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# The Challenge of Reversing Theories to Hybridize Structures with Fiber Metal Laminate Design Concepts

René Alderliesten

To further optimize aeronautical structures, an increased level of material hybridization is required. Optimization efforts aim to identify optimal design solutions that satisfy prescribed requirements. However, this demands reversal of currently available knowledge on hybrid structural technologies, which are often formulated as theories predicting performance based on known load cases and selected material configurations. After briefly reviewing the available fundamental theories for strength, fatigue, and damage tolerance of hybrid structures, this paper discusses the challenges in reversing these theories. Solutions are proposed in which theories can be approximated to significantly reduce the computational time while maintaining the required level of accuracy.

## 1. Introduction

Where metallic structural design solutions have dominated aeronautics for many decades since first introduction of aluminum in aircraft primary structures after the first world war, composite design solutions have demonstrated their maturity recently with the introduction on the Boeing 787 and Airbus A350.<sup>[1]</sup> The application of fiber reinforced polymer composites on the primary structures of these airframes constitutes a major break-through, because it has matured the discussion on structural material selection. Where initially a known and matured metallic material technology was competing with the forecasted potential of composites, nowadays both structural solutions can be compared based on similar maturity levels and in-service experience.

For example, although significant weight saving potential was claimed in the competition for composites over metallic solutions, comparison of airframe performance figures of both the Boeing 787 and Airbus A350 with former metallic airframes of equivalent dimensions, easily demonstrates the limitation of that potential.<sup>[2–5]</sup> To some extent, this limitation may be attributed to the fact that composites structural design is still in

development, illustrated by the discussions on “black metal design” of current composite structures.<sup>[6]</sup> However, compliance to damage tolerant design certification requirements demands concepts like the “no-growth” concept for damages that cannot be easily detected. This aspect of inspectability is characteristic for composite structures, but practically non-existent for metallic structures.

What this experience has brought to light is that in order to fully benefit from the composite nature, aspects must be resolved that require metallic-like properties such as ductility. Hence, various studies conclude that hybrid material solutions can further increase the structural performance,<sup>[7,8]</sup> followed by research where composites are hybridized with the addition of metallic constituents.<sup>[9–13]</sup> Because the laminar structure of composites with metallic inserts resembles the typical lay-up configuration of Fiber Metal Laminates (FMLs), the first step in hybridization of composites requires learning from this hybrid FML technology.

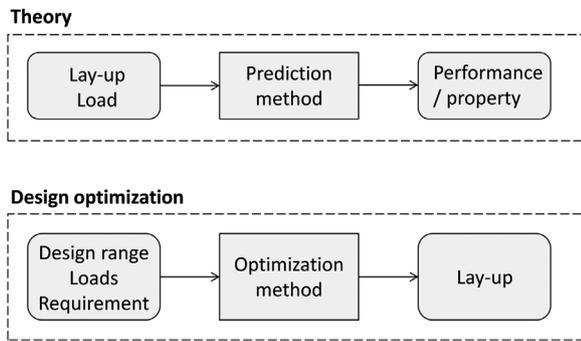
In recent years, fundamental understanding of FMLs has been developed with theories for various strength properties, fatigue resistance, and damage tolerance characteristics.<sup>[14]</sup> This knowledge may aid in optimization studies for hybridizing structures. However, optimization requires a different formulation of theories compared to the currently available forms.<sup>[15–17]</sup> These theories relate the performance or property to the known load case and preselected laminate configuration, while optimizations aim to identify the laminate configuration based on required performance in relation to identified load cases. Hence, the theories must be reversed in their structure, as illustrated in **Figure 1**. In literature, few studies are presented with the aim to optimize the FML configuration for given performance. What characterizes all of them is that they relate to optimization for a single specific condition, like vibration and damping characteristics<sup>[18]</sup> or impact resistance.<sup>[19,20]</sup> None of these studies considers the combination of multiple constraints related to different properties.

Hence, the major question addressed in this paper is how the currently available theories for FMLs can be efficiently exploited in the optimization methodologies for hybrid materials and structures. To answer this question, this paper first reviews several fundamental theories developed in the past decade to evaluate the strength, fatigue, and damage tolerance characteristics of FMLs. In this review, the structure of the theories, or flow-charts, will be assessed for reversibility, and concepts are proposed to overcome the irreversibility of various theories.

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**Figure 1.** Illustration of the difference between the available theories and the required optimization methodology.

## 2. Fiber Metal Laminates

The structural concept of Fiber Metal Laminates (FMLs) has been developed at Delft University of Technology with ARALL and GLARE as the FMLs based on aramid fibers and glass fibers, respectively. Where ARALL was initially developed for lower wing structures, but applied on cargo doors of the Boeing C17, GLARE was developed as fuselage skin material with successful application on the Airbus A380.<sup>[14]</sup>

For both ARALL and GLARE various lay-up sequences have been standardized, generally referred to as grades. As illustrated in **Table 1**, all ARALL grades, and the grades GLARE1 and GLARE2 were unidirectional, while the other GLARE grades constitute cross-ply lay-ups.

