Creating a suitable wing box structure engineering essay

This report was written in the pursuit of creating a suitable wing box structure for AMYE, in which a suitable design for the structure has been researched. As a result of the design study on wing box loading cases and requirements imposed on the concept, a finished structure plan has been created.

The finished design structure has been created in recognition of design criteria calling for a wing box able of carrying a 2. 5kN bending load without any buckling, and a 5kN bending load before failure as final parameters.

The analytical study of all options of design has shown how the number of stringers, stiffeners, and geometrical rivet spacing can all be used to vary and tailor the wing box structure in order to meet design parameters.

The conclusion of the report is that in order to meet requirements to the fullest extent and simultaneously not have any over-design present in the structure, a dimensioned wing box plan has been formulated. Summarising, the wing box has 6 stringers, 5 stiffeners on the short web plate, 7 stiffeners on the longer web plate, 2 spar webs and a rivet spacing of 30 mm all equidistant in order to meet criteria.

Introduction

Part of a wing box design, construction and testing process, this report will focus on a final wing box design for the AMYE company. The AMYE company has issued a request for a wing box design for one of their aircraft. This report will provide information on such a design. The design report will be influenced by findings done in the literacy report.

AMYE will focus on designs meeting their needs and financial possibilities. Therefore, this report will provide information on the wing box design and choices made to come to this design. The report also meets AMYE’s request for a construction proposal.

There are certain requirements for the design of the wing box. This report contains a basic design as well as our own input to meet all the needs of the client. The goal is to make a basic design meeting all the requirements and then adding our own design choices making the design better in a way of for example lower weight, or lower production costs. There will also be a production plan cut out.

Structure of the report is as follows. As in any design project, requirements are formulated first. After discussion of a number of key concepts, design is made based on calculations. From this design a construction plan is made, followed by a weight and cost estimation, which is to be reported to AMYE.

Design

Requirements

Design of any aircraft component is based on the requirements imposed on the part. For the wing box load bearing capabilities AMYE has set clear requirements, being (Brugemann et all, 2010):

The wing box has to withstand a tip load of 2, 5 kN without buckling.

The wing box has to withstand a tip load of 5, 0 kN without failure. Buckling is allowed at this extreme situation.

The design must be optimized with respect to weight and producibility. The number of stingers and rivets must therefore be kept as low as possible. It has to be taken into account that a structure that can withstand much higher loads than the 5 kN failure load is overdesigned.

The wing box should have at least one intermediate stringer attached to the lower skin, in order to avoid buckling in a reverse situation since landing causes compression in the lower skin of the wing box.

Besides restrictions on load bearing capabilities, outer dimensions of the wing box have also been given. When these dimensions aren't stuck to, proper testing is not possible and the design will be rejected. Dimensional restrictions are found in appendix A. (GENERAL DIAGRAM)

Key concepts

Throughout this report references will be made to a few key concepts. These concepts are discussed and explained below.

Moment of inertia

In order to calculate bending stress the moment of inertia is computed. The moment of inertia with respect to the x-axis is calculated through a variety of steps. First the position of the centroid without any attached stiffeners is calculated, together with effect of added stiffeners on the centroid's position. This is done in excel in order to compute variable combinations to find the optimum in different configurations. The position for the centroid in vertical direction is given by where A is surface area in the cross section and y is the distance of a component’s centroid to a certain reference point (usually y= 0). The moment of inertia is then calculated using the formula:

In this formula dy is the distance between centroid and the centroid of the component.

For rectangular shaped objects, as found in the wing box cross section, the formula the moment of inertia is as follows:

The total moment of inertia is found by the summing the individual moments of inertia of each part of the wing box. The stringers are assumed to be made up of two perpendicular rectangles for purpose of calculations. The base shape of the wing box is assumed to be made of four individual rectangles, with stringers used in the four corners to hold the sheets together as shown [IMAGE REFERENCE]. The finished model has a change in moment of inertia as we add and subtract stringers to the top or the bottom of our structure. Thus by adding stringers to our model, we increase the moment of inertia of our structure and thus our structure is able to cope with higher loads.

Compression & shear buckling coefficients

In order to relate sheet geometry and critical buckling stress, buckling coefficients are needed. Two coefficients are distinguished: compression buckling coefficient KC and shear buckling coefficient KS. Both coefficients vary with the ratio width: height (in which width> height) and clamping states of the sides of the area. Three clamping states are distinguished:

clamped, hinged and free. From combinations of these clamping states different situations are created.

