TOWARDS A FASTENERLESS ALL COMPOSITE WING

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Abstract

A generic study of wing structure concepts is presented. The wing concepts are classified according to the bending moment load path through the skins:

A. The load is sustained by the skins. The wing may be multi spar or multi rib.

B. The load is sustained by the spars. Elastically buckled skins or sandwich skins with ±45º fiber directions may be incorporated.

The comparison of the sandwich concept with conventional multi rib and multi spar concepts indicates superiority of the sandwich concept from both weight and cost aspects.

1 Introduction

Current methods for utilization of composites in aircraft structure are often described as "Black Aluminum". The meaning of this is that the design and configuration of composite details is similar to traditional metal parts, and the assembly methods for the individual components into the final structure are almost identical.

The history of aerospace has traditionally incorporated innovations in materials, design and manufacturing techniques. However, many of the inherent advantages of composites, such as complex shape mouldability and part integration that are not possible with metal structure, have not been exploited fully by the aerospace industry.

Conservatism in design and manufacturing has tempered the traditional innovative spirit. This conservatism was caused by liability concerns and also by the nature of the marketplace. The number of aerospace companies has been reduced dramatically by consolidation, eliminating in particular smaller companies where innovations were most likely to occur.

Of course, innovative concepts are still emerging from surviving small, entrepreneurial companies such as Toyota Aviation [1] Scaled Composite, Rocky Mountain Composite, Cirrus, ACS, Diamond, Grob, etc. Appropriate use of composites is also evident in glider design and manufacture and the more recent developments in large, all composite wind turbine blades.

This paper outlines a feasibility study to convert a traditional aluminum alloy wing structure into an all composite lightweight sandwich construction shell with integrated high modulus unidirectional carbon fiber spar caps. The shell is adhesively bonded with thick bond line paste adhesive joints to two spar webs and at the trailing edge to complete the structure. This structural concept has demonstrated high load carrying capacity and long service life under conditions similar in severity to those encountered in aircraft structure.

2 Types of wing structure

Wing design is free from many constraints which exist in fuselage design like: passenger doors, windows, payloads, empennage and engine attachments, etc. For this reason the wing structure can be designed optimally for the dominant load, which is aerodynamic lift, and the torsional stiffness required to avoid flutter. Due to the wing structural simplicity, once the skin design is selected, there is a unique internal substructure which is appropriate.
There is a limited number of design concepts. In this article we will outline a method to evaluate the weight and cost of each one of the design concept families.

This kind of evaluation is important in the preliminary design phase.
Interestingly very few studies on this subject are to be found in literature, [2] : [5].
The wing concepts can be best classified according to the load path through the skin, see figure 1.