Traditionally, materials research aims to develop fundamental understanding on mechanical and physical properties and characteristics of materials for various operational loading and environmental conditions. In a similar fashion, research on FMLs has been performed in past decades, with as result many theories and prediction models to describe and predict the behavior of a given FML under defined loading conditions.

Although this research has brought a lot of knowledge and insight, it has only a limited contribution to the application of this structural concept so far.<sup>[14]</sup> Recent studies have illustrated



Dr. Alderliesten started working in 1999 as a fatigue & damage tolerance specialist at TU Delft. In 2005, he obtained his PhD degree, and holds since then a position as assistant professor until he was nominated associate professor in 2012. The main theme of research is fatigue and damage tolerance of metals, composites and hybrids, with the focus on proper understanding the physics of fatigue damage growth. He has been awarded the Jaap Schijve Award during the 2011 Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity in Montreal. Since 2017, he acts as national delegate of the Netherlands in that committee.

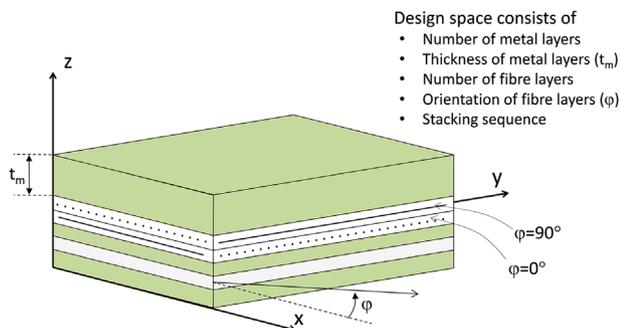
that the design space of Fiber Metal Laminates despite theoretically unlimited, is practically constrained.<sup>[15–17]</sup> One constraint identified is that most of the developed theories cannot be reversed into a form, where predicted performance is used as input following from design requirements.

This means for design optimization methodologies that any solution identified in the design space requires the execution of existing prediction models, which is computationally intensive and very time inefficient. This paper explains the challenges in reversing some of the theories and will discuss alternative strategies to exploit the current knowledge formulated in these theories for design optimizations. This also illustrates how future research objectives can incorporate the reversibility of theory to be developed.

In addition, it explains how the hybrid concept has intrinsic limitations to the design space illustrated in **Figure 2**, which could be used to speed-up the design optimization process if properly identified in advance. In this presentation, the lower wing cover of an aircraft serves as a case study to illustrate and demonstrate the arguments put forward in this presentation.

**Table 1.** Standardized ARALL and GLARE grades.<sup>[14]</sup>

Grade	Alloy	Metal thickness	Fiber Orientation	Fiber	Epoxy	Curing	Condition
ARALL-1	7075-T6	0.3	0/0	HM aramid	AF163-2	120 °C	0.4% post-stretched
ARALL-2	2024-T3	0.3	0/0	HM aramid	AF163-2	120 °C	as-cured
ARALL-3	7475-T761	0.3	0/0	HM aramid	AF163-2	120 °C	0.4% post-stretched
ARALL-4	2024-T81	0.3	0/0	HM aramid	AF191	175 °C	as-cured
GLARE1	7075-T6	0.3–0.4	0/0	S2-glass	FM94	120 °C	post-stretched
GLARE2A	2024-T3	0.2–0.5	0/0	S2-glass	FM94	120 °C	as-cured
GLARE2B	2024-T3	0.2–0.5	90/90	S2-glass	FM94	120 °C	as-cured
GLARE3	2024-T3	0.2–0.5	0/90	S2-glass	FM94	120 °C	as-cured
GLARE4A	2024-T3	0.2–0.5	0/90/0	S2-glass	FM94	120 °C	as-cured
GLARE4B	2024-T3	0.2–0.5	90/0/90	S2-glass	FM94	120 °C	as-cured
GLARE5	2024-T3	0.2–0.5	0/90/90/0	S2-glass	FM94	120 °C	as-cured
GLARE6A	2024-T3	0.2–0.5	+45/–45	S2-glass	FM94	120 °C	as-cured
GLARE6B	2024-T3	0.2–0.5	–45/+ 45	S2-glass	FM94	120 °C	as-cured



**Figure 2.** Illustration of the design space of FML structures.

### 2.1. Fatigue Initiation

In FMLs, fatigue initiation is commonly defined as the lifetime required to form a fatigue crack of 1 mm length.<sup>[14,21]</sup> This definition is the result of a trade-off between longer lengths required to use fatigue life to failure S-N data from literature, and the shorter crack required to eliminate the bridging crack contribution of the fiber layers.<sup>[22]</sup> The methodology initially proposed by Homan<sup>[21]</sup> and later modified and further worked out by Spronk et al.<sup>[22]</sup> utilized the classical laminate plate theory to calculate the stresses in individual lamina, which are subsequently correlated to S-N data to determine corresponding fatigue initiation lives.

