



Cost optimization of composite aircraft structures including variable laminate qualities

Markus Kaufmann, Dan Zenkert, Christophe Mattei

► To cite this version:

Markus Kaufmann, Dan Zenkert, Christophe Mattei. Cost optimization of composite aircraft structures including variable laminate qualities. Composites Science and Technology, 2010, 68 (13), pp.2748. 10.1016/j.compscitech.2008.05.024 . hal-00614619

HAL Id: hal-00614619

<https://hal.science/hal-00614619>

Submitted on 13 Aug 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Cost optimization of composite aircraft structures including variable laminate qualities

Markus Kaufmann, Dan Zenkert, Christophe Mattei

PII: S0266-3538(08)00216-9
DOI: [10.1016/j.compscitech.2008.05.024](https://doi.org/10.1016/j.compscitech.2008.05.024)
Reference: CSTE 4094

To appear in: *Composites Science and Technology*

Received Date: 6 February 2008
Revised Date: 17 May 2008
Accepted Date: 28 May 2008

Please cite this article as: Kaufmann, M., Zenkert, D., Mattei, C., Cost optimization of composite aircraft structures including variable laminate qualities, *Composites Science and Technology* (2008), doi: [10.1016/j.compscitech.2008.05.024](https://doi.org/10.1016/j.compscitech.2008.05.024)



This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Cost optimization of composite aircraft structures including variable laminate qualities

Markus Kaufmann ^{a,*} Dan Zenkert ^a Christophe Mattei ^b

^a*Kungliga Tekniska Högskolan (KTH), 10044 Stockholm, Sweden*

^b*Division of Engineering Materials, Department of Management and Engineering, Linköpings Universitet, 58183 Linköping, Sweden*

1 Abstract

Composite structures can lower the weight of an airliner significantly. The increased production cost, however, requires the application of cost-effective design strategies in which cost, weight and the desired laminate quality are taken into account. This paper proposes an optimization framework for composite aircraft structures that minimizes the direct operating cost on a part level. In addition to previous models, a non-destructive testing model is implemented that calculates design allowables of a laminate based on the ultrasonic scan parameters. In a case study, the effect of the laminate quality on the direct operating cost is discussed. It is investigated how the flaw size and therefore the scan pitch of a composite laminate can influence the optimal solution in terms of cost and weight; thus, the manufacturing cost, the non-destructive testing cost and the weight of a component can be balanced by optimizing the laminate quality in an early design phase.

Key words: A. Structural Composites, D. Non-destructive testing, B. Strength, C. Finite element analysis (FEA), Optimization

14 1 Introduction

Today's performance requirements necessitate the full application of carbon fibers to primary structures of airliners. The shift to composite materials lowers the structural weight significantly; the drawback, however, is the increased manufacturing cost. Through cost-effective design, tradeoffs between the minimum weight and the minimum

* Corresponding author. Tel.: +46 702828588. Fax: +46 8207865
Email address: kaufmann@kth.se (Markus Kaufmann).

cost solution are found, two extremes that often contradict each other. Weight savings are directly associated with a reduced fuel consumption and an increased payload, while the reduced manufacturing cost has an impact on the acquisition cost. Therefore, the focus should not only be on pure weight reduction, but rather on a combined minimization of manufacturing cost *and* structural weight.

Attempts for a combined cost/weight optimization have been done by Geiger and Diltz [1], Heinmuller and Diltz [2], Kassapoglou [3–5], Marx et al. [6], Gantois [7], the Rolls-Royce’s DATUM project [8], Park et al. [9], Edke and Chang [10], and Curran et al. [11]. Further, Kelly and Wang [12], Wang et al. [13], Curran et al. [14], and Kaufmann et al. [15] incorporated the idea of a *weight penalty*; this weight penalty was applied to balance the tradeoff between manufacturing cost and structural weight. Each kilogram of structural weight was given a lifetime fuel burn cost and the sum of fuel burn cost and manufacturing cost formed the objective function. Apart from embedding cost and weight, not much research has been performed on optimizing aircraft structures for life-cycle cost (LCC) or direct operating cost (DOC), as defined by Roskam [16]. Further, no attempts have been done to include the material quality of composite laminates into these optimization frameworks.

In the studies cited above it is assumed that the quality of the raw material is equal and no isolated inspection cost were identified in the cost models. This is due to the fact that the models have been built up for metallic structures, where in-service inspection plays a minor role in the design process or that the cost model was not detailed enough to capture these costs. Unlike their metallic counterparts, however, composite parts are fabricated *in-situ* and the quality of these structures is highly dependent on the process robustness and the workmen skills. As a result, every composite part has to undergo rigorous ultrasonic testing. Here, non-destructive testing (NDT) currently is the key to maintain the quality assurance of the structure. Typical manufacturing generated defects in composite parts are voids, porosity, fiber misalignment, wrinkling, poor cure, resin-rich or resin-poor areas and the inclusion of foreign bodies.

Both the manufacturing of autoclave prepreg parts and the NDT methods have continuously been developed and refined during the last years. Nevertheless, the design is still based on rather conservative presuppositions, such as two percent through-the-thickness porosity and flaws of a size of typically 6mm in diameter. In this work, these presuppositions are challenged. In particular, the optimization framework developed in [15] has been enhanced by an NDT cost and strength reduction model.

The first time NDT cost has been mentioned in the literature was in 1937 by Schmid [17]. Schmid investigated the cost of x-ray, gamma and magnetic testing of metal parts in terms of recurrent and non-recurrent cost. Although the test methods and components were not related to aircraft structures, this article is noteworthy. Schmid pointed out that the choice of an appropriate testing method has to be in proportion to its cost, the cost of the structural part and the cost of possible flaws and damages. Depending on the complexity of the part, different technical skills were needed, thus leading to different labor cost. Simple, similar components, for example, need a less qualified operator than complex, forged components. The cost was further determined by the inspection method, the part size and the accuracy in flaw detection.