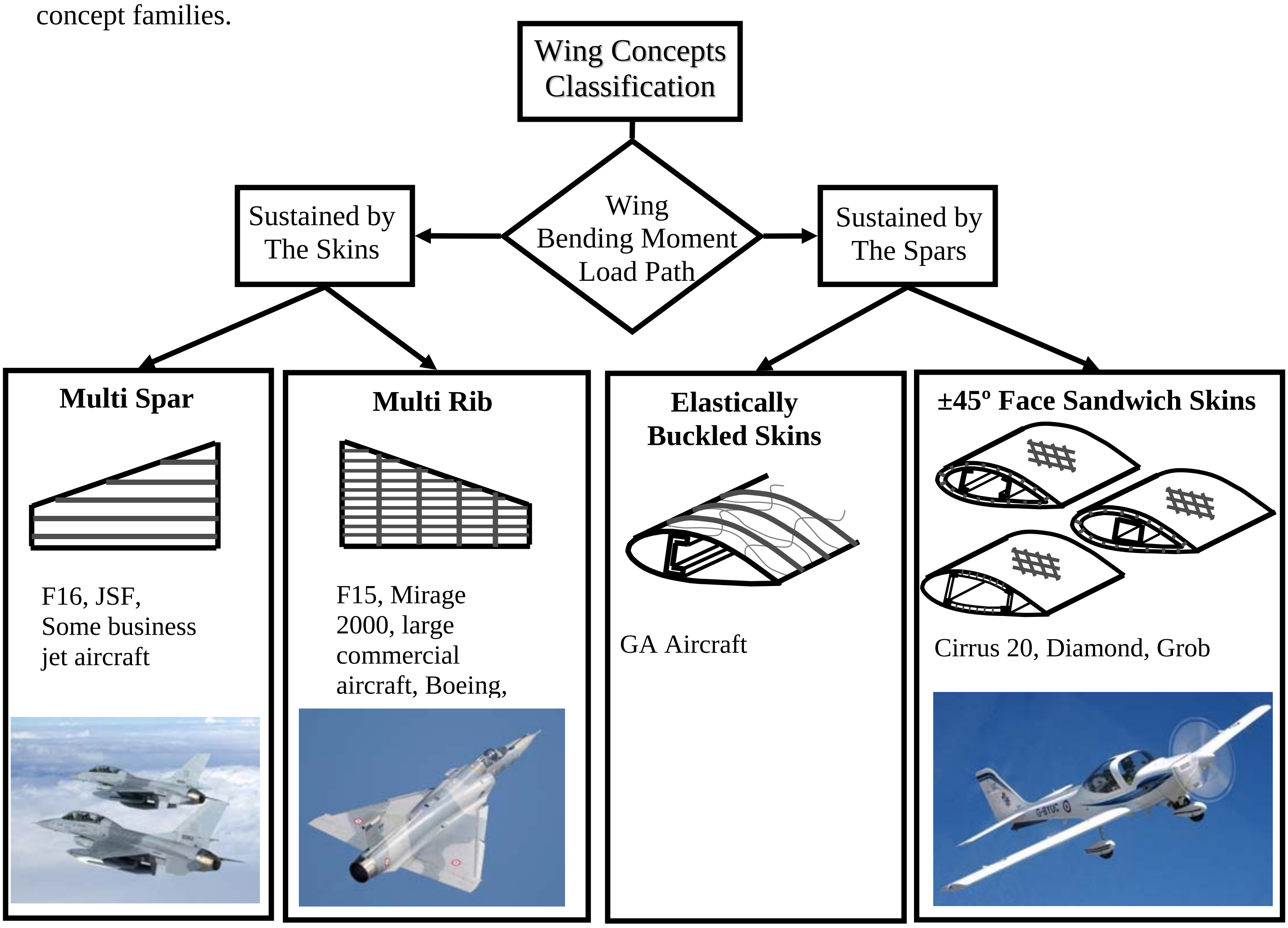


Fig.1: Wing Structure Classification

The way that the various structural options function should be understood before selecting a concept appropriate for the particular wing design. For instance, the limiting criterion for both multi rib and multi spar concepts is skin buckling. Therefore the skin thickness and the weight is directly determined by the skin stability requirement.

By contrast, sandwich construction will not buckle if the sandwich core is thick enough. The core material is usually lighter by two orders of magnitude than the skin material. Therefore, a sandwich skin is much lighter than multi rib or multi spar skins.

2.1 Multi spar

As shown in figure 2, if the bending moment is sustained by the skins, the wing concept will be either multi spar, with stiffened skins; examples are many fighter aircraft, F16, F35 and some business jets,

$$\sigma_{CR\_Plate\_Buckling} = \frac{k \cdot \pi^2 \cdot E}{12 \cdot (1-\gamma^2)} \cdot \left(\frac{t}{b}\right)^2 \qquad (1)$$

