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Buckling Alleviation for Joined-Wing Aircraft

Luke A. Lambert,[*] Jonathan E. Cooper[†] and Raj K. Nangia[‡]

University of Bristol, BS8 1TR, United Kingdom

A novel mechanism is described that increases the critical buckling load of the rear wing of joined-wing aircraft, in an effort to reduce structural weight. The benefits of the joined-wing configuration are briefly discussed, along with its current limitations. The behaviour of the modified structure under lift is investigated by conducting a number of linear structural analyses for varying geometric arrangements. It is shown that the mechanism, called the Buckling Alleviation Component (BAC), is effective in reducing structural weight for a significant proportion of aircraft geometries, even though there is a trade-off between rear wing buckling load and front wing root bending moment. A more detailed structural model is used to investigate the effect of geometric structural nonlinearities. The nonlinear analysis shows that the BAC delays the onset of nonlinear behaviour and that the critical buckling loads of the conventional configuration are drastically overestimated by the linear analysis, which means that BAC performs much more effectively than the initial linear analysis suggests.

Nomenclature

C_L	Lift coefficient	j	Non-dimensional spanwise join location, s_{rw}/s
H_j	Height of join location	l_{BAC}	Non-dimensional BAC length, L_{BAC}/s
H_t	Height of tail	s	Semi-span
L_{BAC}	Length of BAC	*Symbols*	
M_r	Root bending moment of front wing	α	Sweep angle of front wing
M_r'	Normalised wing root bending moment,	β	Sweep angle of rear wing
	$M_{r\,JW}/M_{r\,CW}$	$Æ\!R$	Aspect Ratio
P_c	Critical buckling load of rear wing	*Subscripts*	
V	Volume of structural material	fw	Front wing
X	Horizontal distance between wing roots	rw	Rear wing
	(Excluding BAC length)	CW	Conventional Wing Configuration
h_j	Non-dimensional join height, H_j/H_t	IN	Inboard section
h_t	Non-dimensional tail height, H_t/X	JW	Joined-Wing Configuration

[*]Research Associate, Department of Aerospace Engineering. `l.a.lambert@bristol.ac.uk`

[†]RAEng Airbus Sir George White Chair of Aerospace Engineering, Department of Aerospace Engineering, AFAIAA.

[‡]Honorary Research Fellow, Department of Aerospace Engineering.

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I.   Introduction

THE Joined-Wing aircraft configuration was first introduced by Wolkovitch in 1976 [1] and has been considered in recent years for the design of Unmanned Aerial Vehicles (UAVs) such as Boeing's SensorCraft [2, 3, 4]. In light of much research regarding the achievability of its proposed benefits, this unconventional configuration has not been accepted as a viable design option for transport aircraft. However, the growing demand for lighter, more efficient and environmentally friendly passenger jets is pushing conventional configurations to the limits of their performance, to the extent that they may soon be unable to meet these demands.

Research carried out in the last few years [5, 6, 7] has put forward the joined-wing as a possible solution to this problem by attempting to design medium-range joined-wing passenger jet concepts (see Fig. 1) that are superior to current conventional aircraft such as the Airbus A320 and B737. All of these studies boast significant reductions in induced drag and structural weight, resulting in increases in design range of around 15-20% [5, 6] due to the added fuel efficiency. The increase in efficiency is largely due to the ability of joined-wings to accommodate high-aspect ratio wings, improving the aerodynamic performance, without suffering the weight penalties of conventional cantilever-wings. In addition to these benefits, further claimed [8] advantages of the joined-wing include reduced wetted area and parasite drag, a high trimmed C_L max, high stiffness and good stability and control.
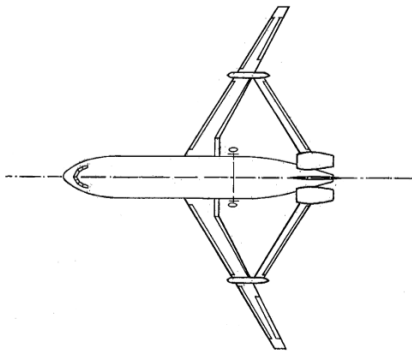

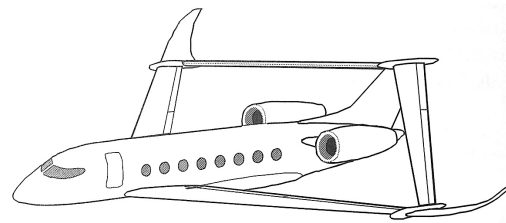Figure 1. Joined-Wing Medium-Sized Passenger Jet Concept [5]   Figure 2. Joined-Wing High Speed Executive Jet Concept [9]

It is important to carefully define what is meant by a 'joined-wing' aircraft, since it has often been used to describe a wide range of aircraft configurations that are quite different from that of Wolkovitch's original patent [1]. For example, the Prandtl Plane, or Box-Wing configuration, for which many good structural and aeroelastic studies have been carried out [10, 11, 12, 13, 14], is often referred to as a joined-wing aircraft, even though it does not share some of the particular characteristics of the original joined-wing. Figures 2 and 3 show respective examples of joined-wing and Prandtl Plane concepts, that illustrate some of the key differences, such as the presence of vertical connecting elements that produce side-force induced drag; the original joined-wing, however, forms a diamond shape in both plan view and front view. Prandtl Planes also typically have overlapping front and rear lifting surfaces, which should not be the case for joined-wings [9]. They typically have lower sweep (adversely affecting longitudinal stability), lower overall aspect ratios and lower fuel volume than the joined wing, as well as being restricted to tip-joined configurations, whereas the

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span-wise join location can be varied for the original configuration, as shown in Figure 2. These distinctions mean that the type of structure considered in this paper cannot necessarily be assumed to exhibit the same behaviour as the Prandtl Plane, even though there are some similarities.
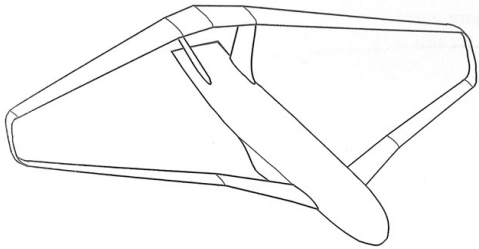

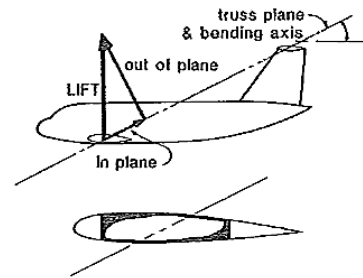**Figure 3. Prandtl Plane Concept of a Large Airliner [9]**   **Figure 4. Tilted Bending Axis of a Joined-Wing Aircraft [8]**

The advantages claimed for the joined-wing are attained by joining the front wing to an out-of-plane rear wing, redefining the global flexural axis and thereby creating a truss structure. Figure 4 demonstrates that the aircraft's tilted bending axis means that out-of-plane wing bending accounts for only a proportion of the total lift. The rest is accounted for by the stiff truss structure formed *along* the flexural axis. This concept drastically reduces the wing root bending moment and hence the overall wing weight, enabling the aforementioned increase in efficiency. However, there are still some major issues that need to be resolved before these improvements are actually within reach. Among these issues, and arguably of primary concern, is the buckling tendency of the rear wing.

When lift is applied to a joined-wing aircraft, deflecting the front wing upwards, the rear wing undergoes compression due to the in-plane component of the lift force. This means that the critical buckling load of the rear wing may have an impact on the final structural weight. Early studies by Gallman et al. [15, 16] showed that when a buckling analysis is carried out, the joined-wing is actually worse than the conventional aircraft, at least in terms of Direct Operating Cost (DOC). The reason for this is that when the buckling load is a critical design parameter, although structural weight is saved on the front wing due to the reduction in root bending moment, weight must be *added* to the rear wing to resist buckling. This negates the effect of the initial weight saving, and since joined-wing aircraft are much more complex to design due to the asymmetric wing box and other issues such as the positioning of landing gear, lower fuel capacity, along with difficulties regarding the prospect of developing a 'family' of aircraft, it is easy to see why the joined-wing has not been accepted as a suitable replacement for current conventional aircraft.