Since then, most of the relevant literature concentrated on the cost of aircraft maintenance and not on *in-production* testing. For instance, the life-cycle cost of aircrafts under the consideration of NDT was addressed by Hagemaiier in [18,19]. Another example is shown by Kale [20] who combined the weight optimization of an aluminum panel with a reliability based model of the periodic in-service inspection.

In this work, an cost/weight optimization framework is proposed that incorporates manufacturing cost, inspection cost and the weight of the component. In addition to previous studies, the NDT cost are calculated separately by means of a feature-based cost estimation model. Moreover, the laminate quality is considered as a design variable; this variable has a distinct influence on the scan parameters and therefore the scan cost, and it controls the strength prediction of the laminate.

2 Method

The optimization framework herein consists of the necessary routines to calculate the objective function and the constraints. In the following these blocks are described in detail.

2.1 Optimization framework

Our problem for the combined optimization of manufacturing cost, NDT cost and weight is formulated as

$$\begin{aligned} & \min \quad \quad \quad \text{DOC of a composite element} \\ & \text{subject to} \quad \quad \text{structural requirements} \end{aligned} \quad (1)$$

$$\underline{x}_i < x_i < \bar{x}_i, \quad i = 1 \dots n$$

where x_i are the design variables and \underline{x}_i and \bar{x}_i the corresponding lower and upper limits. Examples of variables are laminate thicknesses, the distance between two adjacent stiffeners, the height and width of the stiffeners or the laminate quality.

The objective function of the optimization problem is formed by a simplified version of the direct operating cost *DOC*. Here, the *DOC* is formed by the weighted sum

$$DOC = \alpha_1 C_{man} + \alpha_2 C_{ndt,prod} + \alpha_3 N C_{ndt,serv} + pW \quad (2)$$

where C_{man} is the manufacturing cost, $C_{ndt,prod}$ is the cost for non-destructive in-production testing, $C_{ndt,serv}$ is the cost of a single in-service inspection, p is a weight penalty (given as the lifetime fuel burn cost per weight) and W is the weight of the structure. The parameters α_i incorporate calibration factors due to depreciation, overhead cost and other cost adjustments, and N is the number of regular inspections

during the lifetime of the aircraft. In a first step this number is a constant, in future this value could be based on the location, the stress level and the exposure of the part.

In Fig. 1, the optimization routine is illustrated, including an analysis block containing an FE model, a manufacturing cost model, a weight model and an NDT model.

2.2 FE Analysis

The FE evaluation is done in ABAQUS/Standard and comprises a linear buckling analysis and the computation of a composite failure criterion. It is important to note that the results and conclusions presented here are specific to the flaw type and size included in the analysis and the failure modes assumed (buckling and maximum strain failure) and cannot be generalized before other failure modes (e.g. crippling, local buckling of a delamination, impact damage) are accounted for. Hence, the structural constraints used herein are only examples of possible criteria; the modular design of the optimization framework allows also the implementation of a more advanced analysis.

The FE model has been parameterized in terms of variables, shown as x_i in Equation (1). Changes in the variables result in a new set of buckling eigenvalues or maximum strain numbers; these form the structural constraints to the optimization problem and have to be fulfilled in order to provide a feasible solution. All changes in the ABAQUS model are done by means of Python scripts.

2.3 Manufacturing Cost

During the manufacturing of composites, several operations and processes can be related to costs. Examples are the stacking of prepreg plies, debulking, consumables, curing or tooling. Each process represents a time need and the material cost. Time needs can be translated into labor costs; the sum of all cost plus an overhead represents the total cost to manufacture the panel. This kind of feature-based model (see Niazi et al. [21]) is easily parameterizable, as features can be added, removed or modified. The

commercially available cost estimation software SEER-DFM¹ incorporates all these capabilities and is used therefore. Similar to the approach done for the FE calculation, an initial model has to be built up in the graphical user interface of the software. This model contains all the necessary assumptions and work steps of the manufacturing process; it is exported to a text file, parameterized in terms of variables x_i and prepared for running in command line mode, the so-called server mode.

2.4 Weight estimation

The estimation of the weight is done by a simple calculation of the part volume in any given iteration, based on the CAD geometry, the material properties and the actual variables x_i .

2.5 Non-Destructive Testing

Unlike the estimation of the manufacturing cost, it was decided to develop an in-house feature-based tool for the evaluation of the non-destructive testing cost. It contains the estimation of the NDT cost for in-production and in-service testing, and the adjustment of the material strength.

Some preconditions that apply to the manufacturing of composite aircraft structures can be assumed. For example, *all* components are *thoroughly* tested before the assembly, which includes that the total surface of each structural member is scanned. Testing is performed on condition of series production, i.e. the testing process is cost optimal in terms of operator level and test equipment and no non-recurring costs (such as the purchase of probes or other equipment) are incorporated. No reject rate has been implemented; the development of a reliability-based cost model will be developed in a later stage.

In the case of NDT, the generic database provides the following features:

¹ see Galorath Inc. at <http://www.galorath.com>

- Thin flat laminate with access from both sides
- Thin flat laminate with access from one side
- Thick flat laminate with access from both sides
- Thick flat laminate with access from one side
- Radius
- Adhesive bond

Each of these features requires input data in form of the length l_k , the width w_k , the thickness t_k and – in case of radii – the radius r_k , see Fig. 2. On the other hand, the feature definition includes a scanning technique, a complexity index, the educational level of the operator and associated with the latter a cost per hour or per scanned area.

For rectangular scans of plates, flanges and adhesive bonds, the NDT cost of the k^{th} feature is calculated as

$$C_{ndt,k} = \frac{l_k w_k}{v_k d_k} \cdot [C_{\text{machine},k} + C_{\text{operator},k}] \quad (3)$$

where v_k is the scan speed and d_k is the scan pitch (distance between two scan paths) of the feature k . The parameters $C_{\text{machine},k}$ and $C_{\text{operator},k}$ represent the hourly rate of the test equipment and the operator, respectively.