$$t = \frac{M}{H \cdot B \cdot \sigma_{CR\_Plate\_Buckling}} \qquad (2)$$

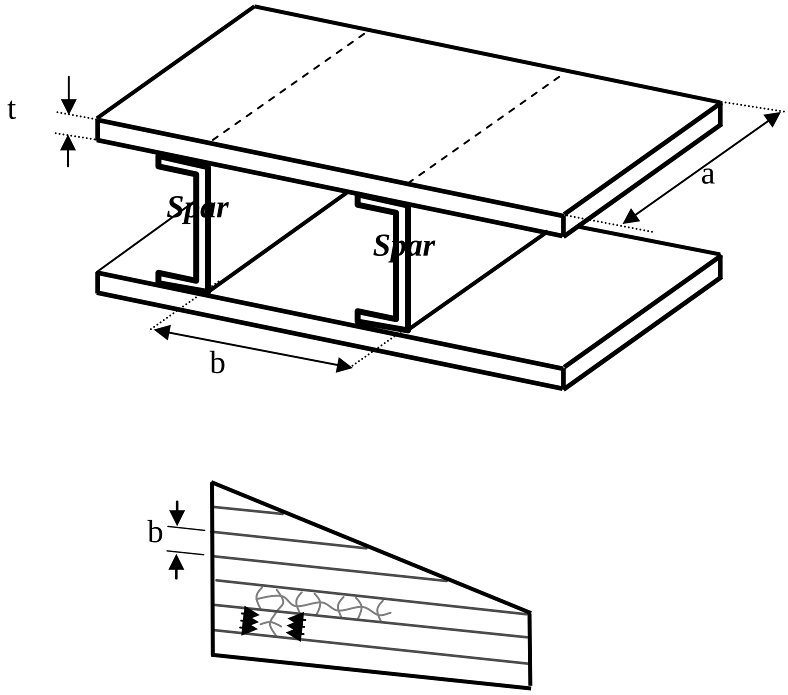
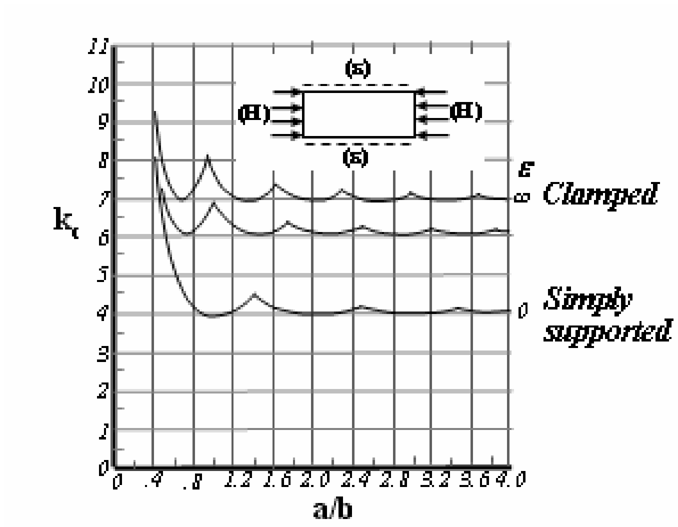


Fig. 2: Multi Spar



k, Coefficients with various edge rotational restraints (Compression).

The length "*a*" does not affect *k*, which is constant for "*a/b*"; therefore there is no need for ribs.