If the buckling tendency of the rear wing could be removed, or at least alleviated to some degree, the possibility of attaining the significant benefits claimed by the joined-wing would be much closer to becoming a reality. This paper presents a preliminary study that seeks to increase the critical buckling load, without adding weight to the rear wing, by introducing the so-called Buckling Alleviation Component (BAC).

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II.   The Buckling Alleviation Component

The Buckling Alleviation Component is simply a horizontal beam connecting the front and rear wings together in a way that reduces the compression applied to the rear wing. As shown in Figure 5, this results in a hexagonal planform as opposed to the diamond shape that is characteristic of the original joined-wing configuration, but the diamond shape in front view is preserved. Figure 6 demonstrates the option to incorporate a pin joint at each end of the BAC. It is important to note that pin joints must only allow rotation about an axis perpendicular to the plane of the rear wing. This ensures that the connectivity of the BAC does not have an adverse effect on the critical buckling load, by making sure the rear wing is essentially clamped at both ends, even if there is a pin joint.

Related work on the buckling behaviour of the Prandtl Wing [10] has explored the effect of a hinged joint that connects a *vertical* component to the rear wing, but it should be clarified that the purpose of this was to prevent the bending moment from transferring from one wing to the other, and as such, the hinge-line was *stream-wise*. In this study, however, the aim is to transfer as much of the bending moment as possible, but to alleviate rear wing compression, and the BAC is an additional *horizontal* stream-wise component with hinge-lines that must be perpendicular to the plane of the rear wing and *perpendicular* to the flow, rather than parallel to it.

There are three possible ways that the BAC can be connected to the front and rear wing (at points A and B, respectively):

(a) Fully fixed at both ends,

(b) Fixed at the front (point A) and pinned at the rear (point B),
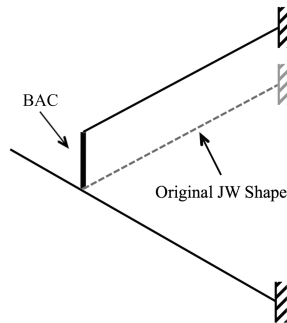
(c) Pinned at both ends.

Figure 5. Plan View of Half-Model Joined-Wing with Buckling Alleviation Component is Hexagonal as Opposed to the Original Diamond Shape
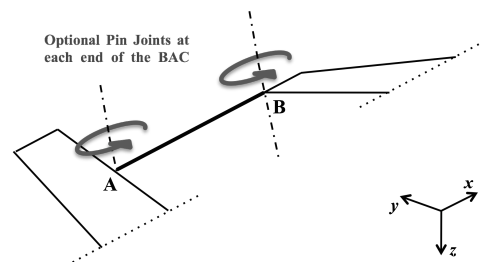
Figure 6. Pin joints at each end of the BAC allow the rotation of points A and B about axes perpendicular to the plane of the rear wing

The reduction in compression is achieved by giving the tip of the rear wing the freedom to move along the plane of the rear wing. When the front wing is deflected upwards, the flexibility of the BAC enables the rear wing tip to remain closer to its original position, as shown in Figure 7. All that remains is to determine which of the BAC connectivity options, (a), (b) or (c), gives the lowest structural loads. Even though it will be argued that (b) is the most effective

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option in general, this may vary for each individual design concept, which is why all three options are included in this paper.
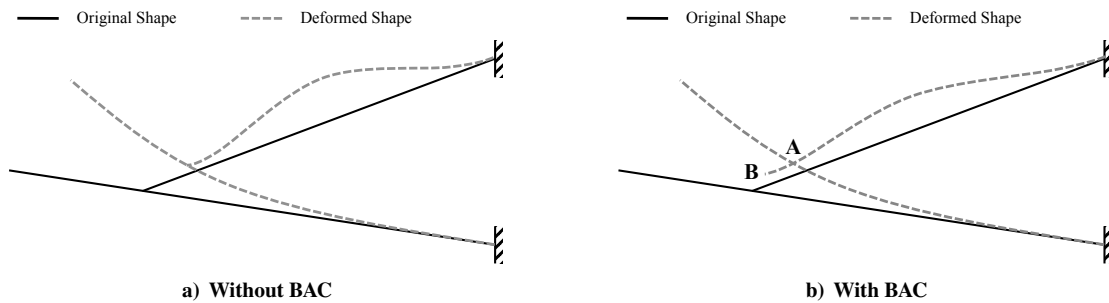

a) Without BAC

b) With BAC

Figure 7. Comparison of (Exaggerated) Deformed Shapes of Joined-Wing from Front View

If the BAC is fixed at both ends (Fig. 8a), it is the flexural stiffness of the BAC that affects the movement of point B in relation to point A. However, if there is a pin joint at B (Fig. 8b), for the same flexural stiffness, the rear wing will not be as compressed because the angle at which it is connected to the BAC is no longer constrained. Further reduction in rear wing compression can be expected if the BAC is pinned at both A and B (Fig. 8c), where the BAC is in tension and carries no moment in the plane of the rear wing. This arrangement allows point B to remain closest to its original position, but dramatically changes the way the aircraft deforms when lift is applied. This is not necessarily a disadvantage but is an important consideration.

a) Fixed at A & B

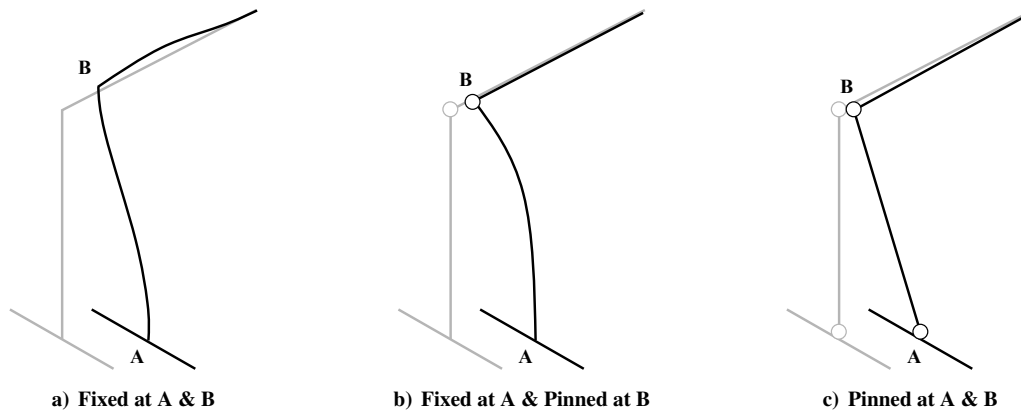b) Fixed at A & Pinned at B

c) Pinned at A & B

Figure 8. Plan View of the Deformed Shapes for the BAC Three Connectivity Options

The purpose of this preliminary study is to make assessment, that is as general as possible, of the effectiveness of the BAC at reducing structural weight. The reduction of the compression on the rear wing does not necessarily mean that weight can be saved. This is because there is a compromise between the increase in critical buckling load, which saves weight, and the resulting increase in the front wing root bending moment, which adds weight. Of course, in order for the BAC to be effective, the weight saving on the rear wing must be larger than the weight increase on the front wing. This means it can be expected that the BAC will be more effective for aircraft that have a higher ratio between rear/front wing weight. Therefore, properties such as the sweep angles, the tail height, the height of the join

location (point A) and the length of the BAC itself, should have an impact on the effectiveness of the BAC. The model used in this study to determine the nature of this impact is outlined in the following section.

It is important to note that, although this paper defines the effectiveness of the BAC purely in terms of structural weight saving, it may offer other advantages such as improved stability and control due to the increased pitching moment. Also, the BAC theoretically allows the aircraft to be 'stretched' to some some degree without the need to completely redesign the wings, which is the main difficulty when it comes to developing a 'family' of aircraft. An assessment of these additional advantages is beyond the scope of this paper, but may be the subject of future research.

