Straightening out the Adoption of Variable Stiffness Composite Laminates in Aerospace Industry

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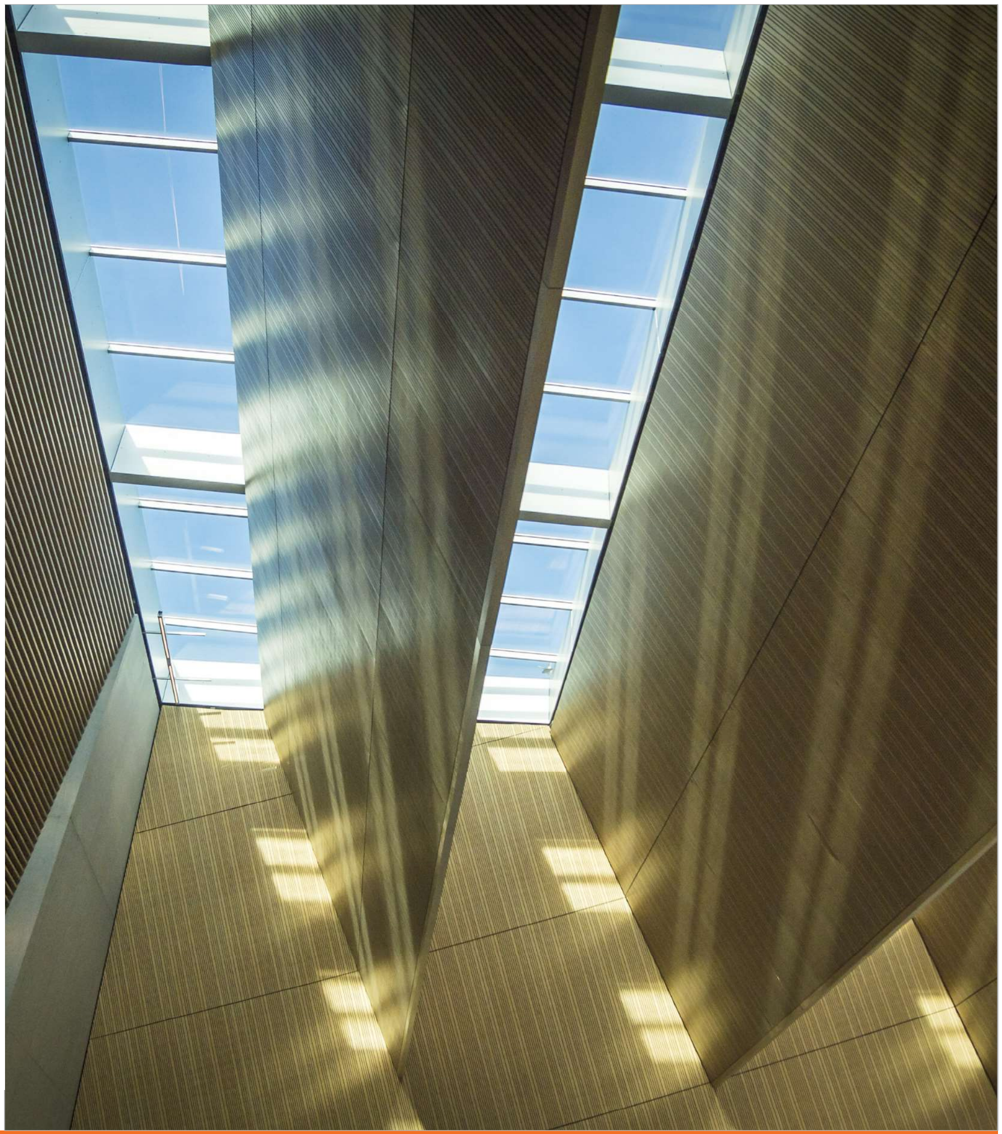

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STRAIGHTENING OUT THE ADOPTION OF VARIABLE STIFFNESS COMPOSITE LAMINATES IN THE AEROSPACE INDUSTRY

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Abstract: *In the late 1960s fibre reinforced composites were first applied in civil aviation. Since their introduction they have made commercial aircraft significantly lighter, and thereby more fuel efficient and cheaper to operate. It is not uncommon that the structure of a modern aircraft consists for more than 50% of composite materials. The concept of variable stiffness (VS) composite structures was first introduced in the 1990s. The performance improvements associated with VS laminates are comparable to the improvements of conventional composite structures over metallic structures. Despite their potential, VS laminates have not been adopted in commercial aviation yet. In this paper we investigate what requirements need to be fulfilled to adopt VS laminates in civil aviation. As a specific example we look at straight-fibre variable stiffness laminates (SFVS), which have been developed at TU Delft to be a low-cost alternative to VS laminates that rely on automated fibre placement.*

Keywords: Variable Stiffness; Performance Improvement; Structural Optimization; Adoption of Technology; Aerospace Industry

1. Introduction

The use of composite materials in civil aviation has steadily gained terrain since their introduction in the late 1960s [1,2]. In 1982 the first primary structure made of carbon fibre-epoxy was certified for the Boeing 737 [1]. The Boeing 787 in terms of structural weight consist for more than 50% of composite materials [2]. The adoption of composite materials in civil aviation can safely be called successful. Composite materials have delivered on the expected improvements: 10-20% weight reduction compared to metallic structures, integrated manufacturing instead of manufacturing and assembling a large number of parts, better fatigue performance, and structural efficiency. Of course, composite materials have also introduced new challenges, but these are outweighed by the benefits.

