ICAS-86-4.2.1

THE DESIGN AND CONSTRUCTION OF A POST BUCKLED CARBON FIBRE WING BOX STRUCTURE

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Abstract.

Design and construction techniques are developed for a post buckled carbon fibre reinforced plastic (cfrp) wing box to be used on an aerobatic light aircraft. Following studies of post buckled stiffened panel behaviour and the evaluation of various design techniques, a wing box structure has been designed. Construction techniques have then been developed and appraised so that the wing box can be manufactured easily and that the expected high structural efficiency can be realised in practice.

Notation.

P_{cr}	Buckling load of skin element.
P_x	Load in x direction (major loading axis)
P_y	load in y direction
τ_{cr}	critical shear load
P_s	load due to stiffeners
P_{tot}	total panel load
a	length of skin elements
b	width of skin elements
t	skin thickness
D_{11}-D_{33}	bending stiffness matrix terms for skin
H	elastic constant defined by eq.7
E_s	stiffener cap material modulus
E_{11}	major loading axis modulus
E_{22}	transverse modulus
E^*	effective post buckled modulus
ν_{12}	poissons ratio
G_{12}	shear modulus
W	total panel width
A_s	stiffener cross sectional area per unit width
d	stiffener depth
EI	total panel column stiffness
ε	strain
u	displacement

Introduction.

Post buckled wing box structures in composite materials can provide significant weight savings compared to non buckled designs. This is due to the technique of locating the wing bending material in concentrated areas of unidirectional fibres. The skin panels can then be allowed to buckle without overall failure of the structure occuring, as the stiffeners take proportionally more load than the skin. Loading can then be increased until column failure of the stiffeners occurs. This mode of failure may interact with the local buckling of the panel to reduce the buckling load. Failure may also occur because of skin/stiffener delamination due to excessive local buckling of the skin panels causing peeling loads, or due to failure of the material itself.

Design techniques.

The first requirement for designing such a structure is to be able to predict the behaviour of postbuckled stiffened panels. It is desirable that any design technique to be used in the initial stages should be quick and simple to use, so that parametric studies can be made of structural configuration. The initial design technique may also be used as part of an opimisation loop to find the best layout. Data generated from experimental work by Belgrano (1) was used in assessing the accuracy of three design techniques.

Finite element methods.

Using the finite element program LUSAS, one of the experimental panels was modelled. Semiloof 8 noded thin shell elements were used to model the skins and stiffener walls. Isotropic 20 noded solid semiloof elements were employed to model the stiffener cores as shown in fig. 1.

A geometrically non-linear analysis was performed using incremental displacement of the panel ends. This is an analysis technique where the stiffness matrix of the structure is updated at each incremental end displacement. Although imperfections were not introduced, the model started buckling as a result of out of plane bowing. This was caused by the difference in stiffness between the stiffener caps and the panel skin.

This method gave a detailed insight into the performance of the panel with good accuracy as can be seen in fig. 2. The reactions from the panel end nodes could be analysed, showing the way in which the stiffeners took up increased loading after the skin panels had buckled, as shown in fig. 3.