For linear scans of radii, the NDT cost is calculated as

$$C_{ndt,k} = \frac{l_k}{v_k} \cdot [C_{\text{machine},k} + C_{\text{operator},k}] \quad (4)$$

and the total cost of non-destructive testing is the sum of all features

$$C_{ndt} = \sum_{k=1}^N C_{ndt,k} \quad N = \text{Number of features.} \quad (5)$$

Apart from the scanning cost per area, one has to consider a dependency of the cost on the laminate thickness. Several approaches of how to tackle this problem have been examined. Finally, it has been decided to introduce the very flexible method of adjusting

the structural allowable due to the higher risk of porosity or flaws in thicker structures. Hence, a relationship between testing cost and weight is found through the quality of the laminate. The following two reductions of the material strength are evaluated.

- Strength $\hat{\sigma}_{p,k}$ due to possible porosity; a function of the thickness and the material of the cross-section.
- Strength $\hat{\sigma}_{f,k}$ due to possible flaws or foreign bodies; a function of the scan pitch, the thickness, the material properties (based on coupon tests) and the NDT equipment.

Note that all strengths are calculated feature-wise and the strength that is applied in the FE calculation is the minimum of each $\hat{\sigma}_{p,k}$ or $\hat{\sigma}_{f,k}$. Both mechanisms are described below.

2.6 Strength reduction due to porosity

In the design of composite structures, a certain level of porosity is tolerated and included in the calculation of the structural performance. Typically, a level of two volume percents is stated, a level that has been kept constant during the last two decades. With regard to new material systems, optimized manufacturing methods and more accurate NDT techniques, this porosity level is about to be challenged.

A lot of work has been done to investigate the effect of the laminate thickness and the laminate porosity on the mechanical properties, see [22–27]. It has been concluded that there exists an exponential degradation of the compressive strength $\hat{\sigma}_c$, although this decline does not appear as distinctive as for the interlaminar shear strength $\hat{\tau}$. In the context of isotropic materials, the equation

$$\hat{\sigma} = \hat{\sigma}_{max} e^{Bv_p} \quad (6)$$

has elevated to describe this behavior; here, $\hat{\sigma}_{max}$ is the strength at zero porosity, v_p is the volume fraction of porosity and B is an empirical constant that depends on orientation, shape and size of the pores.

As the proposed method is a part of the design process, the laminate thickness t has to be passed into an anticipated porosity level v_p for a given material and manufacturing technique. Lee and Soutis [26] performed a study on the void content with respect to the thickness of the specimen and concluded that this value is highly dependent on the stacking sequence of the laminate.

2.7 Strength reduction due to foreign bodies

All manufactured composite parts have to be tested for the inclusion of foreign bodies (e.g. parts of the release paper of the prepreg) or other delaminations. Nowadays, the composite manufacturer defines a minimum flaw size that has to be detected, typically being around 6mm in diameter.

The probability of detection never reaches 100%. Instead, a stochastic value based on the material, the NDT method and the thickness of the material is assumed; quoted levels are 90% or 95%, see [28]. According to Huang et al., typical stochastic models used are the Gamma distribution or the two-parameter Weibull distribution, see [29]. For the Weibull distribution, the cumulative distribution function of the probability of detection (POD) is given as

$$POD = 1 - e^{-(f/\lambda)^k} \quad (7)$$

where f is the flaw size, and λ and k are the two shape parameters. A typical curve plot for different settings of λ is shown in Fig. 3.

As can be seen in this figure, the POD is higher for thinner laminates (the actual value depends on the material, the stacking sequence and the NDT method) and for larger flaw diameters. Today's 6mm flaw diameter would require a scan pitch d_k of approximately 2mm, the latter having a direct influence on the NDT costs. By varying the maximum flaw size, the quality of the laminate becomes a design variable and the material strength experiences an according modification.

Different ways to relate the strength to the flaw size exist. Here, open hole compression

is proposed, as it represents the most conservative strength reduction for a flaw of a certain size. For examples on the strength reduction of notched laminates, see Soutis et al. [30]. Other options could include a separate strength prediction model in FE (e.g. the simulation of a CAI coupon test) which takes into account the actual stacking sequence and the flaw size of the section, or the implementation of local delamination buckling as a function of the flaw size and the through-the-thickness location of the flaw.

The variable quality level can be explained as follows: Let us assume that an allowed flaw diameter f of *less* than 6mm is applied to a laminate. All flaws that are bigger than f will be detected, thus causing the part to be rejected. In this case, the (cost) optimum is found as the tradeoff between the higher NDT cost on one side and the lower structural weight and manufacturing cost due to higher strength on the other side. On the other hand, a flaw diameter f of *more* than 6mm would lead to lower NDT cost, a higher structural weight and higher manufacturing cost due to the additional plies needed.

The resulting algorithm is shown in Fig. 4. It can be seen that the thickness t and the maximum allowed flaw size f form the inputs to the NDT module. In the first step, the scan pitch d_k is adapted until a desired probability of detection is met. The direct cost for non-destructive testing C_{ndt} is a function of the scanned area (length l and width w) and the scan pitch d_k . Simultaneously, the strength reduction is calculated and fed into the FE module where the constraints for the optimization are computed.

2.8 Solver

Based on the results of the analysis, the objective function and the optimization constraints are evaluated. Then the solver calculates adjusted variables and triggers the execution of the next iteration. For that purpose, a solver was sought that would incorporate the analysis blocks in the form of *input-output* models, not be too sensitive to disturbances in the form of non-smooth objective and constraint functions, and thus lead to a good convergence rate. In order to minimize the number of FE evaluations, the method of moving asymptotes (MMA) has been chosen, see Svanberg [31,32]. One can

see in the case study below that the parametrization of the design variables as continuous variables is a rough simplification which accommodates the use of this gradient-based method.