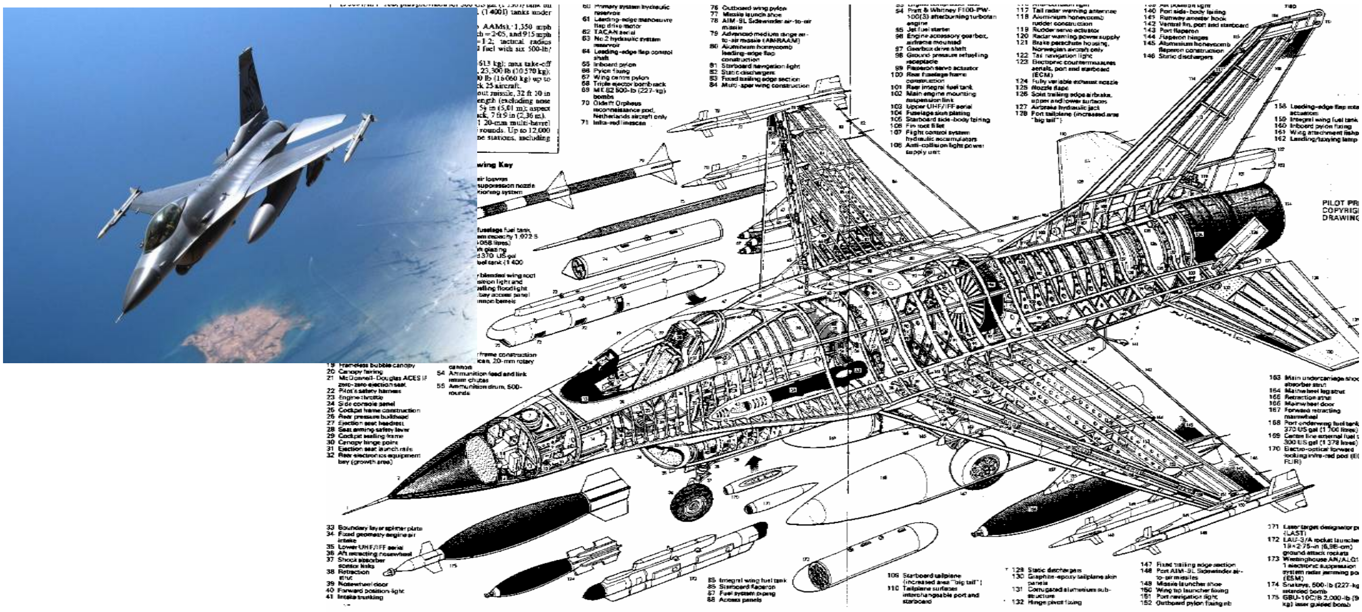


Fig. 3: F-16 (Multi Spar)

2.2 Multi rib

Or multi-rib, with stiffened skins; examples are almost all large commercial aircraft, business aircraft and some fighter aircraft like F15, Mirage 2000 etc.
The theory of primary failure for this type of structure was first developed by P. Seide and M. Stein, and confirmed by an experimental study [2] [4].
The dominant mode of failure in this structure is Euler buckling. In this case there is no need for spars but the ribs are needed to avoid buckling.

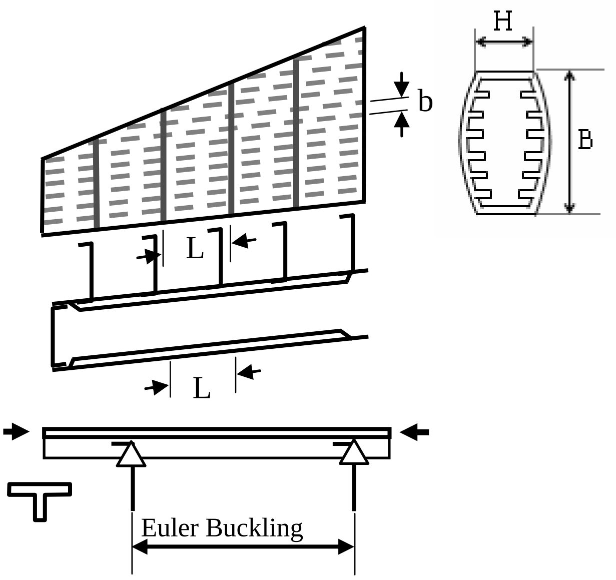
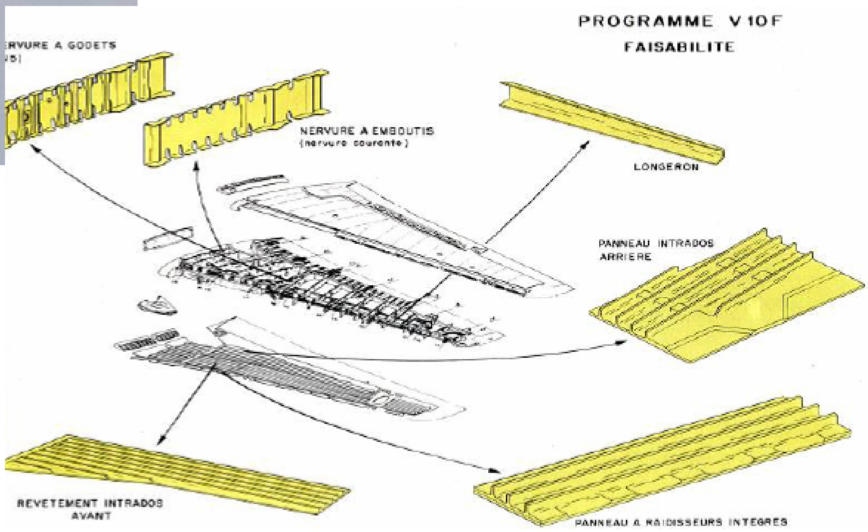