The disadvantage of this form of

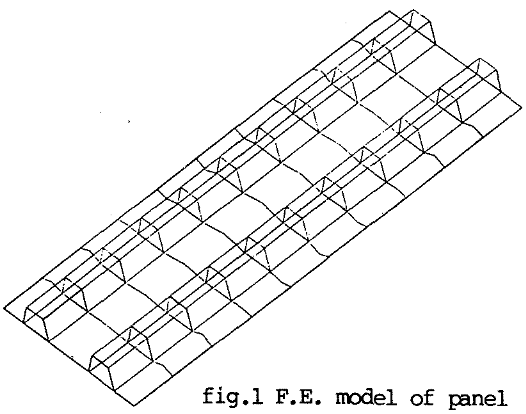

fig.1 F.E. model of panel

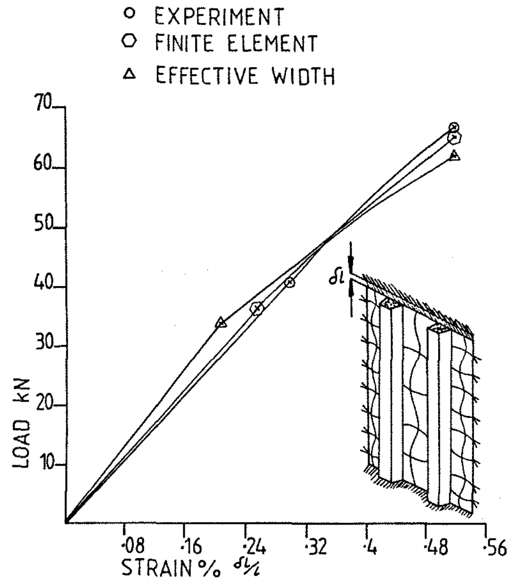

fig.2 3 design methods for panels

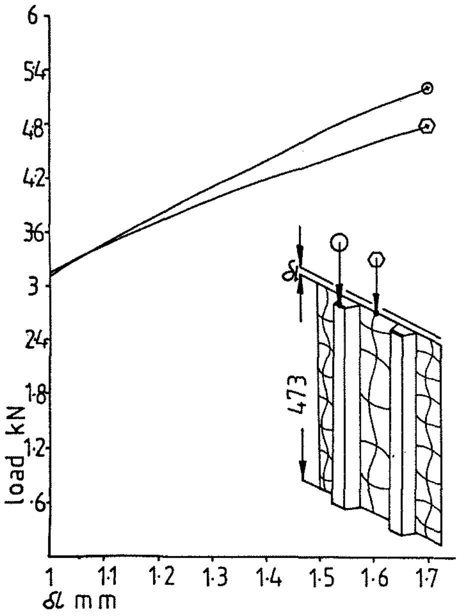

fig.3 F.E. node reactions

analysis at present is in the long computer processing time and large memory requirements required. This is because the structure has to be solved at each incremental displacement in order to build up the load/displacement curve. This factor made it impractical to analyse a box structure in this way, as the DEC VAX750 machine took 13 hours of CPU time to analyse the panel only.

Finite strip analysis.

The computer program PASCO was also used (4). This uses a finite strip method to determine the buckle shape across the plate. The plate is built up from repeating elements which are then linked together to form the desired cross section. PASCO is a program which incorporates VIPASA, the actual buckling analysis, in a method of structural optimisation. This can be used to optimise the panel at the point of buckling. The design solution tends towards the use of deep, very closely spaced stiffeners if allowed to optimise without constraints.

This program is quick to use and accurate at the point of buckling. The disadvantage is that the program cannot analyse post buckled panels.

Orthotropic plate equation with effective width concept for post buckling.

This analysis was used by the author as a means of quickly sizing post buckled specially orthotropic panels for initial design purposes. As a program for use on a 48k microcomputer, it was later developed to optimise the spacing of ribs and stiffeners. It was found to give results to a good engineering accuracy.

In the experimental results for all of the test panels in ref.1 it was noticed that due to the torsionally stiff nature of the stiffener design, they tended to remain stable up to overall column failure. The only effect of the stiffeners was in taking up relatively more of the panel loading as the skin panels buckled. For these reasons it was assumed that the stiffeners could be considered to be a linear - elastic part of the structure until overall failure occured.

The behaviour of the whole stiffened panel was thus approximated to be that of a series of plates which would locally buckle, held in simple support at each side by a series of linear - elastic stiffeners.

Buckling of the skin panels.

Compression.

The length of the panel is allowed to vary, and the buckling load is determined for simple-support conditions by the equation below, which has been derived from the differential equation describing the free vibration of a specially orthotropic plate.

$$P_{CR} = \frac{\pi^2}{b}\left\{D_{11}\left(\frac{b}{a}\right)^2 + 2\left(D_{12}+2D_{33}\right) + D_{22}\left(\frac{a}{b}\right)^2\right\} \quad (1)$$

Shear.

The critical load on the plate for shear buckling is given by the equations below, also derived from the overall plate differential equation, from ref.2.
When D11D22>(D12+2D33)↑2,

$$\tau_{CR} = \sqrt{\frac{2D_{22}\left(D_{12}+2D_{33}\right)}{(b/2)^2 t}}\left\{8.3 + 1.525\frac{D_{11}\,D_{22}}{\left(D_{12}+2D_{33}\right)^2} - .493\frac{D_{11}^2 D_{22}^2}{\left(D_{12}+2D_{33}\right)^4}\right\} \quad (2)$$

When D11D22<(D12+2D33)↑2,

$$\tau_{CR} = \frac{\sqrt[4]{D_{11}\,D_{33}^3}}{(b/2)^2 t}\left\{8.125 + 5.64\sqrt{\frac{\left(D_{12}+2D_{33}\right)^2}{D_{11}\,D_{22}}} - .6\,\frac{\left(D_{12}+2D_{33}\right)^2}{D_{11}\,D_{22}}\right\} \quad (3)$$

Interaction.

From Leknitski (5) it has been shown that the plate buckles when:

$$\frac{P_x}{P_{xCR}} + \frac{P_y}{P_{yCR}} + \frac{P_{xy}}{P_{xyCR}}^2 \geq 1 \quad (4)$$

Displacement and strain.

