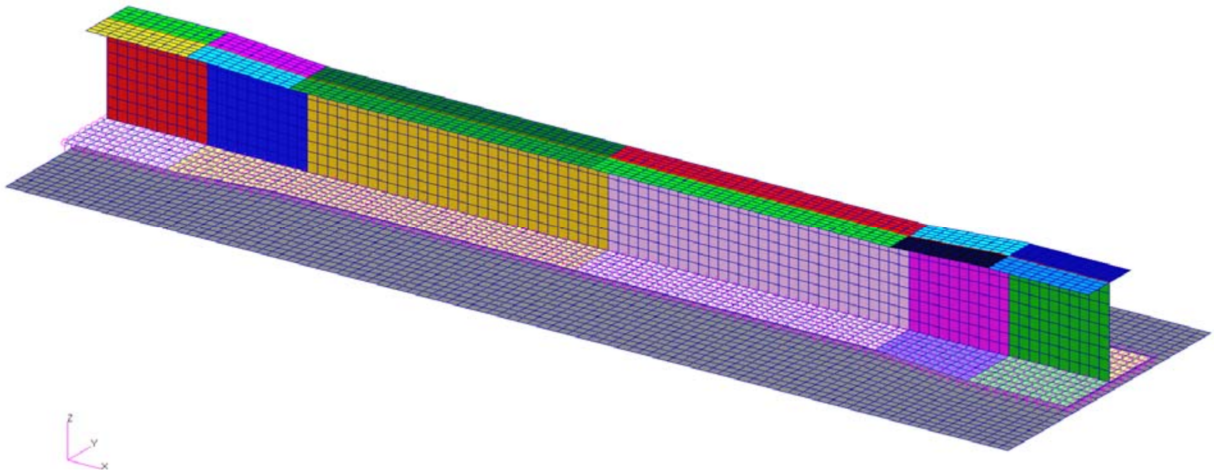

Fig. 4. I-stiffened super-stringer with colored property regions

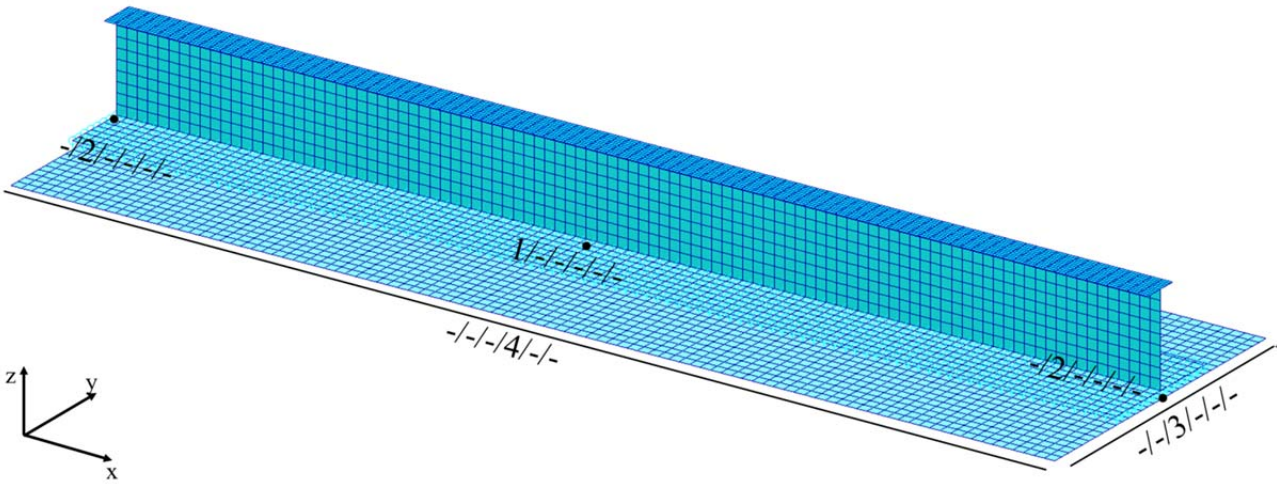

Fig. 5 I-stiffened super-stringer with Boundary Conditions, no RBE elements shown for clarification

is present. Therefore, the in-plane x-y-deformation is prohibited at specific point on the centerline of the super-stringer, while the out-of-plane deformation is restricted at the short edges, where ribs would be attached at a wing panel. At the long edges of the skin fields, symmetry conditions are applied assuming, the adjacent super-stringers have the same properties and dimensions. In Fig. 5 the boundary conditions are shown. The boundary conditions in z-direction (3) and x-rotation (4)

2.2 Optimization process

The aim of the structural sizing and optimization process is the minimization of the structural weight W_{struct} with respect to a set of constraints, where all Reserve Factors (RF) must be above 1.

$$\begin{aligned} &Min\ W_{struct} \\ &w.r.t.\ RF \geq 1 \end{aligned} \tag{3}$$

Safety Factors are already considered in the Reserve Factor, which is evaluated during the optimization.