Fig. 4: Multi Rib

$$P_{CR} = \frac{k \cdot \pi^2 \cdot E \cdot I}{L^2} \qquad (3)$$

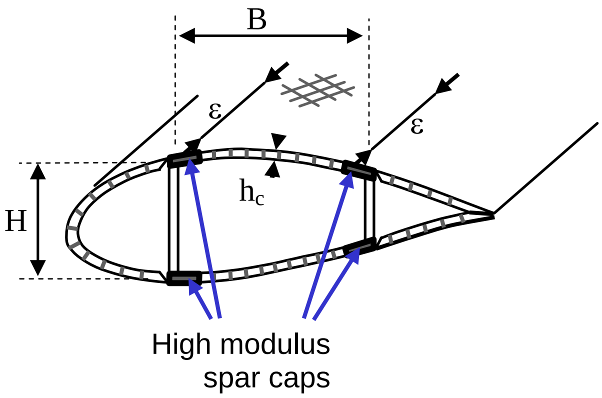
$$t = \frac{M}{H \cdot B \cdot \sigma_{CR\_Euler\_Buckling}} \qquad (4)$$

Fig. 5: Falcon 10 (Multi Rib)



2.3 Sandwich Skin Composite Wing

Sandwich Skin Stability



ε_{CR} - Sandwich buckling critical strain

h_c - Sandwich core thickness

B - Distance between the spars

$$\varepsilon_{CR} \sim \left(\frac{h_c}{B}\right)^2 \quad (5)$$

Is a function of core thickness only

$$\varepsilon_{CR} > \varepsilon_{ULT} \quad (6)$$

(Does not affect the weight)

Area of spar cap A

Wing weight ~ A

$$A = \frac{M}{\sigma_{ULT} \cdot H} = \frac{M}{\varepsilon_{ULT} \cdot E \cdot H} \qquad (7)$$