The displacement of the plate in compression at buckling is given by:

$$u_{CR} = P_{xCR}\frac{a}{t\,E_{11}} \quad (5)$$

from which the strain at buckling follows from:

$$\varepsilon_{CR} = \frac{u_{CR}}{a} \quad (6)$$

Post buckled stiffness.

This is analysed using the approach found in ref.3.
First the elastic constant H is found:

$$H = \left(\frac{1}{G_{12}} - \frac{2\,\upsilon_{12}}{E_{11}}\right) \quad (7)$$

This is applied to the following equation for the reduced stiffness of a simply supported plate:

$$\frac{E^*}{E} = \frac{2 + \left(1 + E_{11}\,H(b/a)^2 + 3\frac{E_{11}}{E_{22}}\left(\frac{b}{a}\right)^4\right)}{2 + 3\left(1 + E_{11}H(b/a)^2 + 3\frac{E_{11}}{E_{22}}\left(\frac{b}{a}\right)^4\right)} \quad (8)$$

The effect of stiffeners.

The stiffener areas and properties are then superimposed on those for the skin panels to obtain the whole plate stiffness. This can be determined at the point of buckling, and for any desired strain level above this.
The stiffener area is assumed to be 90% unidirectional fibres in the stiffener cap only. The area neglected is assumed to be 45 degree fibres in the stiffener sides, which constitute shear webs. These are assumed to carry insignificant compression load, as shown in the finite element analysis.

The loading due to the stiffeners is thus:

$$P_S = A_S\,E_S\,u \qquad N/M \quad (9)$$

so that the total panel loading per unit width is given by:

$$P_{tot} = \frac{P_S}{1000} + W P_{SKIN} \qquad KN/M \quad (10)$$

Overall buckling of the panel.

Here the stiffener/skin combination is considered to act as a beam in the overall Euler mode. The skin and stiffener caps are assumed to be thin so that the second moments of area are calculated from the centroids of their areas.
The second moment of area of the panel is:

$$EI = A_S\left(\frac{d}{2}\right)^2 E_S + tw + \left(\frac{d}{2}\right)^2 E_{11} \quad (11)$$

From which the critical length for overall panel failure is found from:

$$L = \sqrt{\frac{\pi^2 EI}{P_{tot}\times 1000}} \qquad M \quad (12)$$

This is used to determine the rib pitch required.

Weight of the panel.

The stiffeners are assumed to be of square cross section, and to be filled with 71 kg/m^3 foam. The stiffener walls are assumed to be half the thickness of the skin panels, and the stiffener caps to be 1.5 times as thick. These ratios are close to those employed in the stiffened panels which have been optimised in ref.1.
Knowing the density of the composite material, the weight of the panel per unit area is easily determined.

This technique was used to size the skin panels from running loads obtained by engineers' bending theory. It was also used to find the degree of reduced stiffness of the skin panels after buckling. These skin sizes and reduced stiffness values were then applied to a linear finite element analysis of the whole structure to check deflections and strain levels under load when in a post buckled condition, as seen in fig. 4.

These methods have been used to size the structure prior to finite element analysis of the complete wing box. The finite element model (fig 4) incorporated reduced stiffness properties for the skin panels derived from the above analysis. By this means the effect of buckling could be modelled over the whole structure.

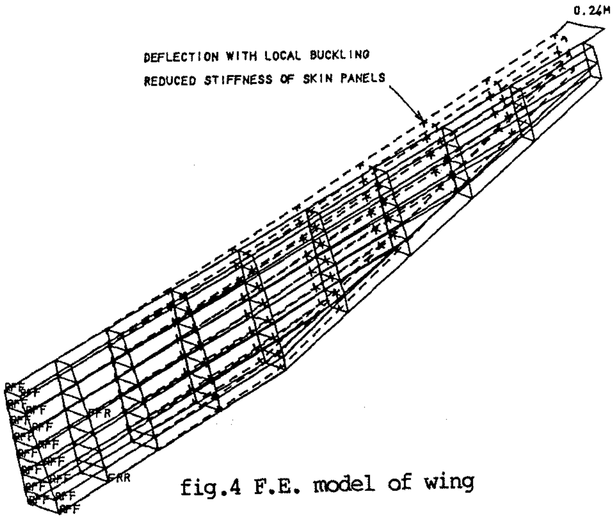

fig.4 F.E. model of wing

Design philosophy.