In reality, the thickness is not a continuous variable and it is possible that a gradient-based method will miss some designs that may be more efficient than the ones obtained from a gradient-based optimization. Hence, the results from the present study are viewed as representative of the trends and relative differences of alternate designs but may not point to the "best" solution.

3 Case Study

In a case study, a generic skin/stringer element has been optimized in order to show the influence of the NDT cost and the quality level on the overall design. The panel (seen in Fig. 5) consists of a laminated composite skin and two I-shaped stiffeners that are adhesively bonded to the skin. As can be seen the skin/stringer element is parameterized in terms continuous variables, such as the stringer pitch, the panel thickness, the profile thickness, the web height and the flange width. The discrete stacking sequence $[0_m/90_n/\pm 45_p]_s$ has been simplified to a $[0/90/\pm 45]_s$ layup with continuous thickness variables. Note that the laminate generally consists of a 70% fibers in the direction of 0 degree, 20% in ± 45 degrees and 10% in 90 degrees. This allows the application of one single variable while maintaining the design guidelines that require at least 10% fibers in each ply direction. Here, it is again emphasized on the fact that the chosen test case is representative for a typical problem in aircraft design, and that the geometry, the load case, the material and the failure criteria could easily be exchanged. Moreover, further optimization is possible by allowing the stacking sequence to change. This can lead to more efficient load distribution among skin and stiffeners and result in lower weight and cost configurations.

For the sake of simplicity, it has been chosen to neglect any depreciation factors and

cost adjustments (i.e. $\alpha_1 = \alpha_2 = \alpha_3 = 1$) and apply the same equipment and operator rates for in-production and in-service inspection. The prescribed probability of detection has been set to 95%.

Here, five regular inspections during the lifetime of the aircraft have been assumed.

Therefore, the objective function results in

$$DOC = C_{man} + C_{ndt,prod} + 5C_{ndt,serv} + pW \quad (8)$$

The attention is drawn to the quantification of the weight penalty. One can imagine that the cost/weight tradeoff is dependent on factors such as *accumulated flight distance during aircraft life, engine specific fuel burn, thrust level during flights, environmental impact penalties* or *fuel price*. Note that an objective determination of p is difficult, as it may vary from customer to customer, the application (civil, cargo, military version of the same plane), whether it is optimized for additional payload, fuel saving or additional passengers and the way the customer evaluates his product. The literature proposes a weight penalty between €45/kg and €380/kg. Own research based on the fuel consumption of an airliner in the A330 class and today's fuel price, however, reveals a different picture. In this case, the weight penalty $p = \text{lifetime fuel burn cost/kg aircraft mass}$ would then result in about €1840/kg. The mass reduction of one kilogram might involve a reduction of the gross weight that is significantly higher, as the weight of engines and systems can be lowered. And when taking the revenue of an additional passenger into account, this value could be one order of magnitude higher. Nevertheless, it has been decided to apply a value of €1500/kg to the case study in order to accommodate both values from the literature and our own calculations.

The FE model has been built up in ABAQUS/CAE according to the drawing in Fig. 5. It is constrained by periodical boundaries along the sides and meshed with shell elements of the type S4R. The introduction of the compressive load has been realized by two rigid bodies, simulating the adjacent frame structure. The adhesive bonds have been

approximated by tie constraints, thus preventing any separation of skin and stringers. Two failure criteria were checked during the FE analysis. First, the maximum strain values (MSTRN) were sought in all integration points of the skin and stringer nodes, and second, the eigenvalues of a linear perturbation analysis is calculated. Both are fed back to the optimization solver. Rather high loads have been applied to this structure (2.5 kN per mm width) in order to obtain comparable failure loads for buckling and strain; as can be seen below, the model will consist of rather short and stubby stiffeners. The maximum strain criterion has been set to 0.005, -0.004 and 0.008 for tension, compression and shear, respectively.

Referring to the description of the NDT model above, the structure is divided into features, such as the skin laminate, further two stringers with two flange laminates, one web laminate and four radii each; the two adhesive bonds between skin and stringer are two other features.

The adjustment of the allowables due to porosity is estimated according to Equation (6). The value of $B = -3.14$ has been adopted from Uhl et al. [23] who performed a number of test series for a 16 ply quasi-isotropic carbon/epoxy laminate. The void content v_p as a function of the thickness is required as an input for the equation above. The approximate function $v_p = 0.0025t$ has been extracted from the figures presented by Lee and Soutis [26]; in their work they studied the void content with respect to the thickness of the specimen. In this first attempt, the strength due to flaws of a given size f is based on the work done by Soutis et al. [30], from which the value of $\hat{\sigma}_f(f) = \hat{\sigma}_0(-\frac{12.4}{444}(f - 6) + 1)$ has been extracted. Here, $\hat{\sigma}_0$ refers to the strength of a coupon test with 6mm hole size.

First, a panel has been optimized for a series of weight penalties, thus resulting in a parameter study covering the whole range from pure cost optimization ($p = 0$) to pure weight optimization ($p = \infty$). Therefrom, three configurations have been chosen: A low-cost panel (a), a cost/weight optimized panel with a fuel penalty of €1500/kg (b), and a low-weight panel (c). All three baselines have been obtained without the novel

NDT tool presented in this paper.

Finally, the behavior of each configuration is investigated when varying the quality level and laminate thicknesses while the geometry is kept constant. Further the influence of the probability of detection POD on the direct operating cost is examined.

4 Results and Discussion

The first part of this section refers to a parameter study done without the activation of the NDT model. Hence, the results are obtained by optimizing a skin/stringer element with an objective function given as $DOC = C_{man} + pW$ and the weight penalty p varying between 0 and infinity. The results are shown in Fig. 6.