The methodology in itself is based on first principles, in which the accuracy in initiation life predictions is mostly defined by how close the reference S-N curve conditions are to the conditions of the predicted case.<sup>[22]</sup> The methodology is characterized by that the flow in the prediction model is continuous from input to result, that is, no iterations are

required, see **Figure 3**. This may imply that the method has a high likelihood of providing a unique relation between input parameters and result, allowing the theory to be reversed.

However, Şen<sup>[17]</sup> demonstrated that such unique relation only exists between the predicted fatigue initiation life and the Metal Volume Fraction (MVF) of the FML, defined as

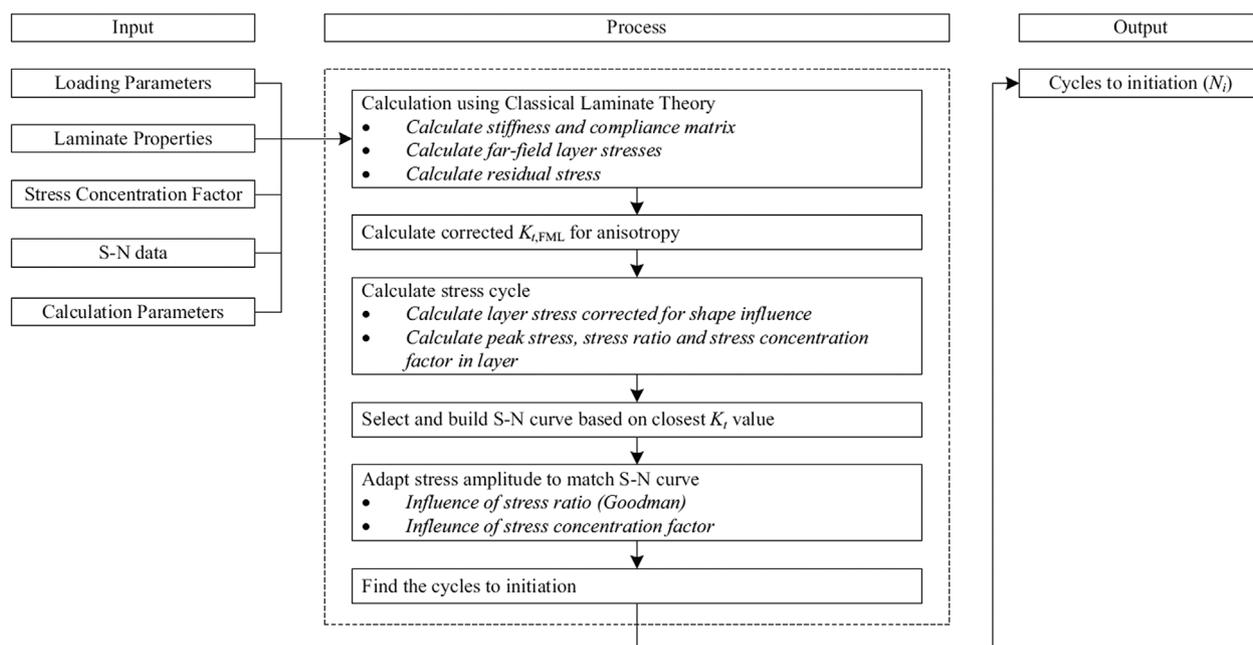
$$MVF = \frac{n_m t_m}{t_{FML}} \quad (1)$$

with  $n_m$  the number of metal layers,  $t_m$  the individual metal layer thickness, and  $t_{FML}$  the total laminate thickness. However, the MVF does not relate uniquely to a single lay-up, that is, multiple FML lay-ups correspond to a specific MVF, as illustrated in **Figure 4**.

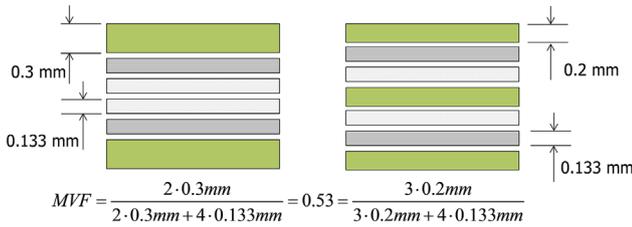
### 2.2. Fatigue Crack Growth

Fatigue crack growth in FMLs can be described with the theory presented in ref. <sup>[23]</sup>, which was further developed to a generalized form by Wilson.<sup>[24]</sup> Input for the prediction method are the crack growth resistance of the metallic constituents, and the delamination growth resistance at the interface between metal layers and composite plies.