For a wing box, shear buckling coefficient is used on web plates and compression buckling coefficient is used in the upper skin. On the web plates all stiffeners are assumed to be hinged supports. The connections to the upper and lower skin are considered clamped. This results in situations 2 for areas between stiffeners and situation A for outer areas, as shown in figure 2. Since the value of KS is bigger for A than for 2, all areas can be considered number 2 when considering failure (Brugemann et all, 2010). On the upper skin all connections to the clamps, spars and web plates are considered fixed as supports are deemed heavy and strong enough. Connections to stringers are considered hinged. This leads to situation 3 and 5 for the upper skin, as shown in figure 1 (Brugemann et all, 2010).

Figures 1 and 2, showing the clamping states of the upper skin(1) and web plates(2)

Loads

As stated the wing box will be tested for tip loading. An illustration for such a tip load is shown in figure 3, with the tip load drawn in red. Resultant forces as shown in blue and green.

Figure 3: A tip force (red) and resultant shear and normal forces

From statics it is known that shear forces will be induced in the web plates of the torsion box to provide equilibrium of forces in y-direction. To provide moment equilibrium a force couple will act in the upper and lower skin, causing the former to be in compression and latter to be in tension (Wright & Cooper, 2007).

Shear force

The approach taken to compute the number of stiffeners required on each web plate is as follows. First the forces which have to be dealt with by the web plates will be computed. After this the number of stiffeners required to cope with these forces without buckling will be calculated.

The magnitude of the shear force in the web plates can be computed from equilibrium of moment around the y-axis, which states that the shear forces in the web plates are equal. Since the two shear forces together must equal P for equilibrium each shear force is equal to ½P.

From mechanics it is known that shear stress is shear force over area. Given that the web plates have a thickness t and a height of 2h we know the formula for the shear stress (Brugemann et all, 2010):

Filling in the given values of P= 2500N, h= 75mm and t= 0, 8mm we find Ï„ = 10, 42 MPa. However, at this point sweep of the wing hasn’t been taken into account yet. The influence of wing sweep on the shear stress is given by (Brugemann et all, 2010):

Filling in Ï„(0â)°) = 10, 42MPa gives Ï„ = 13, 89 MPa . This is the shear stress the web plates of the wing box should be able to cope with without buckling. Now progress can be made to computing the number of stiffeners.

Knowing the value of shear stress to be dealt with, a look at the shear stress at which plate buckling occurs is needed. The formula for the initial buckling stress is as follows (Brugemann et all, 2010):

In which KS is the shear buckling coefficient, E is the E-modulus of the material used, t is the thickness of the material used and b is the stringer pitch.

For the placement of the stiffeners the two web plates of the wing box have to be considered individually, since both differ in length. Since the wing box during testing is clamped over 110mm and 60mm the first web plate has an effective length of 1099 mm and the second an effective length of 1330mm. The stringer pitch can then be computed by dividing web plate length by the number of intervals on the plate.

At this point the reader is referred to the key concept of the shear buckling coefficient, where the determination of the buckling situation is done. This assessment is used for determining the KS coefficient.

The following table can be made up for various numbers of stiffeners on the shorter web plate:

Number of stiffeners [-]	Stiffener Pitch [mm]	a/b [-]	Ks[-]	Ï„ [Mpa]
1	549, 5	3, 663333	8, 4	1, 289028
2	366, 3333333	2, 442222	8, 8	3, 038424
3	274, 75	1, 831667	9, 4	

5, 769936

4

219, 8

1, 465333

9, 8

9, 399164

5

183, 1666667

1, 221111

10, 3

14, 22535

6

157

1, 046667

10, 8

20, 30219

7

137, 375

0, 915833

–

–

8

122, 1111111

0, 814074

–

–

A similar table can be made up for the longer web plate of length 1330mm:

Number of stiffeners [-]

Stiffener Pitch [mm]

a/b [-]

Ks[-]

Ï„ [Mpa]

1

665

4, 433333

8, 3

0, 869668

2

443, 3333333

2, 955556

8, 6

2, 027478

3

332, 5

2, 216667

9

3, 772053

4

266

1, 773333

9, 35

6, 123037

5

221, 6666667

1, 477778

9, 7

9, 147228

6

190

1, 266667

10, 2

13, 09217

7

166, 25

1, 108333

10, 6

17, 77056

8

147, 7777778

0, 985185

–

–

Comparing the values in the tables with the given shear stress of 13, 89 MPa shows us that the shorter web plate will require five stiffeners and the longer web plate will require seven stiffeners.

Normal forces

The second reaction forces in the wing box to be taken into account are the normal forces in the upper and lower skin. The same approach is to be taken as in determining the number of stiffeners. First loads to be dealt with are determined, then the number of stringers is to be determined.