The constraints that can be used are:

1. Buckling, the eigenvalues are derived from the SOL105 calculation to calculate the Buckling RF
2. Skin Damage Tolerance, the strain field at the upper and lower surface of the elements is evaluated in order to calculate the DT Reserve Factor of the skin
3. Stringer Damage Tolerance, the strain is taken from 1D elements with almost no stiffness, which are placed at the top of the stringer web.

For the optimization, a gradient based optimizer (SLSQP) from the NLOPT package is used [5]. The gradients are calculated using Forward Finite Differences. As constraints, the Failure Criteria are used. The constraint functions are implemented as

$$1/RF^2-1\leq 0. \qquad (4)$$

This way, the optimizer calculates large gradients if the solution is far away from fulfilling the constraints, while the gradients close to the optimum are a very low. Equation (4) is fulfilled, if the Reserve Factor is above one which must be true for every RF. Due to the formulation of the RF, which is defined as:

$$RF = Allowable\,/\,SF^{*}present\ value \qquad (5)$$

a RF cannot be zero. SF represents the Safety Factor that defines an additional factor on the loads, which the structure has to withstand. An example is the factor between Limit Load and Ultimate Load, which is 1.5.

For the optimization, the analysis process shown in Fig. 3 is placed inside an optimization framework. Instead of calling it once per Input File for an analysis, it is called n+1 times, where n is the number of design variables. N additional calculations are performed to calculate the gradients with the Finite Differences approach. The input files for the Finite Difference calculation are created at the beginning of each iteration. Convergence is achieved, if all constraint functions are fulfilled and all design variables are converged itself. The desired results are a minimum buckling eigenvalue of 1 and a strain in skin and stringer of -5000 microstrains.

3 Optimization of stiffened panels for enhanced Damage Tolerance capabilities

The developed automated framework enables enhanced design and sensitivity studies with a wide range of different parameters. Based on the optimization results, the skin & stringer laminate influence on buckling and damage tolerance is investigated.

3.1 Model description

The model used for the optimization is the same as shown in Fig. 5. The optimization criteria applied are:

- Buckling, with a reserve factor $RF_{Buck} \geq 1$
- Damage Tolerance with a target compression strain of -5000microstrains

The investigated structure has a length of $l = 800mm$ and a stringer pitch of $s = 240mm$. For the optimization, a, for a long range aircraft representative, combined ultimate compression – shear load case is used. The applied loads are $n_x = -7500N/mm$ and $n_{xy} = -1000N/mm$. Furthermore, an internal pressure of $p = -0.16N/mm^2$ is applied. Design variables are the thicknesses t_{Skin}, t_{Foot}, t_{Web}, t_{Flange}, the width of flange and foot and the stringer height. Nine materials for the skin and seven materials for the stringer are used. They are shown in Table 1. In total, 63 concepts are optimized.

Table 1 Materials for skin and stringer

Object	Materials
Skin	00/100/00, 10/80/10, 20/60/20, 25/50/, 40/50/10, 44/44/12, 50/40/10, 60/30/10, 70/20/10
Stringer	25/50/25, 40/50/10, 50/40/10, 50/50/00, 60/30/10, 70/20/10, 80/20/00

3.2 Results

The first result of interest is the structural weight of the super-stringer. In Fig. 6 the masses of the optimized super-stringers is shown. Between the different configurations,

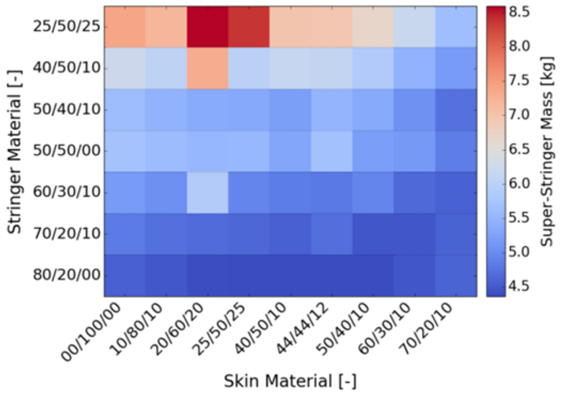

Fig. 6 Super Stringer Mass after optimization

the difference in mass is up to factor 2 in range from 4.2kg to 8.5kg. This maximum value is more of an outlier, but it is nevertheless clearly visible, that the stringer longitudinal stiffness has a significant influence on the structural mass. With a high longitudinal stiffness, lighter structures can be realized. Independently from the skin material, the heaviest result is calculated having a stringer with a quasi-isotropic material.