The post buckled concept is central to this work, and so a configuration of buckled skin panels stabilised by ribs, stiffeners and spars had to be realised in practice. In the case of this wing, the values of shear loading in the spar shear webs is low so that a multiple spar design would result in impractically thin guages for the shear webs. For these reasons a single cell torsion and bending box with stiffened skin panels was designed to take the major loads.

Construction techniques.

Panels.

The construction techniques for producing panels incorporating co-cured, foam cored, trapezioidal section stiffeners have been well proven in ref 1. The use of an enclosed section for the stiffeners in post buckled design is important. Due to the high torsional stiffness of the stiffeners, stiffener rolling and consequent failure due to modal interaction of local and stiffener flexural buckling may be avoided. The desired mode of failure is by column buckling at or near to 0.4% axial strain.

Construction of these foam cored stiffeners is relatively straightforward as the foam is used as tooling to maintain the desired cross section during curing. After cure, the foam remains in position and helps to stabilise the stiffener walls. In order to acheive good compaction of the laminate at the stiffener/panel junction, silicone rubber presssure intensifiers are used. A layer of polytetraflouroethylene (PTFE) cloth release film is placed between these and the laminate to avoid silicone contamination of the epoxy matrix.

Ribs.

The original design concept was to produce a box structure by curving flat skin/stiffener panels over ribs. The ribs would then be bonded to the skins along the rib flanges. The ribs were designed as flanged mouldings in CFRP at +-45 degrees to the fore and aft axis as it was intended that the bending material would be built into the panel skins at the rib stations. The rib flange was continuous so that a bond could be made to the panel and stiffener surfaces, so maximising the bond area.

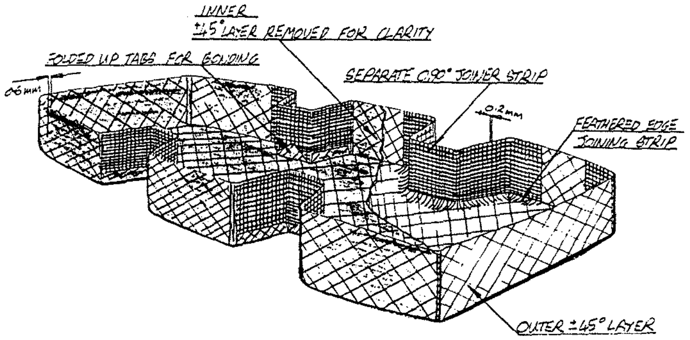

fig.5 rib design

Using channel section spars, the ribs were firstly bonded to these components by using a high viscosity cold curing epoxy adhesive. This operation was easy, but the bonding of the ribs to the skin presented more difficulty. Problems were encountered in build-up of tolerances between the rib flange and stiffener profiles. Difficulty was also experienced in clamping the joint effectively. Eventually blind rivets were used here to close the joint, with aerodynamic penalties.

Co cured design.

To solve these problems a new means of construction has since been developed whereby the rib flanges are produced integrally with the stiffened panels. Tooling for these is produced by means of setting a template of the desired rib flange against the tool surface which has sections of dummy stiffeners placed onto it (fig 6).

Starting with a very fine tissue of glass rovings, a wet laminated glass or carbon fibre contact moulding is produced which follows the form of the rib/stiffener/skin junctions. The moulding is then cut at the apex of each stiffener into segments, so that variations in thickness of the CFRP part to be produced can be accomodated.

The stiffened panel is then produced as shown in fig 7. The panel skin laminations are firstly positioned on the tool, followed by the stiffener cores, stiffener cap unidirectional