The crack increment is calculated in conjunction with the delamination growth, after which the stress state at the crack tip must be updated to calculate the subsequent increment. As a consequence, this methodology is an iterative procedure, in which the flow chart is described by a repeated flow until the defined critical crack length is obtained, see **Figure 5**. This means that no unique analytical relationship can be obtained between the input variables and the resulting crack growth life by reversing the theory.



**Figure 3.** Flow chart illustrating the fatigue initiation life prediction for FMLs. Reproduced with permission<sup>[17]</sup> 2015, I. Şen.



**Figure 4.** Example of two FML lay-ups with the same MVF.

### 2.3. Residual Strength

Residual strength, defined as the remaining strength of FMLs in presence of (fatigue) damage, can be described with a theory following a similar iterative flow as the crack growth model. This theory was developed by Rodi<sup>[25]</sup> based on the critical crack tip opening angle calculated in the metal layers of the FML, while accounting for the plasticity formed in the crack tip vicinity. Similar to the fatigue crack growth theory, this theory is iteratively updated each time a crack increment is predicted. The corresponding flow chart therefore has a similar structure as Figure 5, except that the load is variable rather than the number of load cycles.

### 3. Problem Formulation

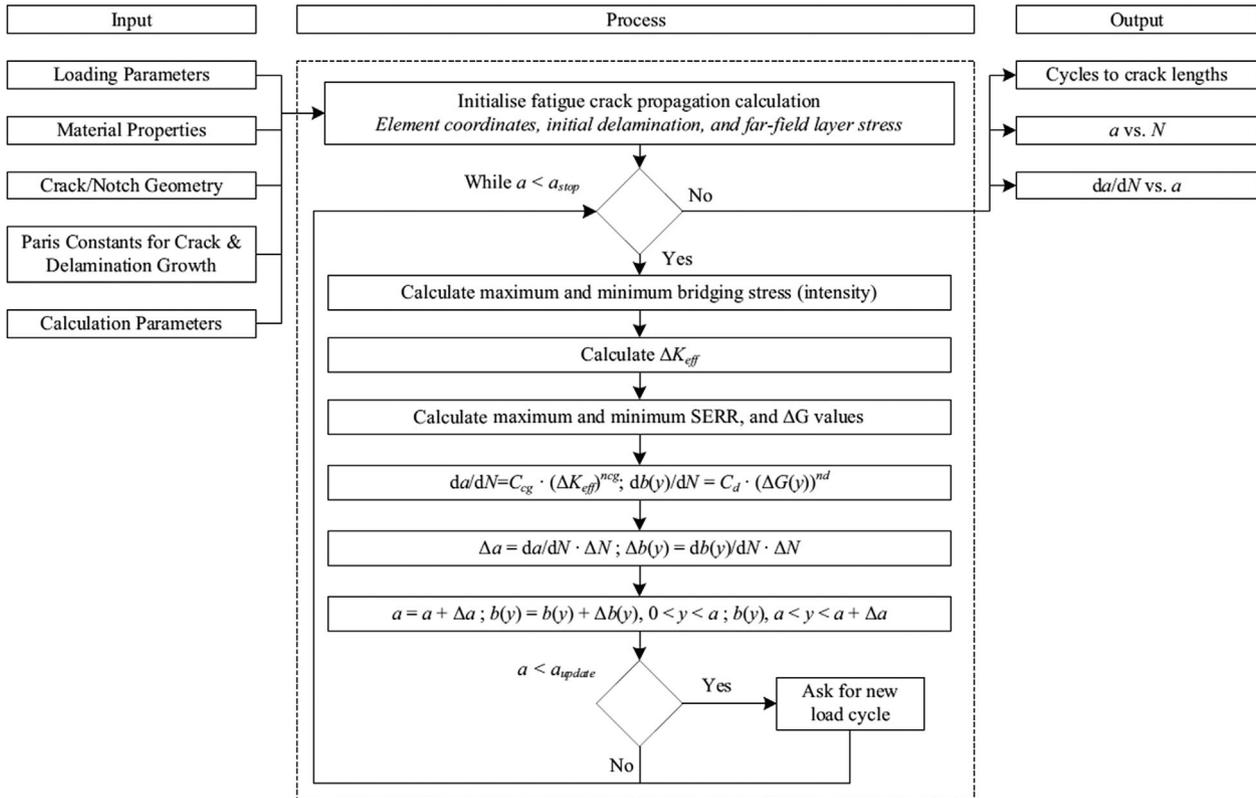
Three aspects can be distinguished in the problem formulations. First, the theories described in previous section allow the

prediction of properties and performance for many FMLs and load conditions. However, these theories are formulated opposite to what is required, as illustrated in Figure 1. The laminate lay-up is part of the input for the methodologies, instead of the result. The iterative nature of most theories does not allow straightforward reversal of the formulation. In addition, there is not necessarily a unique relationship between the properties of the FML and the lay-up, as illustrated in Figure 4.