The transition from metallic structures to composite structures has been very successful. Similar significant improvements in the mechanical performance of a laminated composite structure can be achieved by spatial variation of the stiffness properties within the laminate. Such a variable stiffness (VS) laminate, typically is created by steering the fibres within the laminae, result in in an in-plane variation of stacking sequence and thus an in-plane variation of mechanical properties of the laminate and subsequent load-redistribution within the laminate.

Since the early work on VS laminates [3–5] more than 30 years have passed. In these years, significant improvements in the design, analysis and manufacturing of VS composite laminates have been made. Buckling load improvements more than 100% (compared to the best constant stiffness design) are reported for VS laminates [5], and there are numerous examples of case studies on (aerospace) structures [6]. Nevertheless, to the knowledge of the authors, there is

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still no widespread adoption of VS laminates in the aerospace engineering industry. This raises the question, why VS laminates are not being adopted, and what can be done to change this.

Recent work done at the TU Delft has demonstrated that it is possible to achieve variable stiffness laminate designs by means of laminate blending and patching operations, instead of fiber steering. The result is a straight-fiber variable stiffness (SFVS) laminate. These laminates stay very close to conventional laminates in terms of required manufacturing infrastructure but offer performance improvements similar to those of VS laminates.
In this paper we investigate which boundary conditions in terms of structural performance, certification and cost need to be met to introduce a new type of composite material to civil aviation, and we will try to answer the question whether it is likely for variable stiffness laminates to find their way into civil aviation in the coming two decades. First, an overview of the potential performance improvements associated with variable stiffness laminates is given. Second, we will look at the drivers for the adoption of a new technology in civil aviation and the obstacles that need to be overcome. Then, the class of straight-fibre variable stiffness (SFVS) laminates is considered as a case study. This is followed by a discussion and outlook for the coming two decades.

2. The Potential of Variable Stiffness Laminates

Hyer and Lee [3] were the first to spatially optimize the fibre orientation to increase the strength of a rectangular plate containing a circular cut-out at its center. Iteratively the fibre orientation was matched to the “principal stress direction” in 120 unique elements and a curvilinear design was generated that fails at a 60% higher tensile load. An adoption to their model and optimization procedure resulted in a design optimized for buckling in uni-axial compression of the same model. Load alleviation to simple supported sides away from the central cut-out results in a load carrying capability increase of more than 100%.

The concept of variable stiffness laminates was formulated by Gürdal and Olmedo [5]. In the following decades many sophisticated design frameworks addressing stiffness, strength and manufacturing constraints have been developed for a range of applications as can be found in a comprehensive review paper by Sabido et al [6]. Design methods for plates, shells, cylinders, and beams have been developed, optimizing, strength, stiffness or thermal response. There seems to be the capability to design VS composite structures, and the performance improvements reported are in the double digits. The manufacture of VS composite structures at an industrial scale seems to be slightly more challenging, but manageable. The biggest hurdle for adoption in aerospace seems to be lacking certifiability criteria for VS laminates [6].

3. Adoption of a new Technology in Aerospace Industry

In the previous section it has been established that variable stiffness (VS) laminates offer a significant improvement in mechanical performance over conventional laminates. In this section the question will be addressed what boundary conditions need to be met before we will see adoption of VS laminates in civil aviation. Above all else, civil aviation has a high price elasticity and is therefore very sensitive to cost. The hypothesis underpinning this work, is therefore, that VS laminates will only be adopted, if the benefits outweigh the cost incurred when introducing the new technology. Below, we will focus on the expected benefits when VS laminates are adopted. Furthermore, we look at the expected cost of certification and manufacturing. Here we point out, that this analysis is by no means complete.

3.1 Benefits of implementation

The main benefit of adopting VS laminates in civil aviation will be weight reduction of the aircraft structure, which in turn will lead to a reduced fuel consumption. Our preliminary analysis showed that application of VS laminates to an A320-type aircraft would result in a 7% reduction in fuel consumption.

Apart from weight reduction, VS laminates do not offer any apparent benefits compared to conventional laminates. Therefore, it can be concluded that the adoption of VS laminates in civil aviation will be strongly dependent on fuel cost. It will only be attractive to develop VS laminate technology for civil aviation if fuel cost stays at its current elevated level or increases even further, e.g. by increasing the taxation of fuel.