III. A General Joined-Wing Beam Model

A. Finite Element Model

In order to determine the aircraft geometries for which the BAC is most effective (if at all), a large number of structural analyses were carried out on a simple beam model, which is shown in Figure 9. The beam cross-sections are constant along the wingspan but different for each wing. The rear wing typically has a higher aspect ratio than the front wing because it generates only a small proportion of the total lift. In this case it was assumed that 15% of the total lift is taken by the rear wing.
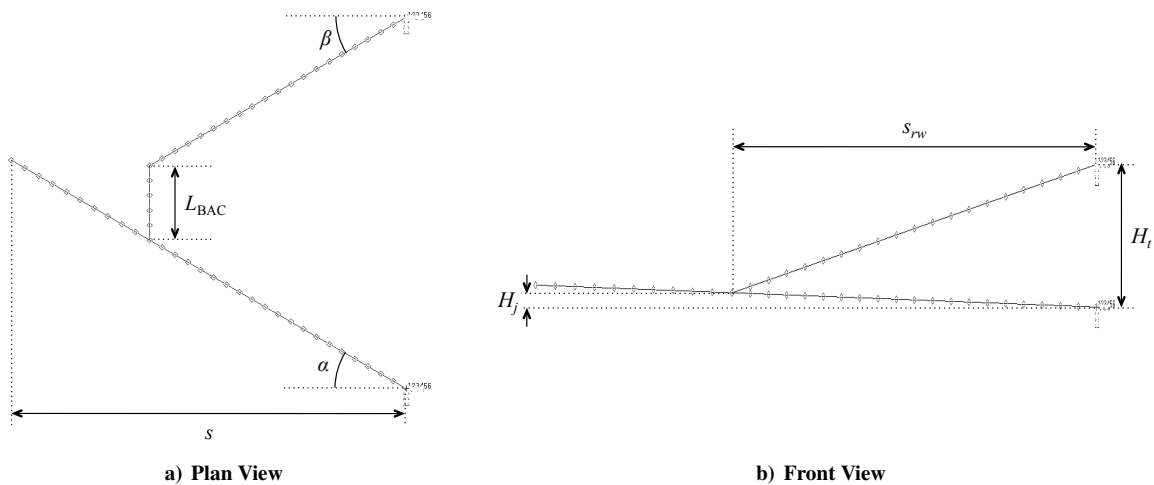

a) Plan View   b) Front View

Figure 9. Finite Element Model of the Joined-Wing with BAC

Even though the model does not contain any aerodynamic elements, the dimensions of the beam cross-section for each wing are defined as proportions of the chord. Since the length of each wing is determined by the properties shown in Figure 9, it is the aspect ratio of an individual wing that determines the dimensions of its wing box. All of the other geometric parameters apart from the semi-span and the sweep angles are non-dimensionalised, enabling the model, and therefore the findings, to be as general as possible.

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B. Structural Analysis

For the structural analysis, there were three parameters for which a range of possible values were considered: non-dimensional BAC length l_{BAC}, non-dimensional tail height h_t, and non-dimensional join height h_j. Also, two join locations were considered: 70% and 100% of the semi-span. All of the the other model parameters were kept constant for every analysis. The values used for some of the key parameters are shown in Table 1.

Parameter	Value	Units
$A\!R_{fw}$	18.0	-
$A\!R_{rw}$	20.0	-
α	30.0	deg
β	30.0	deg
s	12.0	m

Table 1. Values of Key Model Parameters

Variable	Minimum Value	Maximum Value	No. of Values
l_{BAC}	0.0	0.4	20
h_t	0.1	0.4	20
h_j	0.1	0.9	9
j	0.7	1.0	2

Table 2. Ranges of Values Chosen for Each Variable

Table 2 shows that for a single join location, allowing for every possible combination of l_{BAC}, h_t and h_j, 3600 individual structural analyses were carried out. These analyses were performed using the MSC NASTRAN linear buckling analysis (SOL 105). The key assumption to note is that of linearity, i.e. the differential stiffness is assumed to be proportional to the applied load. It has been shown [17, 18] that, in fact, the behaviour of the joined-wing under lift is highly nonlinear due to its inherent flexibility, and the effect of this is considered later.

For each analysis, a total lift of 1 kN (for small deflections) was applied vertically, uniformly distributed across each wing according to the proportion of lift it generated (85% for the front wing and 15% for the rear). The root bending moment of the front wing and the critical buckling load of the rear wing were calculated for each of the 7200 possible structural arrangements.

IV.   Results & Discussion

A.   Behaviour of Modified Joined-Wing Structure

This study is primarily concerned with increasing the critical buckling load of the rear wing, in order to reduce its weight, but the effect of the BAC on the weight of the front wing must also be considered so that the impact on the total weight of the aircraft structure can be determined. Changes in wing root bending moment are a good indication of changes in structural weight for the front wing, but it is worth taking a brief look at the bending moment distribution across the entire span. The example presented in Figure 10 shows that the joined-wing configuration has a huge impact on the shape of the bending moment distribution, reducing the bending moment between the root and the join location due to the presence of the rear wing. It also shows the difference that the BAC makes to the distribution, along with the effect of the three different connectivity options.

The most important observation from Figure 10 is that, although the BAC is introduced to increase the critical buckling load, it clearly increases the root bending moment of the front wing, depending on the way it is connected at each end. Unfortunately, the pinned-pinned option, which was expected to produce to highest critical buckling load,
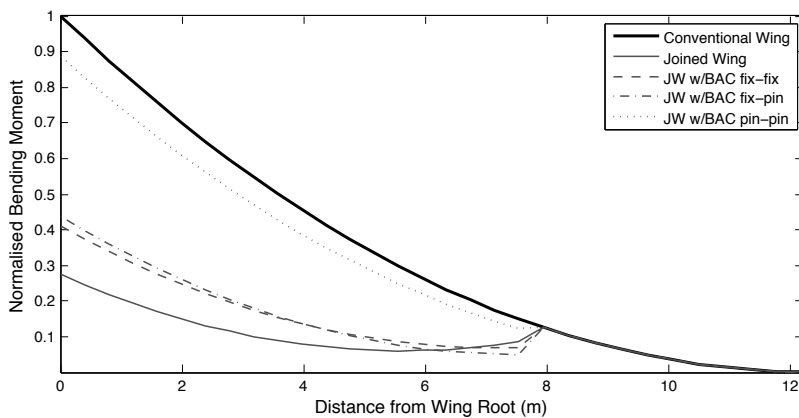
Figure 10. Bending Moment Distributions for a Joined-Wing with Varying BAC Options Compared with a Conventional Wing

results in a root bending moment so high that it virtually negates the effect of having the joined-wing configuration in the first place. However, the first two connectivity options look promising at this stage, especially the fixed-pinned option, as it displays only a very small increase in bending moment compared to the fixed-fixed option, even though it is expected to lead to higher buckling loads.

Since it evident that a great deal of the benefit of the joined-wing is not lost when the BAC is included, the question remains as to how much benefit is gained in terms of the critical buckling load. Figures 11b, 12b and 13b seek to answer this question by displaying the buckling load variation from the structural analyses described in the previous section for each of the BAC connectivity options. In order to avoid repetitive figures, only the case of the join location at 70% semi-span is shown here because the results for the tip-joined (100%) case are quite similar. Perhaps the most notable observation is that the introduction of the BAC always results in larger critical buckling loads. Furthermore, for the fixed-fixed and the fixed-pinned arrangements, increasing the BAC length leads to a significant increase in critical buckling load, whereas the corresponding increase in bending moment appears to be relatively small. In the case of the pinned-pinned option, the structure seems to behave in a completely different way, and although in many cases the buckling is prevented (negative eigenvalues), the resulting high bending moment remains almost constant for all the geometric arrangements. Until a better understanding of this unexpected behaviour can be gained, only the fixed-fixed and the fixed-pinned connectivity options will be considered. The following section will look at how effective each of these options are at saving structural weight, and also how the aircraft geometry impacts their effectiveness.