ε_{ULT} = 4500 μs

E – Cap elastic modulus

Fig. 6: Wing Ribs with Fuel Passages

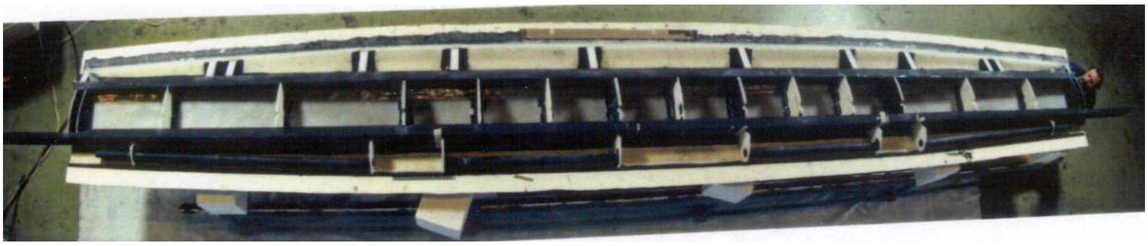


Fig. 7: Lower Wing without Upper Skin

3 Selection of wing structural concepts

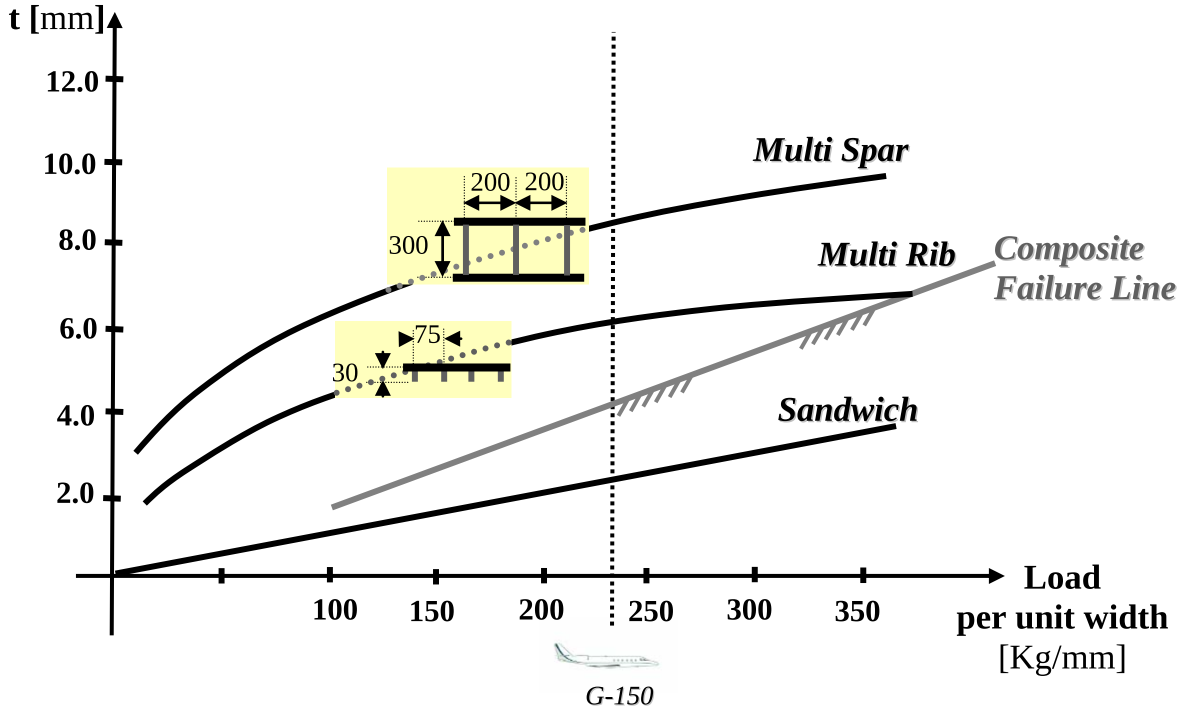


Fig. 8: Load – Thickness Curves for Composites

4 The weight, cost and optimum efficiency of sandwich concepts

The advantages of sandwich construction are best illustrated in wind turbine blades. Large wind turbine blades are in many respects structurally similar to a fixed wing. Due to the competitive market requirement for low cost (7.5 $/Lb), wind turbine blades are usually designed as sandwich structure.

The low cost is achieved by reducing to zero the number of ribs, and by using thick paste adhesive joints instead of mechanical fasteners. The thick paste adhesive is used as an attachment as well as a gap filler. Dimensional mismatch tolerances between the skin and spar are increased from the ~ 0.2 mm typical for wing design to ±5 mm. The application of design and assembly concepts for wind turbine blades to aircraft wings produces a predicted reduction in the cost of wing assembly by about an order of magnitude, compared to conventional aircraft industry practice.

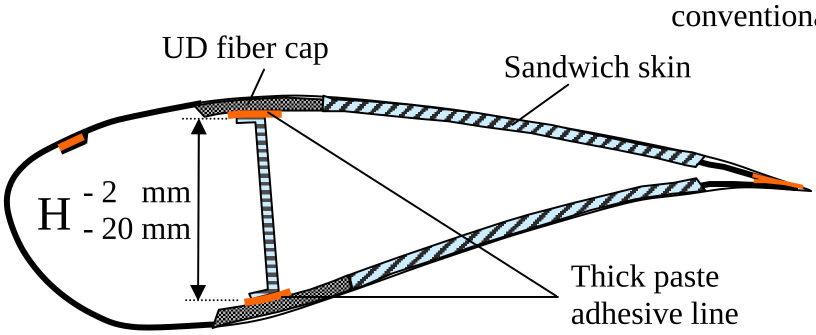


Fig. 9: Turbine Blade – Typical Design

5 Thick paste adhesive

The use of paste adhesive bonding is a key technology which is necessary for the effective introduction of the sandwich concept.

Paste adhesives enable substantial dimensional tolerance mismatches between the faying surfaces of the physically large details during bonded assembly of sub-components of blades, such as spars and internal details, to the shells. Paste adhesives can conform to the resultant variable bond line thickness. Also, paste adhesives usually cure at low temperatures, simplifying tooling and manufacturing processes.

Little data is available on many technical aspects of unconventionally thick bond lines, additional to basic strength parameters. The effects of bond line thickness on long term service behavior, especially damage tolerance and fatigue, are largely unknown. Also, maintaining positional stability of very thick bond line adhesive layers prior to gel is not straightforward. This stability is frequently achieved by additives to the adhesive such as fumed silica, chopped glass fibers and more recently various nano-sized additives that generate thixotropic behavior. Knowledge of these aspects is vital to the design process and the certification of structures for service use.

The influence of adhesive bond line thickness on joint strength has been investigated in many studies, e.g. [7], [9] and [11], and is typically of the form shown in figure 10.

In this study, a series of paste adhesive formulations was evaluated, initially by flexure testing of notched ENF, MMF and DCB coupons. This was followed by design, manufacture and test of scaled demonstrators representative of an aircraft wing torsion box. The demonstrator comprised two sandwich shells with embedded integral spar caps, bonded by thick paste adhesive joints to two spar webs such that the shear load path was through the bond lines. Loads were applied via three conformal frames bonded externally to the torsion box. Care was taken in the demonstrator design to ensure that failure occurred in the bond lines and distant from the load introduction points, so providing a realistic test of the structural concept.