A distinctive change in configuration can be seen at a weight penalty of €1000-10'000/kg. To the left of this change, a low-cost solution is preferable. There, the skin/stringer panel consists of a thick skin and bulky stiffeners with maximum pitch – as fewer stringers are used in the low-cost solution, manufacturing costs can be saved in spite of the higher cost per stiffener. Further, the buckling constraint but not the maximum strain constraint is active. Hence, the structure is not performing optimally, and some more cost saving could be possible by enlarging the design space. To the right, the low-weight configuration comprises a densely stiffened, thin skin with rather fine stringers and both the structural constraints are active. Three design solutions have now been chosen as the starting point for the subsequent investigation, see Table 1.

Properties marked with asterisks are kept constant in the subsequent investigation.

Quality optimization of the low-cost panel ($p = \text{€0/kg}$)

First, the cost optimized panel with a stringer pitch of 300mm has been investigated. This panel has been optimized for a series of flaw sizes, varying from 2 to 20mm. The results of this study are compiled in Table 2, where a flaw size of 6mm represents the baseline.

As can be seen, the variation of the laminate quality has a considerable impact on the objective function DOC . At a flaw size of 2mm, the laminates have to be scanned much tighter in order to guarantee a probability of detection of 95%. The result is an NDT cost that is 2.74 times the baseline and a DOC that is 46% higher than the baseline. It also can be seen that only the buckling constraint is active for small flaw sizes. As the buckling load is independent of the strength of the material, it is evident that no weight reduction is possible in this case.

The cost for inspection C_{ndt} decreases when the flaw size increases, as the scan time is reduced. The optimum configuration can be found at a flaw size of 16.3mm. There, the active constraint switches from buckling to maximum strain and the objective function DOC is 14% lower than the one of the baseline. Any further increase of the flaw size is disadvantageous, as the impact of the manufacturing cost due to additional material (to resist material failure) is too high.

Quality optimization of the intermediate panel ($p = \text{€}1500/\text{kg}$)

Second, an intermediate panel design with $\text{€}1500/\text{kg}$ has been investigated. Similar to the preceding example, the cost of this panel was recalculated adding the cost for in-production and in-service inspection with a standard flaw size of 6mm. Then the panel has been optimized for a series of flaw sizes, see Table 3.

As seen before, the objective function is the highest for a very small flaw size of 2mm due to the high NDT cost. As the panel thicknesses are constraint by the active buckling condition, no weight or cost saving is possible for this laminate quality.

As long as buckling governs the design, an increased flaw size mainly results in lower NDT while the weight and the manufacturing cost remain the same. At a flaw size of 12.4mm, buckling and maximum strain are active, and the DOC achieves its minimum at 96%. Any increase of flaw size results in increased weight and manufacturing cost, thus forcing up the objective function. The stringer cross-sections are very thick at flaw sizes of 14mm and 20mm due to the reduced strength. As the cross-sections are

extraordinarily thickened, more scanning is necessary in order to guarantee a probability of detection of 95%. The result is an increase of NDT cost, despite the existence of a lower laminate quality.

Quality optimization of the low-weight panel ($p = \infty/kg$)

Third, a weight optimized panel has been exposed to the inclusion of NDT cost. In Table 4, these results are shown. As the manufacturing and non-destructive testing costs are a very small part of this objective function, the *DOC* mainly depends on the weight. As anticipated, the optimum laminate quality is found at very small flaw sizes, and both structural constraints are active.

*Variation of the *POD**

Non-destructive testing theoretically never reaches a probability of detection of 100%. In practice, an artificial limit is therefore set to this value, representing a measure of trustworthiness for the testing method. The effect of the *POD* limit on the results is now investigated.

The results shown in Table 5 apply for the intermediate panel with a weight penalty of $p = 1500/kg$. As expected, the quality of laminate is not influenced by the *POD*, and the optimal design solution is found independently. On the other hand, an increase in NDT cost and thus an increase in the objective function can be seen for higher probabilities. This is the cost one has to account for when a higher NDT reliability is desired.

5 Conclusion

A framework for the cost/weight optimization of composite structures under consideration of a variable laminate quality has been proposed. A generic skin/stringer element has been adopted as a case study; the main focus has been brought to a parameter study in which the allowed flaw size was varied.

According to the definition of direct operating cost, an objective function has been selected that included manufacturing cost, in-production and in-service inspection and a weight penalty. Starting from a standard flaw size, the effects of the laminate quality on the objective function have been investigated. The optimal flaw size depends on the structure, the material data, the load case and the weight penalty; hence, it has been shown that cost savings are possible by revising the laminate quality already in the design phase. Nevertheless, the conclusions drawn here suggesting that the flaw size does not have to be 6 mm should be viewed as specific to the assumptions and analysis made and they may not be valid when, for example, fatigue is taken into account. Larger flaw sizes may shorten the fatigue life. Further work is needed in this area before the conclusions can be generalized.

This optimization framework may be used in applications outside the aerospace industry; as an example, one could consider its implementation for the production of rotor blades for windmills.

6 Future Work

The proposed optimization framework represents a first approach to include quality management aspects into the design process. More work, however, has to be done in order to improve the NDT cost and the NDT strength reduction model. First, the difference between in-production and in-service testing has to be more elaborate by applying different scanning techniques and overhead adjustments. Second, the strength reduction should be applied as a function of the stacking sequence, the material properties and the manufacturing technique. Third, it has to be investigated whether a stiffness reduction due to porosity should be included in the structural model. Fourth, the inspection interval should be adapted to the stress level and the structural function of each concerning member. And finally, a probabilistic damage model should be included to capture the failure and repair of a structural member. This could include a more detailed ultrasonic analysis, which in turn causes a cost increase.