Figures 11a, 12a and 13a demonstrate that not all the geometric arrangements actually result in bending moment reductions as significant as the example shown in Figure 10, but in every case there is still an improvement on the conventional configuration. The variable that has, by far, the largest impact on the root bending moment is the tail height. This is not surprising because the advantage of the joined-wing is achieved by increasing the angle of the out-of-plane flexural axis, which is entirely dependent on the non-dimensional tail height.
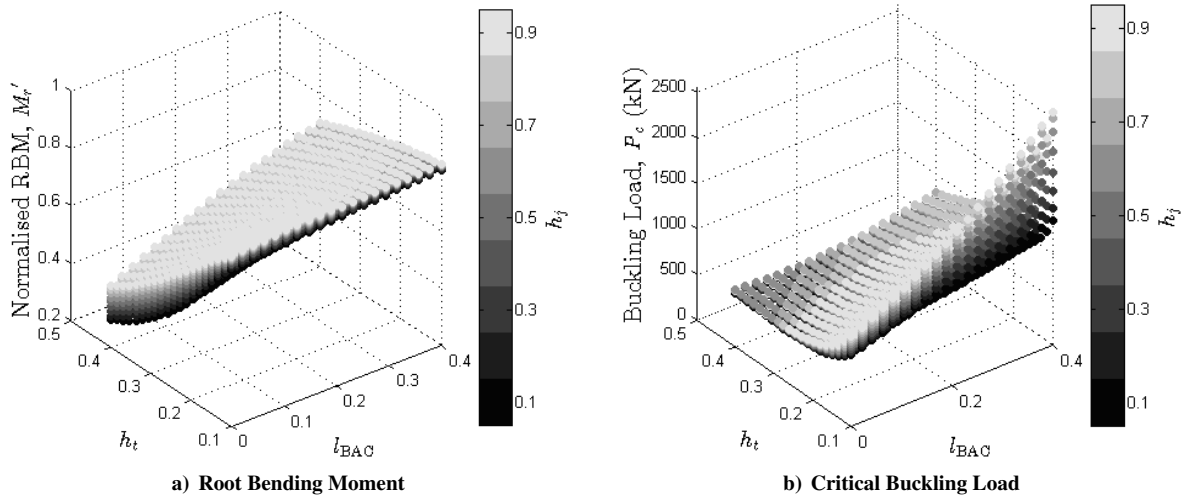
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a) **Root Bending Moment**

b) **Critical Buckling Load**

Figure 11. Effect of Geometry on Loads when the BAC is *Fixed* at A & B

a) **Root Bending Moment**

b) **Critical Buckling Load**
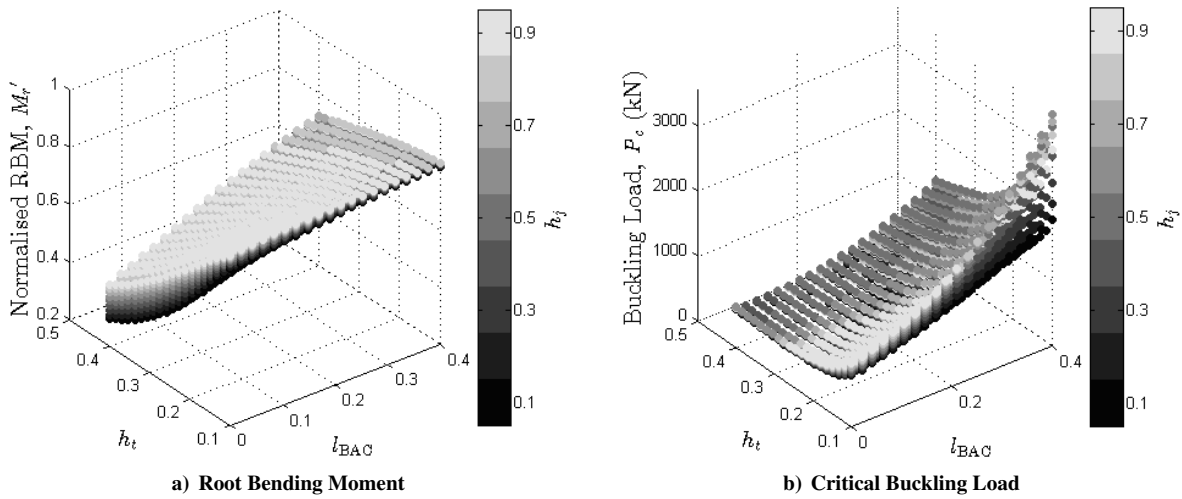
Figure 12. Effect of Geometry on Loads when the BAC is *Fixed* at A & *Pinned* at B

a) **Root Bending Moment**

b) **Critical Buckling Load**
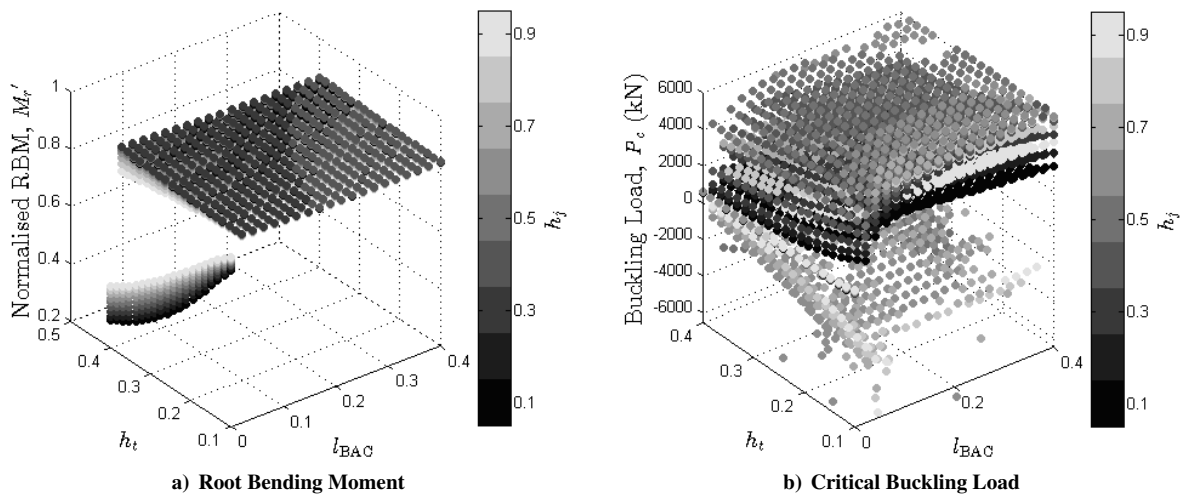
Figure 13. Effect of Geometry on Loads when the BAC is *Pinned* at A & B

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B.   Effectiveness of Buckling Alleviation Component

Since the root bending moment and the buckling load both have a linear impact on the weight of their respective wing, in order to save weight, the ratio between the percentage increase in critical buckling load ΔP_c and the percentage increase in root bending moment ΔM_r, must be greater than the ratio between the weight of the *inboard section* of the front wing[a] and the weight of the rear wing. Given that the material properties are the same for both wings, the condition that must be satisfied in order for the BAC to be effective can be written as

$$\frac{\Delta P_c}{\Delta M_r} > \frac{V_{fw\,\text{IN}}}{V_{rw}} \tag{1}$$

Also, since the wing box geometry is defined as a proportion of the chord, which is determined by the aspect ratio for a given span, it is not necessary to calculate $V_{fw\,\text{IN}}/V_{rw}$ for every single case. A very good approximation is given by

$$\frac{V_{rw}}{V_{fw\,\text{IN}}} = j^2 \frac{\cos\alpha}{\cos\beta} \frac{\mathcal{R}_{fw}^2}{\mathcal{R}_{rw}^2} \tag{2}$$

Combining (1) with (2), it follows that the BAC can be considered effective for the geometries that satisfy

$$\frac{\Delta P_c}{\Delta M_r} > \frac{\cos\beta \mathcal{R}_{rw}^2}{j^2 \cos\alpha \mathcal{R}_{fw}^2} \tag{3}$$

It is essential to be clear at this point that in order to obtain meaningful results using Equation 3, we are only interested in the changes in bending moment and buckling load *that are a direct result of an increase in BAC length*. This is because it is only BAC effectiveness that is being investigated. In other words, the effects of changes in H_t and H_j on ΔP_c and ΔM_r must be removed so that the results do not misrepresent the capability of the BAC.