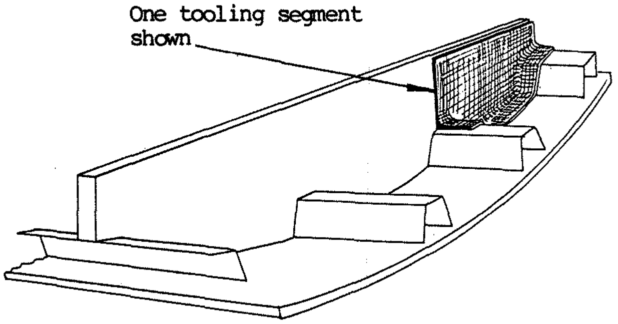

fig.6 tooling for ribs

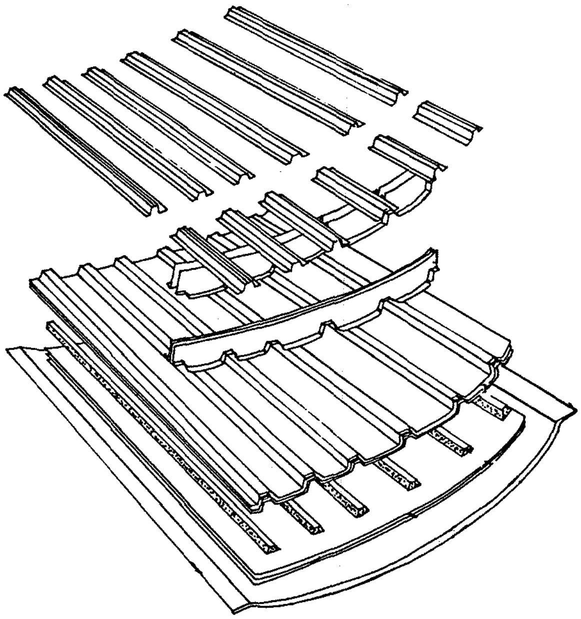

fig.7 panel components

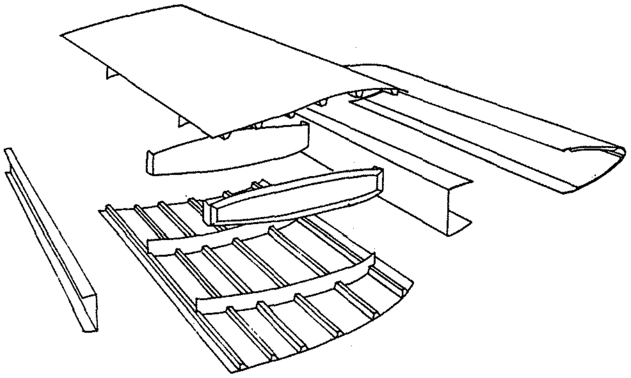

fig.8 box assembly

material, the rest of the skin laminations and finally the rib flange laminations. The flange laminations spread out in both directions on contact with the panel to prevent peel failure of the joint. The rib tools are then placed in position, spray coated with a PTFE release agent. These are followed by a PTFE release cloth and the pressure consolidators for the panel stiffeners. After these parts have been positioned, the whole assembly is covered in a glass wool bleeder pad to ensure equalisation of the vacuum and to prevent vacuum bag failure through bursting against sharp edges. The fact that the vacuum bag bridges across the corners at the stiffener/rib junctions is of no consequence as the pressure is carried by the tooling in these areas. The whole assembly is enveloped in a vacuum bag for subsequent autoclave curing at a pressure of 40-50 psi and 120 degrees C.

Assembly of the box.

Although production of the skin panels is more complex, assembly of the box is much simplified and structural integrity improved by this process, as shown in fig 8. The ribs are now joined to the panels at their shear webs, where a large shear loaded bond can be readily made. Location and clamping devices such as rivets can be incorporated without compromise to the aerodynamic performance of the wing.

Once the panels have been joined to the ribs, the leading and trailing spars are added. To avoid the problem of bondline failure caused by local buckling of the adjacent skin panel, the spars join the skin at panel stiffeners. In this way the bond area is stabilised against peeling loads. The stiffeners here are also specially shaped so that the spars bond to the stiffener sidewall as well as the panel skin.

Spars.

A foam stabilised spar is being used following problems experienced when shear buckling of the spar shear web interacted with compression buckling of the adjacent compression panel. This effect tended to increase the problem of peel loads arising at the spar flange to skin bond.

Experimental programme.

A box structure has been constructed and tested to the original design, with results shown in fig 9. This showed that post-buckled structure has potential in practice, as full elastic recovery was demonstrated through several load/unload cycles to proof load. The fatigue life of such a structure should also be better than in aluminium because of the superior fatigue charecteristics of the material itself and the bonded construction.

Following experience gained with this box, a second structure incorporating the co-cured techniques described above has been constructed, which is currently under test. The work will culminate in the production of a full scale wing box 4m long for static load, acoustic emission and damage tolerance testing.

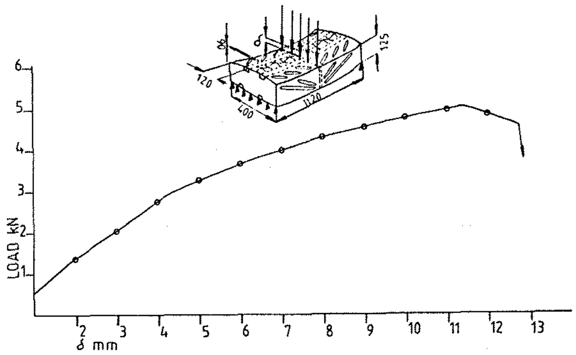

fig.9 test box results

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The work has been supported by the MOD, under agreement no. 2028/0153 XR-STR, RAE Farnborough.