The normal force at an arbitrary point of the wing box can be computed from the formula (Brugemann et all, 2010):

In this formula M(x) is the internal moment at position x, y is the distance from the wing box neutral axis to position x and I is the moment of inertia of the wing box cross section.

First the lower skin of the wing box will be considered. As stated previously, this plate is loaded in tension. A quick calculation will show the lower plate does not require any stringers. Assuming the load of 2500N is applied at the tip of the wing the moment at the wing root is 3, 75 Ã- 106 Nmm. Given that the distance between the couple of forces in the lower skin and upper skin is 150mm, the tension and compression forces in the top and bottom skin are 25000N. To obtain the stress, force is divided by area (400mm width and 0, 8 mm height) and a value of 78, 125Mpa is found, some way under the yield strength of 345 MPa.

However, to comply with requirement four, one stringer will be placed in the middle of the lower skin.

To compute the allowable normal stress in the upper skin the assumption is made at this point that five stringers will be used in the upper skin. This results in a moment of inertia I of 6852580 mm4 for the wing box cross section and a distance y = 64, 1mm. This assumption is to be checked later.

Given the moment at the wing root, the distance y and the moment of inertia I the normal stress in the upper plate is ÏƒCR = 35, 08 MPa at most. Just as with the maximum shear force, wing sweep plays a role according to:

Filling in the formula gives Ïƒ(30â)°) = 46, 77 MPa. This is the stress from which onwards buckling is allowed.

Now a look is to be taken at the number of stringers. It is assumed two spar webs will be equally spaced over 1330 mm, resulting in a spar web pitch of 443, 33mm. Critical stress is determined for some numbers of stringers. This critical stress is given by (Brugemann et all, 2010):

Given all this data the following table can be made:

Number of Stringers

Stringer Pitch [mm]

a/b [-]

Kc (5) [-]

Kc (3) [-]

Ïƒ (5) [Mpa]

Ïƒ (3) [Mpa]

1

200

2, 16665

4, 2

5, 65

4, 86528

6, 54496

2

133, 3333333

3, 249975

3, 8

5, 25

9, 90432

13, 6836

3

100

4, 3333

3, 65

5, 1

16, 91264

23, 63136

4

80

5, 416625

3, 6

5

26, 064

36, 2

5

66, 66666667

6, 49995

3, 6

5

37, 53216

52, 128

6

57, 14285714

7, 583275

3, 6

5

51, 08544

70, 952

The table shows six stringers equally spaced over the width of the wing box will prevent the upper skin from buckling. To double check we compute the moment of inertia of a wing box with six stringers (6770446 mm4) and the value for y (61, 9mm). Filling in these values in the formula gives a normal compressive stress of 45, 7 MPa, a value smaller than the allowable stress. Concluding, six stringers will be used in the upper skin.

Inter rivet buckling

An important aspect to keep into consideration when testing is inter rivet buckling, as this phenomenon causes almost instant failure. Therefore the rivets should be able to cope with the internal loads of the wing box at 5000N. Since rivet buckling only occurs in a state of compression, only the upper sheet is considered.

Failure will occur when our wing box cannot withstand the maximum stress. To calculate the maximum stress, formula 7 is used.

Again the sweep must be taken into account, so using formula 8:

This is the maximum stress the wing box has to handle. Looking at this value we know that the aluminium will not fail because the yield stress of aluminium is 345 MPa. So the wing box will fail at the rivets. If the wing box is designed to withstand a tip load of 5 kN, then the rivets have to withstand a stress of 91, 43 MPa. Inter rivet distance and inter rivet buckling stress are related through (Brugemann et all, 2010):

ÏƒMAX =

In this formula c gives the end-fixity coefficient, which has a value of 2, 1 for the pop-rivets to be used. Parameter s gives the spacing between rivets and t is the skin thickness. Rewriting this formula for s gives

So with a c = 2, 1, t = 0, 8mm, E = 72400 MPa and a = 130. 1MPa the spacing between two rivets becomes 30, 95 mm. However, assembly precision only goes as far a whole millimetres, so for the simplification of fabrication the inter rivet spacing is set at s = 30 mm.

Final design

Summarizing, key aspects of our wing box are as follows. Width and height of the box are 400mm and 150mm respectively. The longer side of the wing box measures 1500mm and the shorter side 1269mm, with the deficit in length being caused by a 30â)° cutaway at one end.

On the shorter web plate, five stringers will be spaced equally over a distance of 1099mm, spanning from 60mm out from the perpendicular edge to 110mm out from the edge connecting to the cutaway. On the longer web plate, seven stringers will be equally positioned over a distance of 1330mm, again spanning from 60mm out from the perpendicular edge to 110mm out from the edge connecting to the cutaway.