In order to achieve this, the loads were normalised separately for every combination of h_t and h_j such that, for the ith BAC length, the jth tail height and the kth join height

$$\Delta P_{ci,j,k} = \left\{ \frac{P_{ci,j,k}}{P_{c(l_{\text{BAC}}=0),j,k}} - 1 \right\} \times 100\% \tag{4}$$

$$\Delta M_{ri,j,k} = \left\{ \frac{M_{ri,j,k}}{M_{r(l_{\text{BAC}}=0),j,k}} - 1 \right\} \times 100\% \tag{5}$$

Although the impact of h_t and h_j on the loads has been removed, their impact on the effectiveness of the BAC can now be shown by plotting these variables against the effectiveness ratios for each case and comparing their values to the line $y = V_{fw\,\text{IN}}/V_{rw}$. These 'trade-off' plots are displayed for each join location in Figures 14 and 15, respectively.
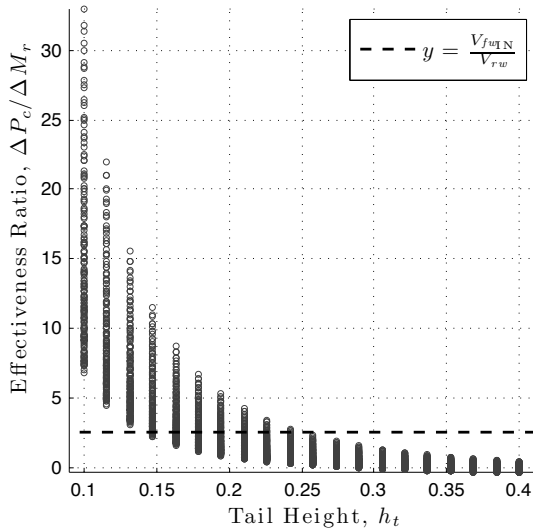
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[a]Figure 10 demonstrates that the weight of the outboard section will be unaffected by an increase in root bending moment because it acts independently as a cantilever.
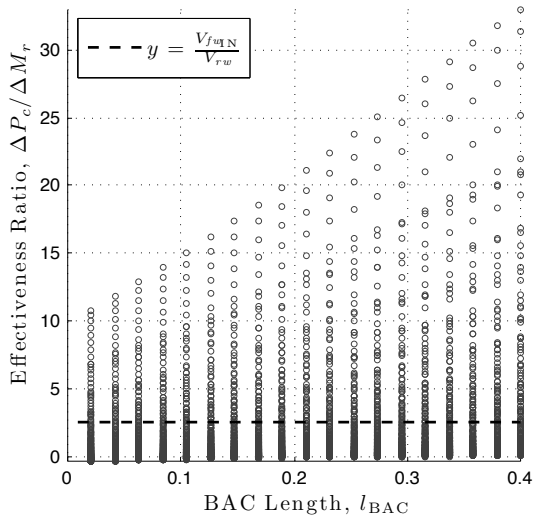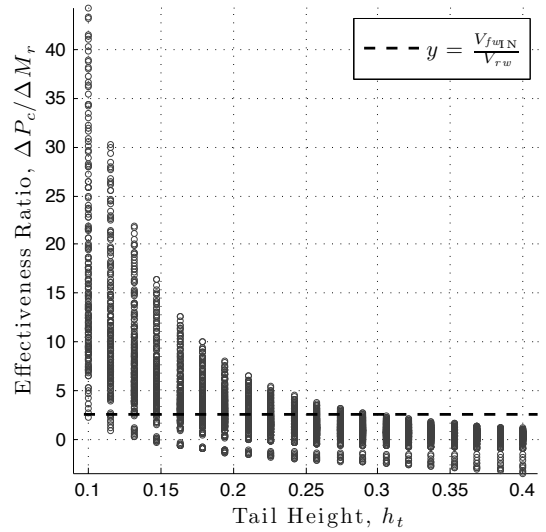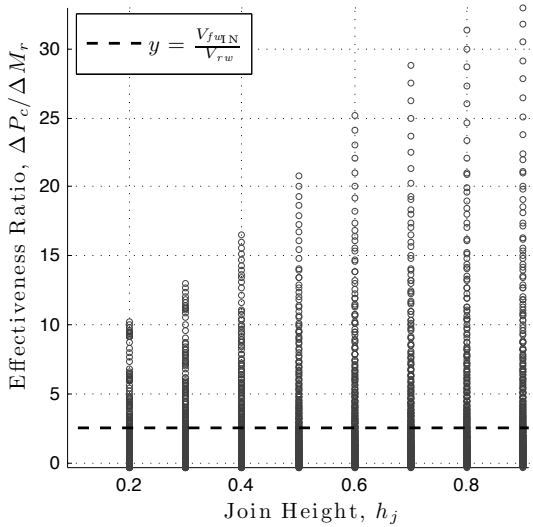
a) **Impact of l_{BAC}: Fixed at A & B**
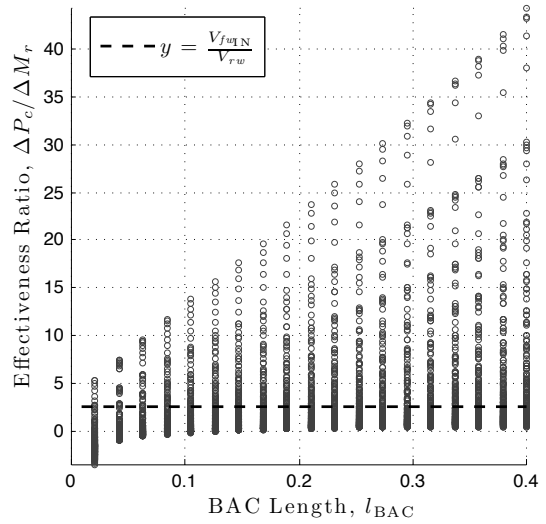
b) **Impact of l_{BAC}: Fixed at A & Pinned at B**
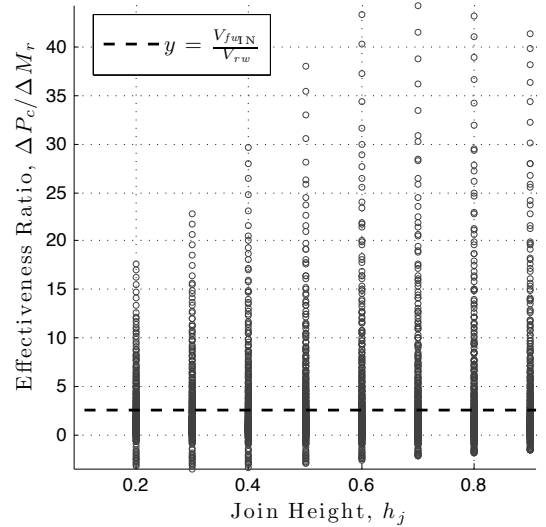
c) **Impact of h_t: Fixed at A & B**