Acknowledgments

This work is part of the European Framework Program 6, project ALCAS, AIP4-CT-2003-516092. Special thanks go to Alfgam AB for the use of Xopt and to Galorath International for the use of the cost estimation package SEER-DFM.

References

- [1] Geiger TS, Dilts DM. Automated design-to-cost: Integrating costing into the design decision. *CAD Computer Aided Design*, 28(6-7):423 – 438, 1996.
- [2] Heinmuller B, Dilts DM. Automated design-to-cost: Application in the aerospace industry. In: *Proceedings - Annual Meeting of the Decision Sciences Institute*, 3:1227 – 1229, 1997.
- [3] Kassapoglou C. Simultaneous cost and weight minimization of composite-stiffened panels under compression and shear. *Composites - Part A: Applied Science and Manufacturing*, 28(5):419 – 435, 1997.
- [4] Kassapoglou C. Minimum cost and weight design of fuselage frames. part a: Design constraints and manufacturing process characteristics. *Composites - Part A: Applied Science and Manufacturing*, 30(7):887 – 894, 1999.
- [5] Kassapoglou D. Minimum cost and weight design of fuselage frames. part b: Cost considerations, optimization, and results. *Composites - Part A: Applied Science and Manufacturing*, 30(7):895 – 904, 1999.
- [6] Marx WJ, Mavris DN, Schrage DP. A knowledge-based system integrated with numerical analysis tools for aircraft life-cycle design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 12:211 – 229, 1998.
- [7] Gantois K, Morris AJ. The multi-disciplinary design of a large-scale civil aircraft wing taking account of manufacturing costs. *Structural Multidisciplinary Optimization*, 28:31 – 46, 2004.
- [8] Scanlan J, Rao A, Bru C, Hale P, Marsh R. Datum project: Cost estimating environment for support of aerospace design decision making. *Journal of Aircraft*, 43(4):1022 – 1028, 2006.
- [9] Park CH, Lee WI, Han WS, Vautrin A. Simultaneous optimization of composite structures considering mechanical performance and manufacturing cost. *Composite Structures*, 65(1):117 – 127, 2004.
- [10] Edke MS, Chang KH. Shape optimization of heavy load carrying components for structural performance and manufacturing cost. *Structural and Multidisciplinary Optimization*, 31(5):344 – 354, 2006.
- [11] Curran R, Gomis G, Castagne S, Butterfield J, Edgar T, Higgins C, McKeever C. Integrated digital design for manufacture for reduced life cycle cost. *International Journal of Production Economics*, 109(1-2):27 – 40, 2007.

- [12] Kelly D, Wang K, Dutton S. A guided tradeoff for cost and weight for generating optimal conceptual designs. Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 2:894 – 904, 2003.
- [13] Wang K, Kelly D, Dutton S. Multi-objective optimisation of composite aerospace structures. Composite Structures, 57(1):141 – 148, 2002.
- [14] Curran R, Rothwell A, Castagne S. A numerical method for cost-weight optimisation of stringer-skin panels. Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 7:5262 – 5277, 2004.
- [15] Kaufmann M, Zenkert D, Wennhage P. Integrated cost/weight optimization of composite skin/stringer elements. In: Ishikawa T, editor, Proceedings of 16th International Conference on Composite Materials, Kyoto, 2007.
- [16] Roskam J. Airplane Design Part VIII: Airplane Cost Estimation Design Development and Manufacturing and Operating. DARcorporation, Lawrence, Kansas, USA, 1990.
- [17] Schmid WE. Costs involved in non-destructive testing of materials. Maschinenbau, 16(19/20):519 – 522, 1937.
- [18] Hagemaiier DJ. Cost benefits of nondestructive testing in aircraft maintenance. Materials Evaluation, 46(10):1272 – 1284, 1988.
- [19] Hagemaiier DJ. Effective implementation of NDT into aircraft design, fabrication, and service. Materials Evaluation, 46(7):851 – 868, 1988.
- [20] Kale AA, Haftka RT, Sankar BV. Tradeoff of structural weight and inspection cost in reliability based optimization using multiple inspection types. Collection of Technical Papers - 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 2:1162 – 1173, 2004.
- [21] Niazi A, Dai JS, Balabani S, Seneviratne L. Product cost estimation: Technique classification and methodology review. Journal of Manufacturing Science and Engineering, Transactions of the ASME, 128(2):563 – 575, 2006.
- [22] Judd NCW, Wright WW. Voids and their effects on the mechanical properties of composites - an appraisal. SAMPE Journal, 14(1):10 – 14, 1978.
- [23] Uhl KM, Lucht B, Jeong H, Hsu DK. Mechanical strength degradation of graphite fiber reinforced thermoset composites due to porosity. Review of Progress in Quantitative Nondestructive Evaluation, 7B:1075 – 1082, 1988.
- [24] Rubin AM, Jerina KL. Effect of porosity on elastic constants of representative aircraft laminates. Journal of Advanced Materials, 25(4):21 – 30, 1994.
- [25] Costa ML, Almeida SFM, Rezende MC. Critical void content for polymer composite laminates. AIAA Journal, 43(6):1336 – 1341, 2005.
- [26] Lee J, Soutis C. Thickness effect on the compressive strength of t800/924c carbon fibre-epoxy laminates. Composites Part A: Applied Science and Manufacturing, 36(2 SPEC ISS):213 – 227, 2005.
- [27] Lee J, Soutis C. A study on the compressive strength of thick carbon fibre-epoxy laminates. Composites Science and Technology, 67(10):2015 – 2026, 2007.