Second, the design optimization objective is often to obtain minimum weight while satisfying all design requirements. Aside from static strength requirements, addressed by Cooper,<sup>[26]</sup> this implies a requirement on the inspection threshold, a requirement on the inspection intervals, and a requirement on residual limit-load.<sup>[17,27]</sup> To this objective, the prediction models could function as constraints in the optimization.

Finally, FML design requires an integer based optimization procedure, because thicknesses and lay-up are limited to discrete variables. Therefore, optimization procedure can be best implemented using genetic algorithms (GA), rather than a gradient based optimization algorithm. GA is a search technique based on survival of the fittest using natural selection and genetics to create design populations. In the optimization procedure the laminates are defined using the vector

$$\bar{L} = [h \ n \ m] \quad (2)$$



**Figure 5.** Flow chart illustrating the fatigue crack growth prediction for FMLs with the while loop illustrating the iterative procedure. Reproduced with permission <sup>[17]</sup> 2015, I. Şen.



**Figure 6.** Illustration of the approximation procedure for the theories; input parameters are related to results using regression analysis.

in which  $h$  defines the FML grade (see Table 1),  $n$  the number of metal layers, and  $m$  the metal layer thickness.

#### 4. Approximation of Prediction Models

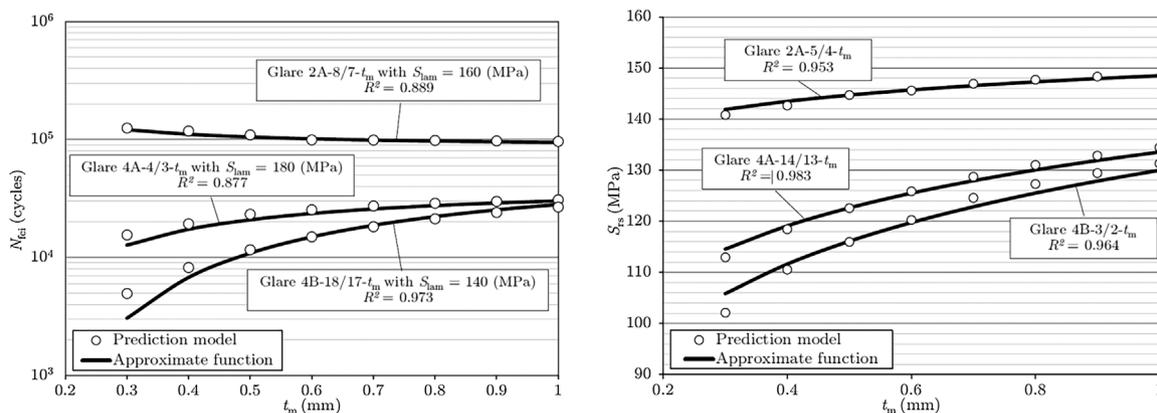
Implementing the prediction models reviewed in section 2, as constraints in the optimization procedure is a computationally inefficient method. In particular, the crack growth and residual strength method require computational time for predictions due to their iterative structure, as illustrated in Figure 5. Hence, for each design generated in the optimization, these methods must be run to evaluate whether requirements are satisfied, which becomes computationally very expensive. An alternative approach would be to approximate the prediction models with a single equation, in which coefficients can be related to lay-up and various other input parameters.

To this aim, a database was generated using the prediction methods within the relevant range of the parameters  $h$ ,  $n$ , and  $m$ .<sup>[17]</sup> Then equations were fitted using regression analysis to the data, and the corresponding coefficients were obtained. The procedure is illustrated in Figure 6. For the fatigue initiation method discussed in section 2.1 and the fatigue crack growth method discussed in section 2.2, the constraint was approximated<sup>[15,16]</sup> using

$$n_m \log_{10}(N_{fci}) = A_1 \ln(S_{lam}) + A_2 \quad (3)$$

While for residual strength the constraint was approximated<sup>[16]</sup> with

$$n_m S_{rs} = A \ln(t_m) + B \quad (4)$$



**Figure 7.** Illustrations of the verification of approximations against the prediction models; Fatigue initiation (left) and residual strength (right). Reproduced with permission<sup>[17]</sup> 2015, I. Şen.