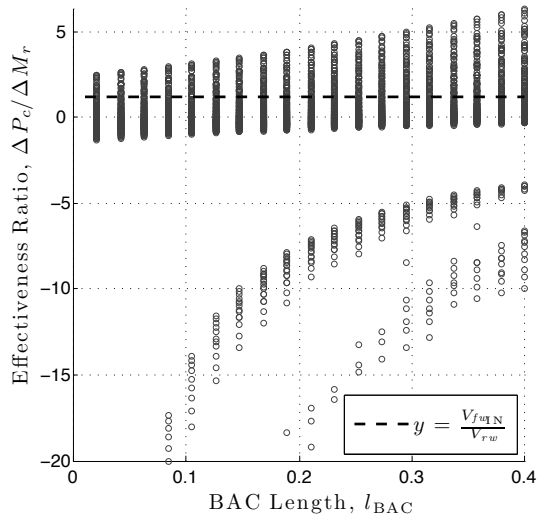d) **Impact of h_t: Fixed at A & Pinned at B**
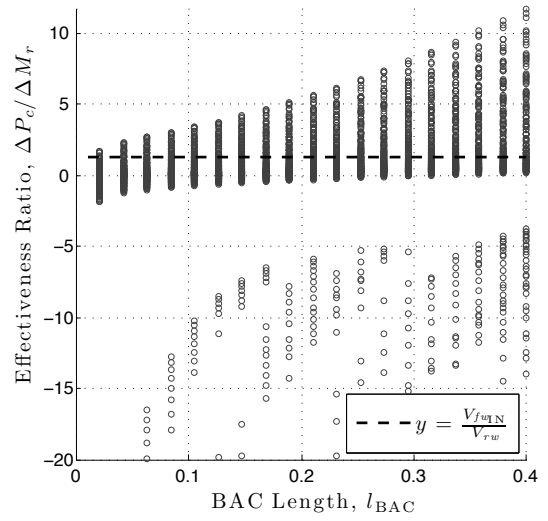
e) **Impact of h_j: Fixed at A & B**

f) **Impact of h_j: Fixed at A & Pinned at B**

Figure 14. Trade-off Plots Showing Impact of Geometry on BAC Effectiveness for $j = 0.7$

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a) Impact of l_{BAC}: Fixed at A & B

b) Impact of l_{BAC}: Fixed at A & Pinned at B

c) Impact of h_t: Fixed at A & B

d) Impact of h_t: Fixed at A & Pinned at B

e) Impact of h_j: Fixed at A & B
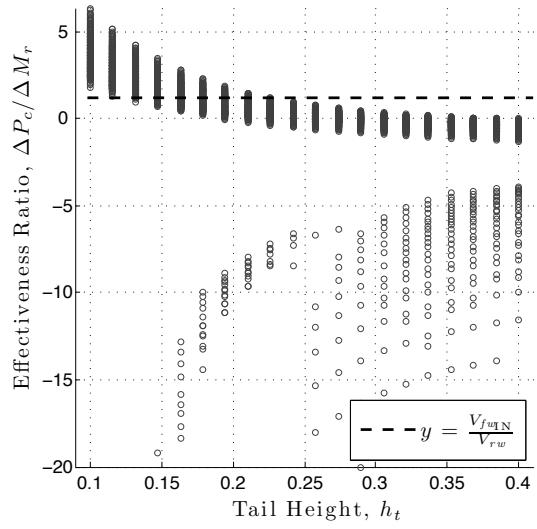
f) Impact of h_j: Fixed at A & Pinned at B

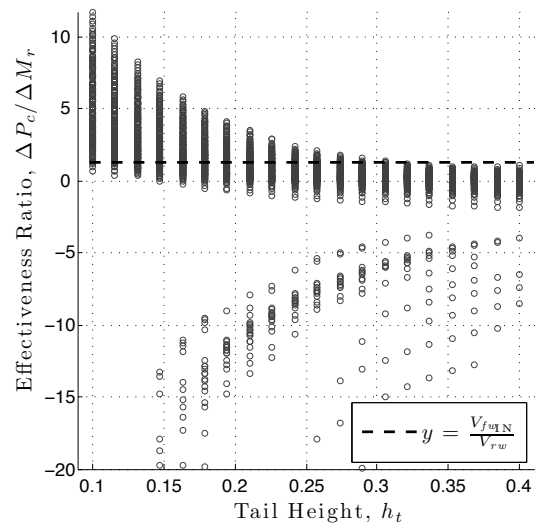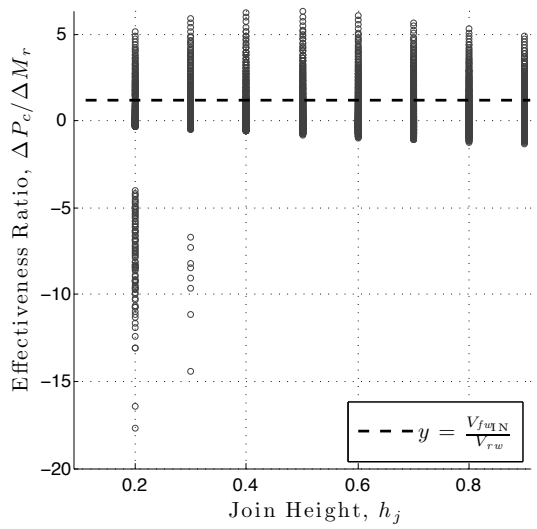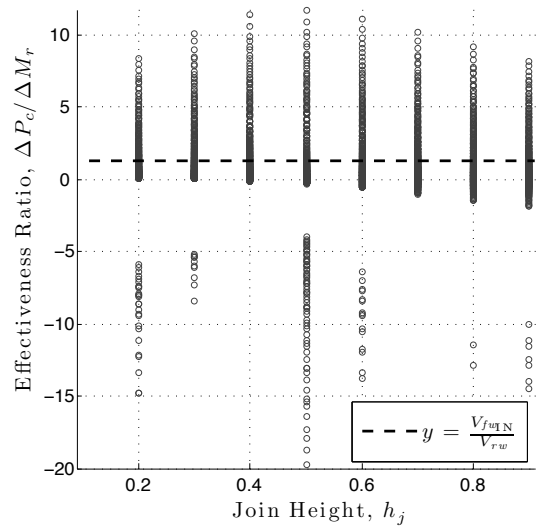**Figure 15. Trade-off Plots Showing Impact of Geometry on BAC Effectiveness for $j = 1.0$**

It is immediately clear from Figures 14e and 14f that the height of the join has very little impact on BAC effectiveness, which is also true for the case where $j = 1.0$ (Fig. 15). However, the height of the tail is extremely influential, which can be seen in Figures 14c and 14d along with Figures 15c and 15d. In each of these figures, the number of cases that are above the $y = V_{fw\,\mathrm{IN}}/V_{rw}$ line increases as the tail height is reduced. This means that the effectiveness of the BAC, i.e. the weight saving, is lower for larger tail heights and therefore increases as the angle of the aircraft's tilted bending (Fig. 4) axis gets closer to the horizontal.

Evidently, the BAC is not effective for all geometric arrangements. Only the that are above the $y = V_{fw\,\mathrm{IN}}/V_{rw}$ line represent combinations of tail and join heights for which the BAC provides an actual weight saving. This means that there are some tail heights for which the BAC is effective, but only if it has sufficient length. For example, when $l_{\mathrm{BAC}} \approx 0.1$, only the tail heights of around 0.18 and below give effectiveness ratios higher than $y = V_{fw\,\mathrm{IN}}/V_{rw}$. But when $l_{\mathrm{BAC}} \approx 0.3$, weight is saved for all of the tail heights up to around 0.25.

Furthermore, by comparing the different BAC connectivity options in the same way, it can clearly be argued that when the BAC is fixed at A and pinned at B it consistently allows larger weight savings than when it is fixed at both ends. For example, the effectiveness ratios in Figure 14b are somewhat higher than those in figure 14a for a given BAC length. This is the reason that Figure 14d exhibits a wider range of tail heights with effectiveness ratios that exceed $V_{fw\,\mathrm{IN}}/V_{rw}$ than in Figure 14c.