- [28] Georgiou GA. Pod curves, their derivation, applications and limitations. *Insight: Non-Destructive Testing and Condition Monitoring*, 49(7):409 – 414, 2007.
- [29] Huang CK, Lin KY. A method for reliability assessment of aircraft structures subject to accidental damage. *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. 1:386 – 395, 2005.
- [30] Soutis C, Smith FC, Matthews FL. Predicting the compressive engineering performance of carbon fibre-reinforced plastics. *Composites - Part A: Applied Science and Manufacturing*, 31(6):531 – 536, 2000.
- [31] Svanberg K. Method of moving asymptotes – a new method for structural optimization. *International Journal for Numerical Methods in Engineering*, 24, 1987.
- [32] Svanberg K. A globally convergent version of MMA without linesearch. In: Olhoff N, Rozvany GIN, editors. *Proceedings of the First World Congress of Structural and Multidisciplinary Optimization*, 1995.

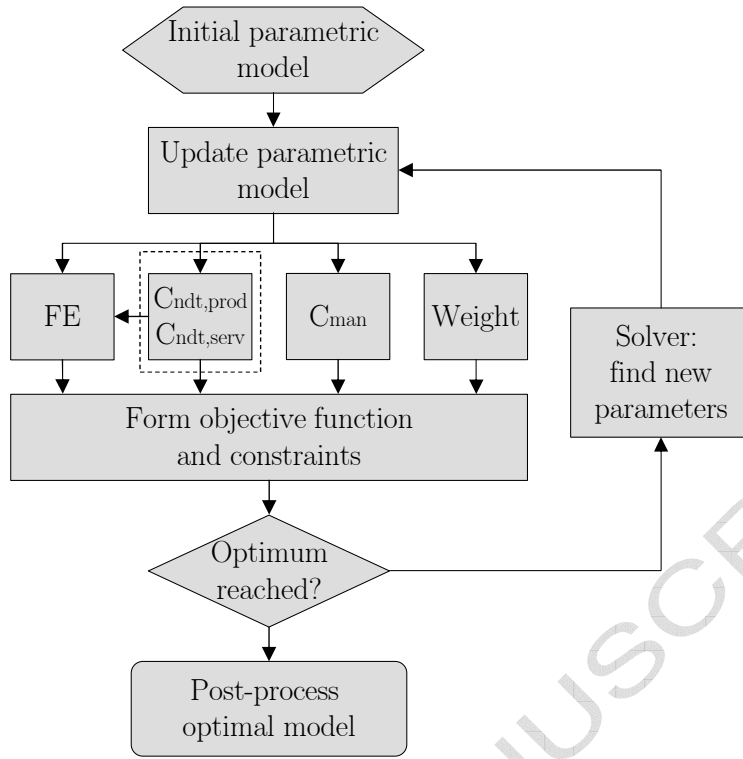


Fig. 1. The optimization loop; the module within the dashed line is subject to further explanation below.

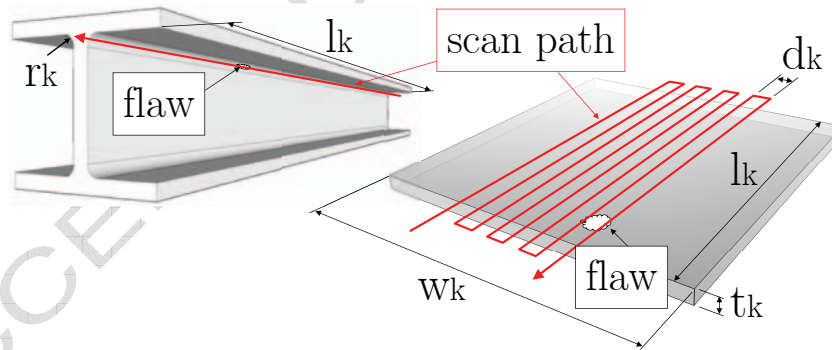


Fig. 2. Ultrasonic C-scan of radii and flat plates

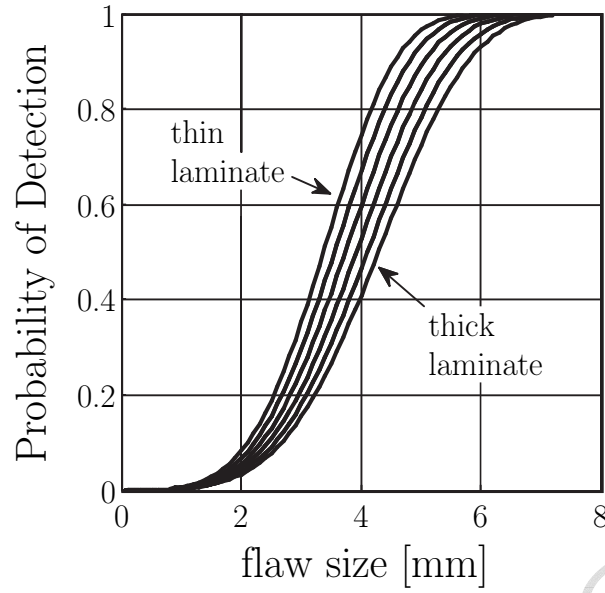


Fig. 3. Probability of Detection vs. maximum flaw size and laminate thickness

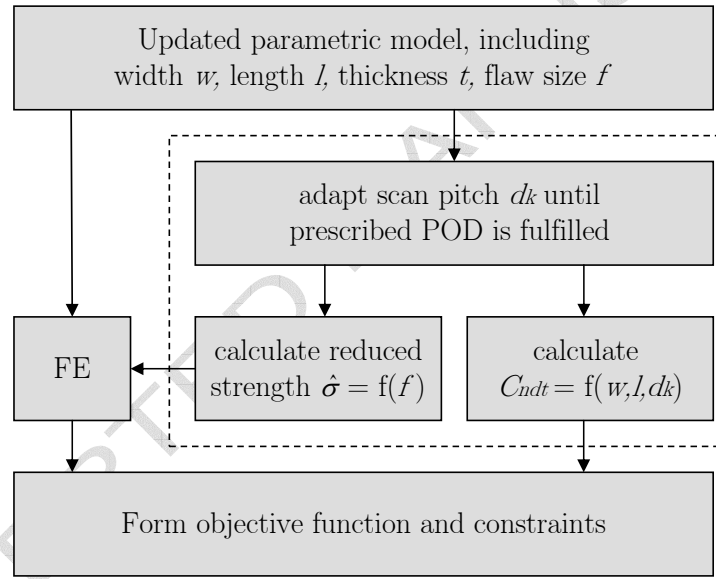


Fig. 4. Flow chart of the strength reduction and cost calculation mechanism for non-destructive testing of one single feature