From a financial standpoint the authors do not expect it to be likely that the weight benefit offered by VS laminates would be used to offset the increased weight of alternative powertrains in civil aviation. This is because, the development budget is more likely to be used for the development of the alternative powertrain itself, than to optimize the structure of the aircraft.

3.2 Manufacturing

Adopting VS laminates in aviation would likely require an investment in manufacturing capability. Automated fibre placement and continuous tow shearing using multiple tows [8] seem to be likely candidates. Next to the investment in new manufacturing equipment, manufacturing time may also be expected to increase. The combination of investment in new manufacturing tools and the increased production time and therefore production cost per part, make the adoption of VS laminates in civil aviation less attractive.

3.3 Certification

The adoption of VS laminates in civil aviation would require a departure from the so-called building block approach, in which first coupons, then elements, sub-components and then components are tested. For a structure with a continuous variation of stacking sequences, such an approach would no longer be tractable. Instead, new analysis techniques and virtual testing may replace the more conventional certification procedure. Making this transition may make for cheaper certification in the longer term, but in the short term it will mean increased certification cost, which may be prohibitive for the introduction of a new technology.

4. Straight-Fibre Variable Stiffness Laminates

In recent work we have demonstrated that it is possible to achieve variable stiffness laminate designs by means of laminate blending and patching operations, instead of fibre steering (Fig. 1). This results in a straight-fibre variable stiffness (SFVS) laminate. Stacking sequence continuity is assured by enforcing relaxed generalized blending guideline [7]. The developed method is computationally efficient. Preliminary results show similar improvements in buckling load improvement as have been reported in literature for fibre-steered variable stiffness laminates. The advantage of the proposed design method is that variable stiffness laminates can be achieved by a wide range of manufacturing techniques.

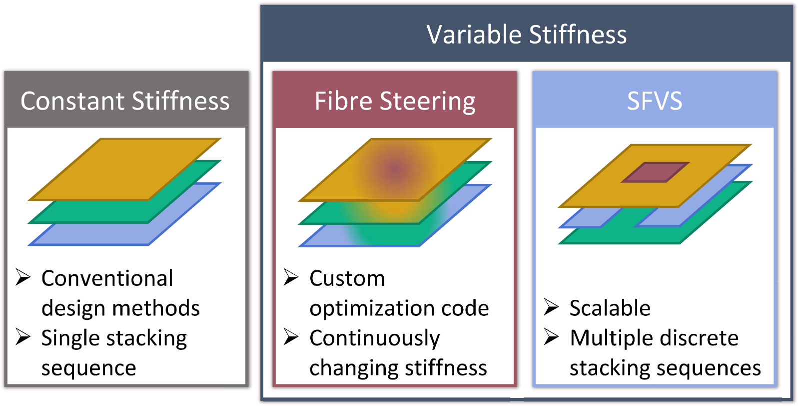

Figure 1: Straight-fibre variable stiffness laminates

A preliminary analysis showed that application of SFVS laminates to an A320-type aircraft would result in a 6% reduction in fuel consumption. SVFS laminates can be manufactured using existing manufacturing techniques, meaning no extra cost will be incurred when manufacturing. Because the manufacturing process remains unchanged, it is expected that the extra effort to certify the new structure will also be minimal. Additionally, there is reason to believe that the architecture of SFVS laminates will be beneficial to its damage tolerance [9], thereby reducing cost that would be incurred by inspection and potential repair.

5. Discussion and Outlook

Variable stiffness (VS) laminates have a lot of potential when it comes to the improvement of structural performance and can therefore are a prime candidate to reduce structural weight in civil aviation. The performance improvement compared to conventional composite structures is similar to the performance improvement that composite structures seemed to provide over metallic structures when they were introduced in the late 1960s. Nevertheless, VS laminates have not been adopted by civil aviation yet.

The analysis presented in the paper is purely qualitative in nature. It indicates that the adoption of VS laminates in aviation would only be likely if there is a prolonged increase in fuel cost, which would make the expected weight savings, and therefore cost savings, outweigh the expected increased cost in terms of manufacturing and certification.

Straight fibre variable stiffness (SFVS) laminates, developed by the authors of this paper, offer performance improvements which are comparable to those of VS laminates, with the added benefit that they can be manufactured and certified within the existing infrastructure for composite structures in civil aviation. This means, that SFVS laminates will be economically viable at lower fuel cost than VS laminates would. Therefore, SFVS laminates could be used to introduce the concept of variable stiffness within civil aviation.
The experience that would be gathered using SFVS laminates could used to develop a certification strategy for more complex VS laminates, such that the certification process for VS laminates is ready, as soon as the technology for mass production of VS laminates becomes available.

The authors are convinced that it will only be a matter of time before VS laminates are adopted by civil aviation. SFVS laminates can play an important role in expediting the process.

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