Finally, a comparison of Figures 14 and 15 shows that when the join location is closer to the front wing tip, the BAC is more likely to be effective because the rear wing has a larger structural volume in relation to that of the front wing. This is consistent with equation 1. However, this increase in effectiveness is not as straightforward as one might expect because, with the tip-joined configuration, the critical buckling load is actually reduced at first for the higher tail heights and shorter BACs. This means that the increase in effectiveness from the reduced volume ratio, $V_{fw\,\mathrm{IN}}/V_{rw}$, is partially counteracted by the change in behaviour that occurs when the join location moves further outboard. So although there a more cases where the BAC is effective for the tip-joined configuration, i.e. $j = 1.0$, when $j = 0.7$ there are much larger weight savings to be had for a given BAC length when the BAC *is* effective.

C. Limitations of this Analysis

Evidently, this research is at a very early stage and there are many other factors that need to be considered before the BAC is definitively shown to be a viable solution to the joined-wing buckling problem. Firstly, recent literature [19, 20, 21] highlights the need to consider potential aeroelastic instabilities that may arise when using the joined-wing configuration. For example, Weisshaar and Lee [22] showed that, depending on the position of the centre of gravity, the joined-wing has the potential for body-freedom flutter involving interaction between the elastic modes and the aircraft pitch mode. So far the effect of the BAC on the aeroelastic performance has not been taken into account.

Furthermore, Fairchild [23] stressed the importance of building a physical joined-wing structural model to check the validity of linear analysis, thus, it is intended that future research in this area consists of building a physical model

for structural analysis that includes the BAC, but a wind tunnel model might also prove to be beneficial.

Most importantly however, there has been a great deal of emphasis [18, 19] on the need to account for the inherent geometric nonlinearity of the joined-wing in any structural analysis if reliable results are to be obtained. This is much more time consuming, however, and would have been impractical for the large number of cases that were considered in this study. Nonetheless, in order to explore the validity of the findings outlined in this section, a nonlinear structural analysis was carried out on a single case, the results of which are presented in the following section.

V.   The Effect of Geometric Nonlinearity

A nonlinear structural analysis was carried out using MSC NASTRAN (SOL 106) so that the effect of geometric nonlinearity on the performance of the BAC could be investigated, along with the validity of the linear buckling analysis. In order to obtain realistic results, a more complex structure was required than the simple beam model shown in the previous section. Instead of a 'stick model,' a 3D representation of each the wing box was created using 2D plate elements, but the BAC itself was still modelled as a 1D beam. The finite element models without and with the BAC are shown in Figures 16 and 17, respectively. The length of the BAC in this case was $0.15s$ and the following non-dimensional geometric parameters were used for both the BAC and non-BAC cases: $h_t = 0.3$, $h_j = 0.5$ and $j = 0.7$. As well as a more realistic structure, the lift distribution was taken to be triangular instead of uniform.
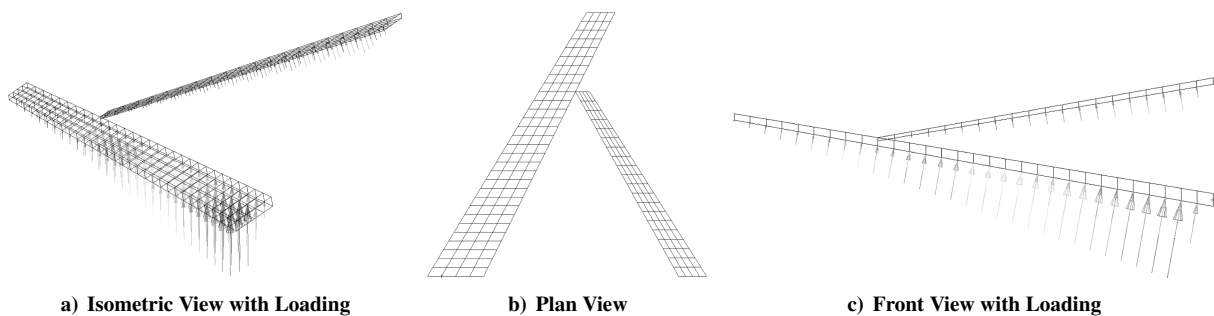

a) Isometric View with Loading	b) Plan View	c) Front View with Loading

Figure 16. Model of Joined-Wing *Without* BAC Using 2D Plate Elements

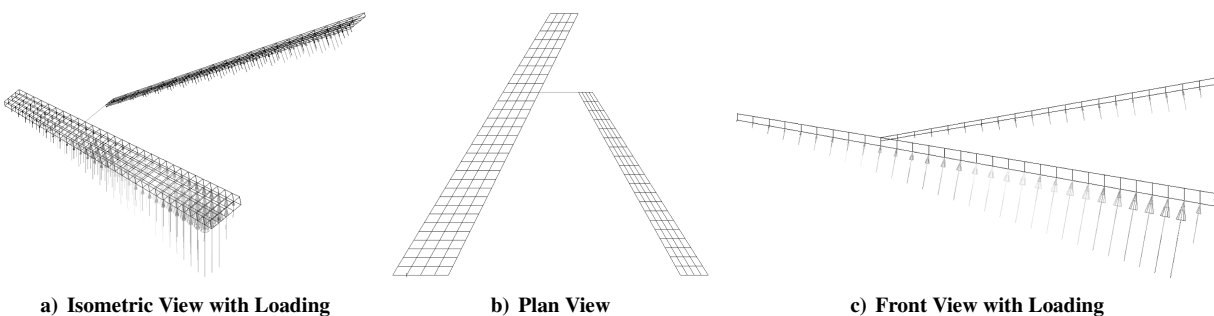|		
a) Isometric View with Loading	b) Plan View	c) Front View with Loading

Figure 17. Model of Joined-Wing *With* BAC Using 2D Plate Elements

Both linear and nonlinear structural analyses were conducted on each model so that the effect of the geometric

nonlinearity on the buckling load could be observed. In order to demonstrate the global behaviour of the structure under load, the (exaggerated) deformed shapes of the aircraft half-models with and without the BAC are shown in Figure 18. Aeroelastic studies on Joined-Wing SensorCraft [24, 25] showed that the buckling instability can be described as a 'flattening' of the entire aircraft, rather than simply a compression of the rear wing, and that it is therefore necessary to model the entire aircraft to capture this behaviour. Nevertheless, only a half model has been used for this analysis, assuming a rigid fuselage, which is not too unrealistic when considering commercial passenger aircraft in contrast to the SensorCraft, which is a rather flexible UAV.

The results of the nonlinear structural analyses are also shown in Figures 19 - 22 in the form of vertical deflections at certain points on the aircraft as the load is gradually increased.
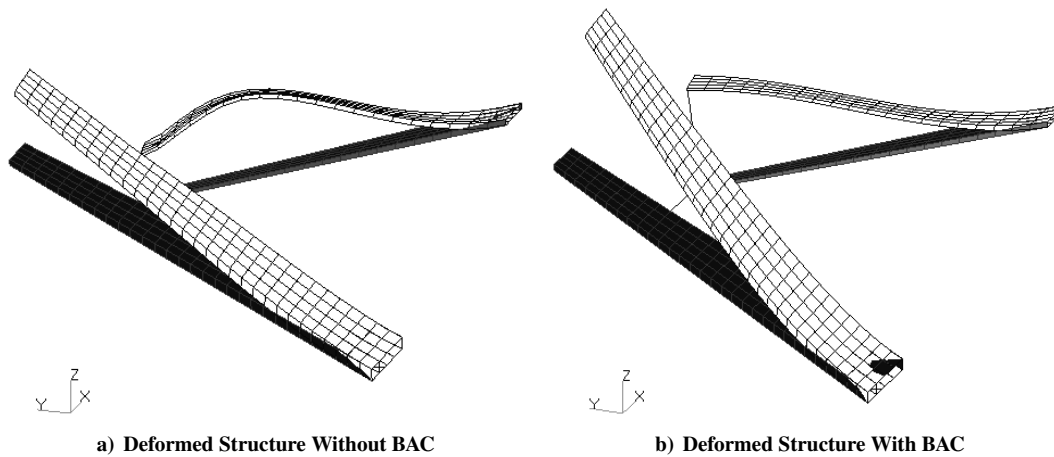

a) **Deformed Structure Without BAC**   b) **Deformed Structure With BAC**

Figure 18. Effect of BAC on the Structural Deformation (Exaggerated)

It is clear from Figure 19 that the linear buckling analysis of the conventional joined-wing configuration does not adequately model the structural behaviour because buckling does not occur in the nonlinear analysis. It has been shown [11] that this is likely to occur with higher sweep models such as the one used in this study, and that it may be appropriate to define a pseudo-buckling load corresponding to the point of inflexion where the stiffening behaviour no longer occurs, which would be around 4000kN from Figure 19. When nonlinear buckling did occur in Ref. [11], it revealed the linear buckling load to be an overestimate in most cases. This would be consistent with a pseudo-buckling load of around 4000kN, compared to a linear buckling load of around 5000kN in this case.