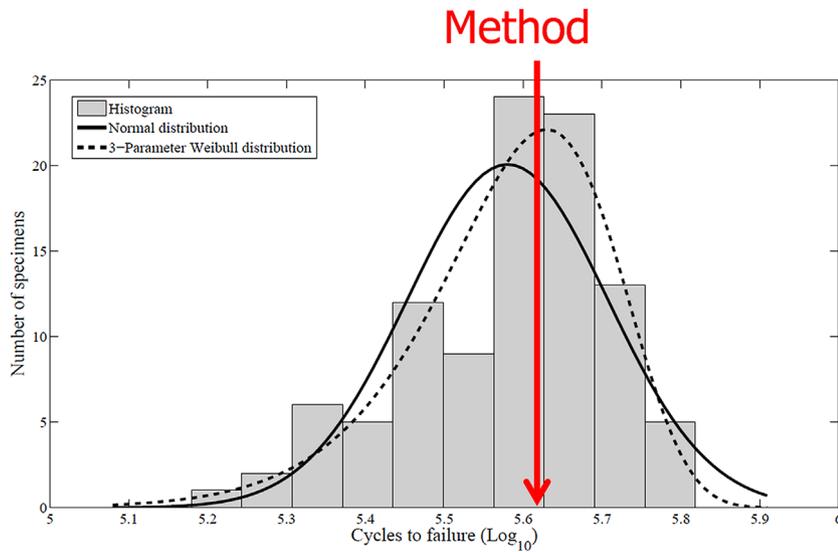
The approximations were verified against the original prediction models to evaluate how accurate the approximations were, see for example, Figure 7. It was observed that the approximations were rather accurate, except toward the extremes of the design space defined by the selected ranges in parameters  $h$ ,  $n$ , and  $m$ .

#### 5. Discussion of the Optimization Method

Adopting the constraints approximation in an optimization procedure clearly has a computational advantage, but it comes with the disadvantage that the prediction accuracy might reduce slightly. In one of the cases, using the fatigue crack growth prediction model in the optimization required 83 min, while with the approximations only 10 s were needed.<sup>[17]</sup> Taking into account that full structure optimization may incorporate both static strength<sup>[26]</sup> and fatigue and damage tolerance requirements,<sup>[17]</sup> then easily illustrates the substantial gain with using constraint approximations. Other advantages that were identified is that laminate properties can be easily extrapolated with an approximation, and that similar approximations also could be developed based on experiments instead of prediction models.

Note, however, that care should be taken in considering proper margins on life time. Take, for example, Figure 8, which illustrates that deterministic prediction models give average or typical values, while the experimental data results in distributions of life time or strength values. This means that slightly below the predicted value an optimization utilizing the approximation will penalize a design, while looking at the scatter in experimental data underlying the original prediction model, this design could be acceptable. Hence, a proper margin may be included before approximating the theories to account for both the accuracy of the original theory, and for the distribution in experimental results underlying that theory.

In this respect, it should be considered that the explicit nature of the prediction methodologies that were approximated, allows to perform sensitivity and uncertainty analyses. The influence of input parameter variation on the output parameters can be evaluated in a probabilistic concept. Hence, to establish proper margins accounting for the distribution of data illustrated in



**Figure 8.** Illustration of the typical or average values predicted by prediction models, while experimental data is distributed over a range of values. Adapted with permission<sup>[17]</sup> 2015, I. Şen.

Figure 8, one can evaluate which input parameters are dominating the results.

An important aspect that should be considered at all times is the initial design space. In theory, the design space of FMLs is unlimited. However, when selecting a large initial design space, the optimization procedure might not find a global optimum in that design space if the solution is not generated by the GA. Optimizations may also converge prematurely to solutions, which were observed to be influenced by the given initial input.<sup>[17,27]</sup>

Hence, large initial design spaces may yield that the optimization does not find any solution in the design space that satisfies the requirements.

To overcome this problem, two solutions can be considered: First, the initial design space could be decreased based, for example, on design experience. Secondly, the GA settings could be adjusted, which obviously requires some knowledge on the optimization procedures. For lower wing covers, for example, the solution could be limited to unidirectional laminates, instead of exploiting the entire design domain for FMLs.<sup>[14,17]</sup> Limiting the initial design spaces improves the convergence of solutions.

To illustrate this second solution, **Figure 9** illustrates that as result of the stochastic nature of the optimization, optimum solutions may not be found, depending on the chosen GA settings.<sup>[15]</sup> For the illustrated optimization based on GLARE2A, both De Jong and Greffenstette1 do not always produce the optimal solution, whereas Greffenstette2 yielded the optimum in all cases.

Ultimately, convergence loops could be added, where the result of a first

optimization is fed into a next optimization. Applying convergence loops was observed to improve the convergence to better solutions, as illustrated in **Figure 10**, where the first and second optimization are compared to the expected trend based on wing bending moments. The second optimization converged better than the first run.