Several demonstrators were tested, with and without bond line defects and with and without nano-additives to the adhesives. Results were compared with the coupon test data and assessed by finite element analysis to provide a better understanding of the thick bond line failure process.
The conclusion from this work and from many others [7] [8] [9] [10] [11] is that the strength reduction with increased bond line thickness is not dramatic.

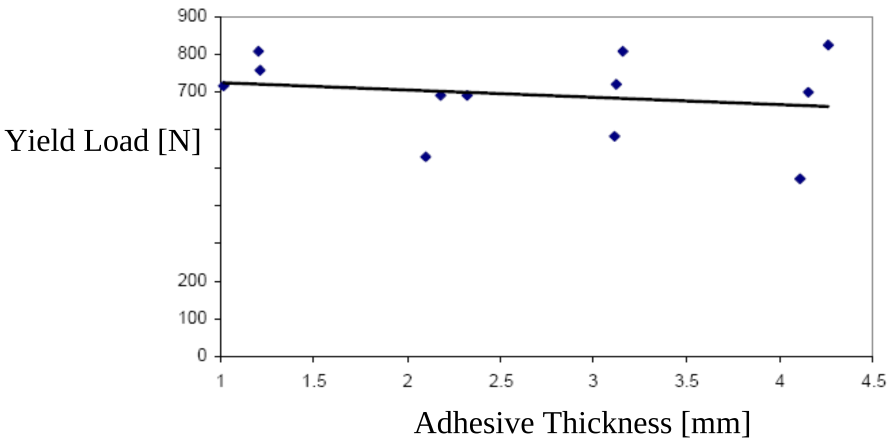


Fig. 10: Yield Load vs. Adhesive Thickness

6 Conclusions

In this study, the structural concepts for aircraft wings have been compared. The possibilities presented by the combination of composite materials and thick bond line bonded sandwich construction have been explained. This innovative (for the aircraft industry) combination enables effective use of composite materials with consequent weight and cost advantages.

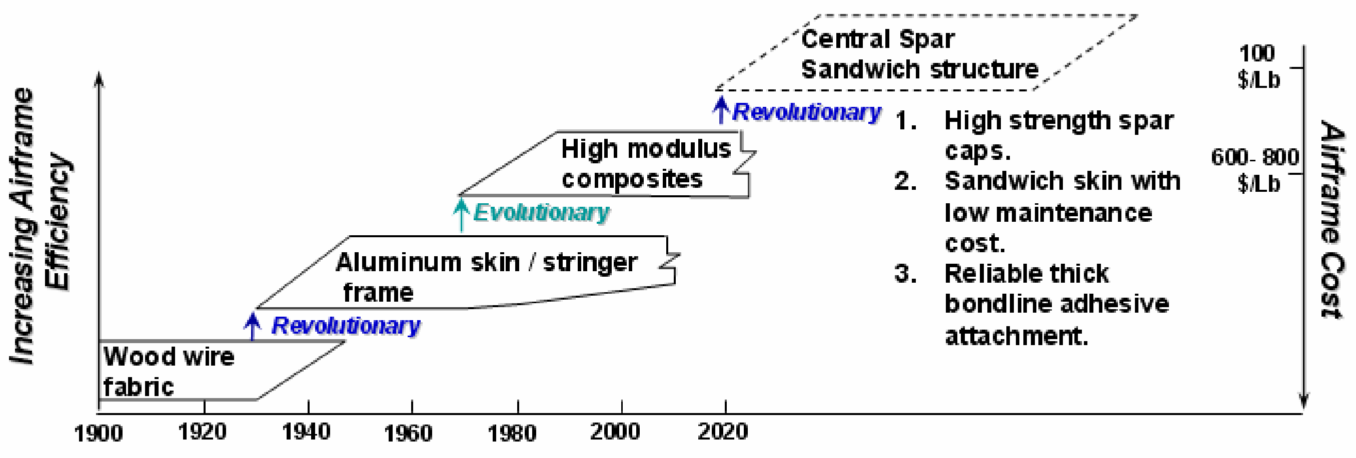


Fig. 11: Revolutionary versus Evolutionary Design Advancement of Airframe Structures

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