On the other hand, the linear analysis of the more realistic structure *with* the BAC did not detect the global buckling mode either and the critical buckling load was only affected by the localised buckling of individual panels on the front wing, even when stiffeners were added to the model. Nonlinear buckling may still occur of course, but would require a much greater load than for the conventional joined-wing configuration. It is also evident that the inclusion of the BAC significantly delays the onset of nonlinear behaviour in the joined-wing aircraft, even though it produces larger overall deflections. This means that, although a linear analysis is clearly not sufficient for this type of structure, it models the behaviour much more closely when the BAC is introduced.

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Although they are difficult to quantify at this stage, the benefits of the Buckling Alleviation Component could be much greater than estimated in the previous section because the increase in critical buckling load may have been overestimated by the linear model. Furthermore, it is believed that tailoring the structural properties of the BAC itself, which to this point have been kept constant, could have an even greater impact on the structural weight of the joined-wing aircraft configuration than has been demonstrated in this paper.
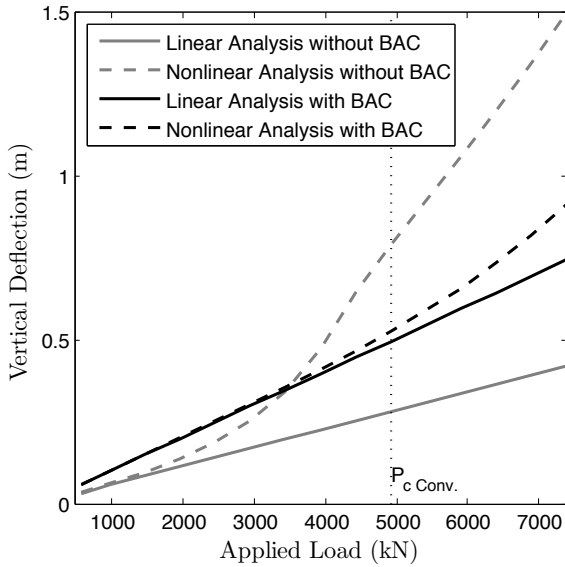

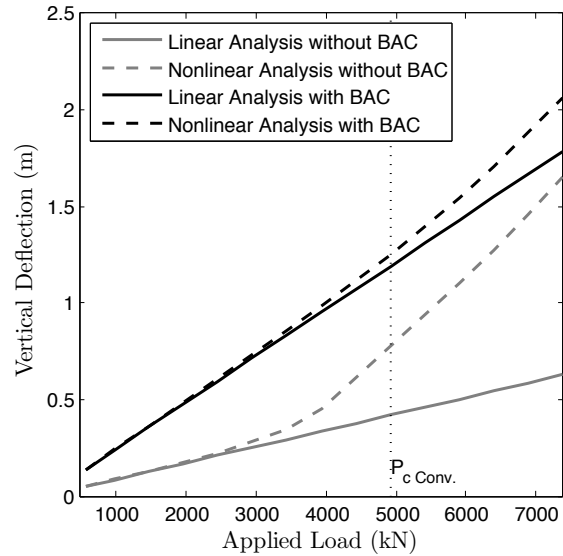Figure 19. Behaviour of Rear Wing Midpoint Under Lift
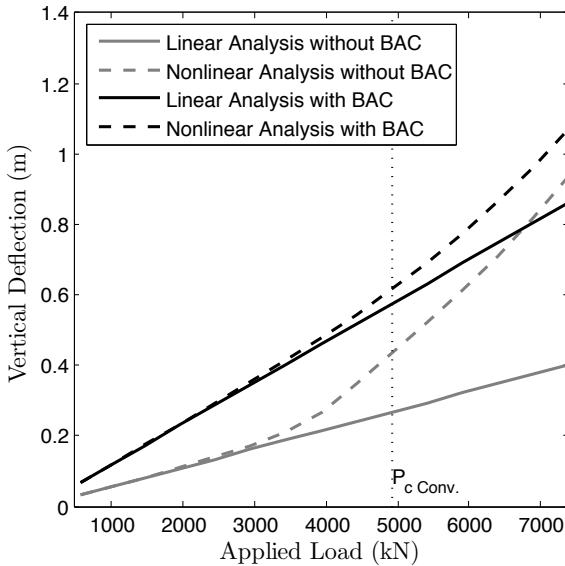

Figure 20. Behaviour of Rear Wing Tip Under Lift

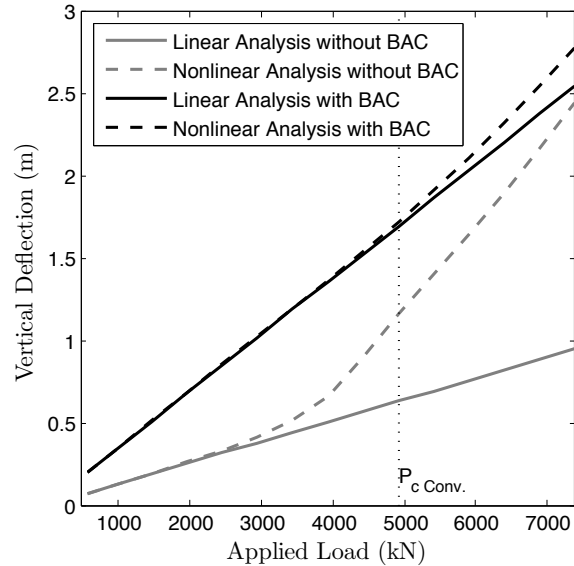

Figure 21. Behaviour of Front Wing Midpoint Under Lift

Figure 22. Behaviour of Front Wing Tip Under Lift

VI. Conclusions

A preliminary study into the effectiveness of the Buckling Alleviation Component was carried out, where the BAC effectiveness was defined as its ability to achieve a structural weight saving on a joined-wing aircraft. It was shown

that the BAC is effective for a significant number of geometric arrangements and that the tail height of the aircraft has the largest impact on the amount of weight that can be saved, the shortest tail heights allowing the largest weight savings. It is clear that the most favourable BAC orientation is fixed at the front and pinned at the rear due to the reduction in rear wing compression as well as the relative stability of the structure.

The self-weight of the BAC was ignored in this study, mainly for the purpose of simplification, but also because the size and shape that its cross-section will take is not yet known. Flexibility in the plane of the rear wing is crucial, but it is expected that it will need to be much stiffer in the plane perpendicular to this in order to prevent a detrimental effect on aeroelastic stability. It is hoped that future work will consist of a structural weight optimisation that includes BAC weight.

Some initial studies considering geometric structural nonlinearities have been made and these have shown that the conventional joined wing structure is more prone to nonlinear behaviour compared to when the BAC is employed. Furthermore, the weight savings that the BAC provides could be even greater when structural nonlinearity is considered, because the linear analysis is known to overestimate the critical buckling load for the conventional configuration, although this was not definitively proven to be the case in this study.

This research shows that, although the Buckling Alleviation Component is at a very early stage in development, the resulting behaviour is promising and will help make the joined-wing aircraft configuration a more viable replacement candidate for when the current configuration reaches the limit of its capability.

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