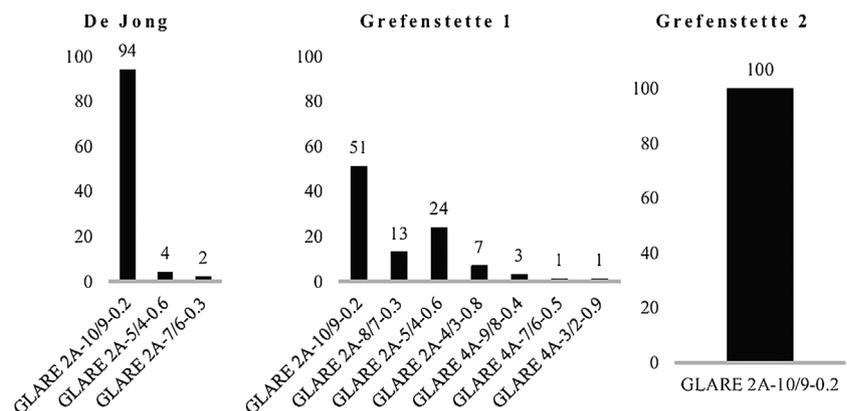
## 6. Evaluation of Results

A design optimization methodology using constraints approximations in combination with GA algorithms allows exploring design spaces for FMLs by finding solutions that meet all criteria. Obviously, such approach won't help in the detailed design phase, where specific design features developed for FMLs<sup>[14]</sup> could be implemented, but it may aid the conceptual and preliminary design phase.

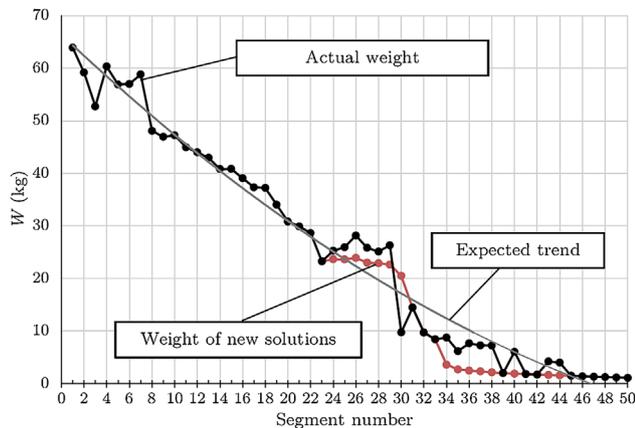
For example, it may illustrate the contribution of each constraint on the obtained design solution. Each element has been determined by the most critical requirement. Comparison of that design solution to the second most critical constraint easily illustrates the design improvement potential in case specific performances are improved. Here, the design potential of novel FML constituents could be identified rapidly, or the benefit of specific damage arrest features embedded within FMLs.<sup>[28]</sup>

## 7. Hybridizing Structures with FMLs

Adopting optimization procedures using GA to generate discrete design solutions (lay-ups and thicknesses), in combination with approximations of existing theories for strength, fatigue, and damage tolerance, yields a powerful and robust method for exploiting FML design potential. Şen<sup>[17]</sup> demonstrated this potential with the case of an entire wing box design optimization,



**Figure 9.** Optimal solutions based on 100 times repeating the search procedure with different GA settings, indicating that best solutions are not always found. Outputs may vary due to stochastic approach when repeated. Reproduced with permission<sup>[15]</sup> 2015, Elsevier.



**Figure 10.** Illustration of the additional convergence loop: weight of optimal cross-section solution per segment improves with respect to the expected trend. Reproduced with permission<sup>[17]</sup> 2015, I. Şen.

in which the element optimization was extended toward a wing box cross-sectional optimization based on a monolithic aluminum upper wing cover and an FML lower cover. In this optimization, compatibility between wing cross-sections was assured, while the requirements and constraints for both upper aluminum and lower FML panel were different. For example, for the upper panel, plate buckling was added as an important design requirement.

Aside from demonstrating how the challenge of reversing the theories could be overcome successfully with constraint approximation, this demonstration highlighted that additional rules may be required. For example, it was observed how the optimization either put most thickness in the cross-section center, or near both ends. It appeared that both solutions occurred within a single lower wing panel design solution. Adding rules that define thickness increments over wing box cross-sections, illustrated how the optimization can be tailored, preventing such undesired mix of design solutions.

What the studies by Cooper<sup>[26]</sup> and Şen<sup>[17]</sup> have shown is that the availability of theories and the potential of constraint approximation allows to study design solutions based on the FML concept. Take, for example, hybridizing composite panels by adding metallic inserts at the edges where panels must be joined with mechanical fastening to other panels. Such concept in fact represents an FML configuration, where the joint properties can be evaluated using existing theories for bearing and joint strength.<sup>[14]</sup> Approximating these theories in a similar fashion as Şen<sup>[17]</sup> did for fatigue and damage tolerance methods, allows for fast exploration of the design potential of this hybrid concept using metallic inserts.

## 8. Conclusions

This paper discussed the reversibility of various FML prediction methodologies for their implementation in the design optimization procedures. The iterative nature of most theories does not allow for reversing the method. In this case, the theory is not iterative of nature, the relationship between input parameters

and final result are not unique, that is, multiple solutions satisfy the same criteria.

Using the theory in an optimization by evaluating each design solution generated by the algorithm is computationally very expensive, in particular if multiple constraints (theories) are accounted for at the same time.