The $RF_{Buckling}$ are shown in Fig. 7. Depending on the concept, the Reserve Factor differs between 1 and 2.5. Interestingly, the buckling mode differs between the concepts. The concepts with high share of 45° layers in the skin (first columns in Fig. 7) show a pure local skin buckling, while the concepts with a lower 45° layer share (lower rows in Fig. 7) and a logitudinally stiff stringer show mixed skin-stringer local buckling mode. The other concepts show a global column buckling behavior. These results correspond with the skin thicknesses, which are shown in Fig. 8.

The lowest skin thicknesses are calculated for configurations in the first two columns, which are the concepts showing a local skin buckling mode without any local stringer buckling. The concepts showing column buckling tend to have a thicker skin, because the stringer stiffness is not sufficient, Therefore, the skin also prevents the structure from global buckling. Examples of the buckling modes are shown exemplarily in Fig. 9.

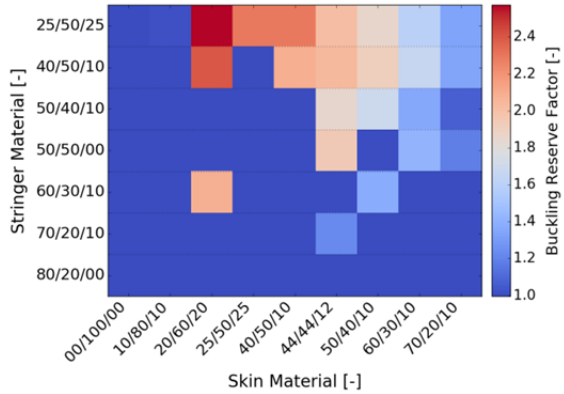

Fig. 7 Buckling Reserve Factors

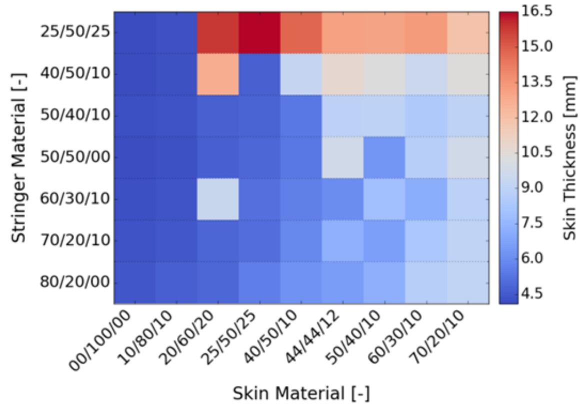

Fig. 8 Skin Thicknesses

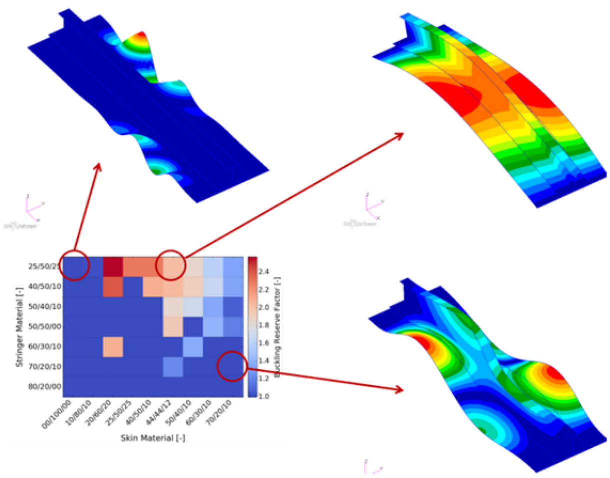

Fig. 9 Examples for the different occurring buckling modes

Evaluating the strain levels of the skin and the stringer, different behaviors are present. In Fig. 10 the skin strains and in Fig. 11, the stringer strains are shown. While almost all stringer strains are close to -5000 microstrains, the strains in the skin reach a maximum compression of -4500 microstrains. Exceptions are the configurations with both very stiff skin and stringer, where buckling is more critical than Damage Tolerance.