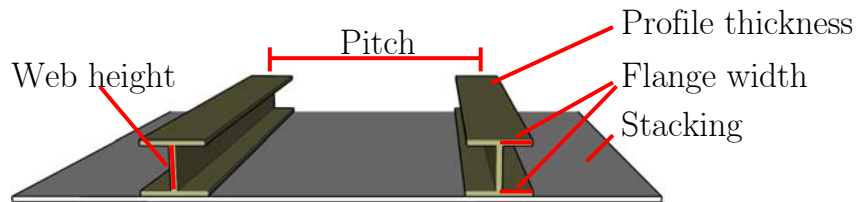


Fig. 5. Generic skin/stringer element

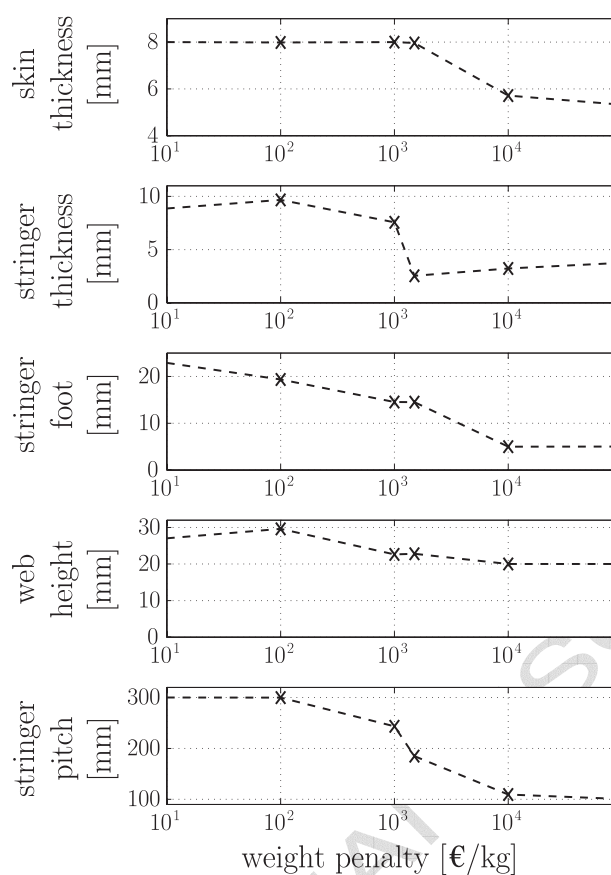


Fig. 6. Results from the preparatory parameter study

configuration	low-cost	intermediate	low-weight
p [in €/kg]	0	1500	∞
skin thickness [mm]	8.00	7.96	5.31
stringer thickness[mm]	8.88	2.53	3.77
stringer foot* [mm]	24.86	14.50	5.00
web height* [mm]	20.96	22.80	20.00
stringer pitch*[mm]	300.00	184.91	100.13

Table 1

Starting points for the investigation of different laminate qualities

flaw size	2mm	6mm	10mm	14mm	16.3mm	20mm
DOC	1.46	1.00	0.91	0.87	0.86	1.00
weight	1.00	1.00	1.00	1.00	1.00	1.14
C_{ndt}	2.74	1.00	0.66	0.51	0.46	0.46
C_{man}	1.00	1.00	1.00	1.00	1.00	1.19
buckling	1.00	1.00	1.00	1.00	1.00	0.92
MSTRN	0.58	0.58	0.67	0.81	0.92	1.00

Table 2

Quality optimization of the low-cost panel ($p = \text{€}0/\text{kg}$)

flaw size	2mm	6mm	10mm	12.4mm	14mm	20mm
<i>DOC</i>	1.16	1.00	0.97	0.96	1.00	1.37
weight	1.00	1.00	1.00	1.00	1.05	1.46
C_{ndt}	2.38	1.00	0.72	0.63	0.65	0.68
C_{man}	1.00	1.00	1.00	1.00	1.05	1.46
buckling	1.00	1.00	1.00	1.00	0.95	0.50
MSTRN	0.78	0.77	0.90	1.00	1.00	1.00

Table 3
Quality optimization of the intermediate panel ($p = \text{€}1500/\text{kg}$)

flaw size	2mm	6mm	10mm	14mm	20mm
<i>DOC</i>	0.99	1.00	1.13	1.36	1.93
weight	0.99	1.00	1.13	1.36	1.93
C_{ndt}	2.07	1.00	0.85	0.75	0.74
C_{man}	1.00	1.00	1.15	1.24	1.36
buckling	1.00	1.00	0.82	0.48	0.22
MSTRN	1.00	0.98	1.00	1.00	1.00

Table 4
Quality optimization of the low-weight panel ($p = \text{€}\infty/\text{kg}$)

<i>POD</i>	80%	85%	90%	95%	97.5%	99%
<i>DOC</i>	0.97	0.98	0.99	1.00	1.01	1.03
weight	1.00	1.00	1.00	1.00	1.00	1.00
C_{ndt}	0.76	0.81	0.89	1.00	1.11	1.24
C_{man}	1.00	1.00	1.00	1.00	1.00	1.00
buckling	1.00	1.00	1.00	1.00	1.00	1.00
MSTRN	0.78	0.78	0.78	0.78	0.78	0.78

Table 5
Optimization with variable *POD* for the intermediate panel ($p = \text{€}1500/\text{kg}$)