This paper discussed the solution of approximating the theories with simple relations of which the coefficients are fitted to input parameters using regression analysis. Running the optimization algorithms with these approximation functions substantially reduces the computational time, while the accuracy is only slightly affected. Depending on the initial conditions for the optimization, not always unique solutions are generated, for which in this paper solutions are discussed related to limiting the initial design space, or modifying the GA settings.

Although the optimization using approximations represents a fast method to explore design potential for conceptual and preliminary design studies, it is strongly recommended to acknowledge practical FML design experience.

## Conflict of Interest

The author declares no conflict of interest.

## Keywords

constraint approximation, design optimization, fibre metal laminates

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- [1] G. Marsh, *Reinf. Plast.* **2013**, *57*, 18.
- [2] [http://www.boeing.com/assets/pdf/commercial/airports/acaps/777\\_2lr3er.pdf](http://www.boeing.com/assets/pdf/commercial/airports/acaps/777_2lr3er.pdf)
- [3] <http://www.boeing.com/assets/pdf/commercial/airports/acaps/787.pdf>
- [4] [www.aircraft.airbus.com/aircraftfamilies/passengeraircraft/a330family/](http://www.aircraft.airbus.com/aircraftfamilies/passengeraircraft/a330family/)
- [5] [www.aircraft.airbus.com/aircraftfamilies/passengeraircraft/a350xwbfamily/](http://www.aircraft.airbus.com/aircraftfamilies/passengeraircraft/a350xwbfamily/)
- [6] A. Beukers, E. van Hinte, *Lightness: The Inevitable Renaissance of Minimum Energy Structures*, Uitgeverij 010 **1998**. ISBN: 978-90-6450-560-7
- [7] R. C. Alderliesten, R. Benedictus, *J. Aircraft* **2008**, *45*, 1182.
- [8] R. C. Alderliesten, *Mater. Des.* **2015**, *66*, 421.
- [9] P. P. Camanho, C. M. L. Tavares, R. de Oliveira, A. T. Marques, A. J. M. Ferreira, *Composites Part B* **2005**, *36*, 372.
- [10] B. Kolesnikov, L. Herbeck, A. Fink, *Compos. Struct.* **2008**, *83*, 368.
- [11] P. P. Camanho, A. Fink, A. Obst, S. Pimenta, *Composites Part A* **2009**, *40*, 1826.
- [12] G. Kolks, K. I. Tserpes, *Composites Part A* **2014**, *56*, 51.
- [13] E. Petersen, D. Stefaniak, C. Hühne, *Compos. Struct.* **2017**, *182*, 79.
- [14] R. C. Alderliesten, *Fatigue and Fracture of Fibre Metal Laminates*, Springer **2017**.
- [15] I. Şen, R. C. Alderliesten, R. Benedictus, *Compos. Struct.* **2015**, *120*, 275.
- [16] I. Şen, R. C. Alderliesten, R. Benedictus, *Compos. Struct.* **2015**, *124*, 77.

- [17] I. Şen, *Lay-up Optimisation of Fibre Metal Laminates, Development of a Design Methodology for Wing Structures*, Delft University of Technology, Delft, The Netherlands **2015**.
- [18] H. Ghashochi-Bargh, M. H. Sadr, *Mech. Adv. Compos. Struct.* **2017**, 4, 99.
- [19] F. A. Ghasemi, S. Raissib, K. Malekzadehfard, *Lat. Am. J. Solids Struct.* **2013**, 10, 391.
- [20] R. Abdi, H. Mozafari, R. M. Abdullah, A. Ayob, *AWERProcedia Inf. Technol. Comput. Sci.* **2013**, 3, 1925.
- [21] J. J. Homan, *Int. J. Fatigue* **2006**, 28, 366.
- [22] S. W. F. Spronk, I. Şen, R. C. Alderliesten, *Int. J. Fatigue* **2015**, 70, 428.
- [23] R. C. Alderliesten, *Int. J. Fatigue* **2007**, 29, 628.
- [24] G. S. Wilson, *Fatigue Crack Growth Prediction for Generalized Fiber Metal Laminates and Hybrid Materials*, Delft University of Technology, Delft, The Netherlands **2013**.
- [25] R. Rodi, *The Residual Strength Failure Sequence in Fibre Metal Laminates*, Delft University of Technology, Delft, The Netherlands **2012**.
- [26] C. A. Cooper, *Development of a Methodology to Support Design of Complex Aircraft Wings*, Delft University of Technology, Delft, The Netherlands **2011**.
- [27] I. Şen, R. C. Alderliesten, F. Bron, J.-C. Ehrstrom, R. Benedictus, *Proc. SAMPE Europe conf., Liege Belgium* **2016**.
- [28] C. Rans, F. Morinière, R. Rodi, R. C. Alderliesten, R. Benedictus, *J. Aircraft* **2011**, 48, 2122.