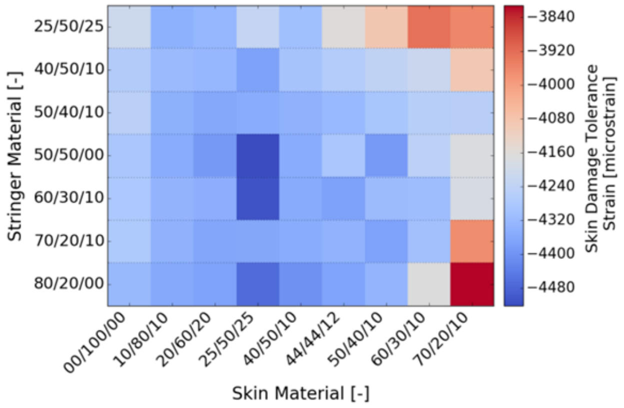

Fig. 10 Skin Damage Tolerance Strain

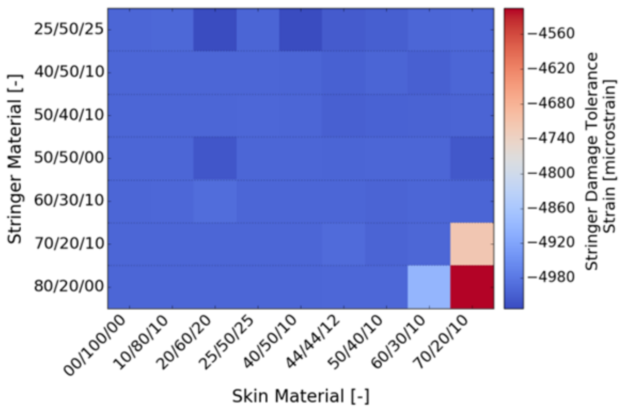

Fig. 11 Stringer Damage Tolerance Strain

4 Discussion

By comparing the results presented in chapter 3, the structural behavior, structural weight and failure modes can be connected to the stiffness ratio of the structure, which is shown in Fig. 12.

First of all, a decrease of the stiffness ratio is connected to the longitudinal stiffness of the skin material. The highest SR is reached by structures with low longitudinal skin stiffness. These structures show pure local skin buckling modes while still having an acceptable skin strain. A pure skin buckling should also be the most uncritical stability failure because additional loads can be carried by the stringer. The Reserve Factors for Buckling and Damage Tolerance are furthermore close together. This points to a well-designed and optimized structure. The small skin thickness of these structures is also an advantage for manufacturing, where fewer layers have to be placed by tape laying machines.

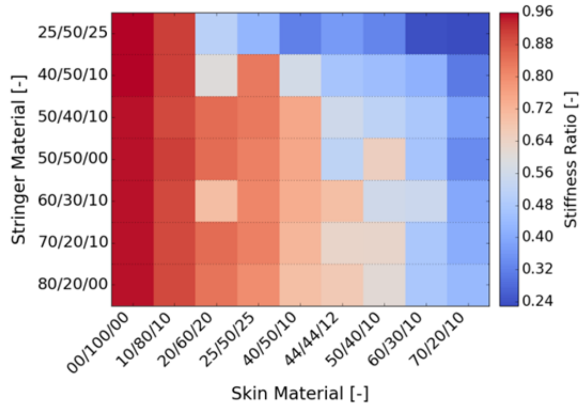

Fig. 12 Stiffness Ratios for the optimized super-stringers

In case of skin and stringer strain, the SR has a diverse influence on the structure. The results of the optimization process show only a limited influence of the SR on stringer strain. Independently from the SR, a strain level close to -5000microstrain is reached. In case the required structural bending stiffness necessary to push the stringer strain below the Damage Tolerance Allowable, the skin thickness is increased. Therefore, the skin contributes a higher part to the bending stiffness. This is partly reflected in the skin strain. For longitudinally stiff materials, the increased thickness reduces the flexibility, resulting in low strain levels. If the skin has less than ~45% 0° layers, higher strain levels are possible.

Nevertheless, a high SR does not lead to less structural mass unconditionally. Comparing Fig. 6 and Fig. 12, a high SR can lead to both light and heavy structures. A high SR is therefore in favor, if the stringer stiffness itself is high independently from the skin, not only in relation to it. A very stiff stringer should always be favored.

5 Conclusion & Outlook

In this paper, a framework for the analysis and optimization of stiffened composite panels with DFEM models was presented.

The influence of the material combinations of skin and stringer on Buckling and Damage Tolerance strains is shown for I-stiffened panels. The most performant structures were calculated for configurations with very high SR and large differences in skin and stringer material stiffness. Depending on the required Reserve Factors, on Stability and Damage Tolerance, other results can be possible. In the performed optimization the required RFs were one because the loads were treated as Ultimate Loads

The results were calculated for a combined compression-shear-load-case, which is representative for a long range aircraft. For lower load levels, the calculations should be repeated.

A common design rule for composites is a maximum difference in poisson ratio of parts to be connected. Usual allowed differences are between 0.05 and 0.1 per connection. This rule is currently not implemented in the optimization process, but will be in the future. In addition, detailed design features like skin pad-ups will be implemented to evaluate the weight penalty of the above mentioned design rule.

Contact Author Email Address

Tobias Bach: tobias.bach@dlr.de

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