Inside the wing box, two spar webs will be positioned at a distance of 503, 3mm and 946, 66mm from the perpendicular edge. Through these spar webs one additional stringer will run over the bottom sheet and six additional stringers will run over the upper sheet, each spaced equally over the full width of the wing box.

Finally, construction will be done through riveting, with the rivets being spaced 30mm from each other. TECHNICAL DRAWING ARE FOUND IN APPENDIX B.

Failure modes

One of the most important things in this wing design is knowing how and when the box will fail. Of course there are different failure modes and all of them have to be taken in to account. An important note: fatigue is not considered yet. The most important failure modes are described below. All the modes are considered for the design. It is necessary to know with stresses are in the design and at which stresses the design will fail, in order to make a good design. Also sweep has been taking into account, as stated in the design.

According to J. Loughlan (1996) it is important to know where the stiffeners are. If the stiffeners are placed beyond the optimum value, then they have no function. The stiffeners then simply add weight, without having a function. Loughlan also states that adding a four percent of weight for stiffeners, causes a box to yield a buckling capacity that is three times higher than the buckling capacity of an unstiffened box. Nagendra et al (1994)experienced that all panels, with our without holes, always fail at or near the stiffeners, at places with high bending gradients. Allow a skin to buckle has weight advantages with respect to the non-buckling designs (Lynch, 2004)

Compression skin buckling of the top skin

The upper skin is loaded in compression due to the bending moment. The bending moment differs with the distance to the wing tip. Thus if the bending moment is too high, buckling will occur. To prevent this, stiffeners and stringers are placed in the design.

As stated the allowable skin stress at which buckling occurs is given by formula 9. Kc can differ for each part of the box. Six stringers are used on the top side, with a Kc-value of 3, 6 at line number 5. This means that the top skin can cope with a 51, 08 Mpa stress without buckling, while the calculated maximum stress that will occur is 45, 7 MPa.

Shear Buckling of the spar webs

Another failure mode is shear buckling of the spar webs. This occurs at the parts that should reinforce the design, the spar webs. In other words, when those reinforcements fail, the whole structure will fail. The initial buckling stress is given in formula 6. Line number 2 is used, with Ks having a value of 10, 6 for the longer web plate(7 stiffeners used). This gives a shear stress of 17, 77 Mpa where the longer web plate can cope with. For the shorter web plate a Ks of 10, 3 is used(5 stiffeners). So the shorter web plate can cope with a stress of 14, 225 MPa. Both calculated values are higher than the shear stress in the plates (13, 89 MPa). Since the shear stress is constant in the all the whole web plates, in this case it is most likely to fail at the shorter web plate.

Inter rivet buckling

Inter rivet buckling occurs at a high compression stress. It’s possible to calculate the stress at which it occurs as given by formula 10. Since the space between the rivets is unknown and can be varied, this probably will the most important failure mode. As stated before the maximum compression stress in the whole structure is 91, 422 MPa. This gives a rivet spacing of 30, 95 mm. To make sure inter rivet buckling does not occur, 30mm spacing is used. The failure stress will then be 97, 3 MPa. So that’s the value at which it fails. 97, 3MPa/ (4/3) = 72, 979 Mpa gives a tip force of 5321N at which inter rivet buckling will occur.

Allowable tension stress in the lower skin

The upper skin is not the only side that can fail, logically. Thus the lower skin has to be taken in to account as well. The lower skin is loaded in tension. The stress can be calculated using formula 7. The centroid lies, due to the stringers 13, 1mm above the neutral axis. The point where the maximum stress will occur is closest to the root, since there the largest moment occurs. The maximum stress in the lower skin is then -(5000Ã-1500Ã-(74+13. 1))/6770446 = 97, 5968 MPa. Taking sweep into account this gives a value of (4/3)Ã-97, 5968 = 130, 1 MPa. This is way lower than the ultimate stress of aluminum (483 MPa).

Clamping effects

For the purpose of testing the wing box will be clamped at both sides as shown in figure 4. The wing box will be attacked to the test clamp structure through the use of bolts. This clamping has an effect on the overall loads experienced by the wing box structure (Yan, 1999) showing that the clamping the wing box helps the wing box experience lower loads. These clamping effects have been taken into account when considering maximum load calculations, through the form of change in KC. By selecting the appropriate KC for application, in this case a two side hinged and two side clamped, KC line 5 (Brügemann et al 2010, p28), clamping effects can be taken into account on the loads and further calculations, to accurately predict failure.

Figure 4, showing a clamped wing box during testing

Production plan

Construction activities

Weight estimates

Knowing the weight estimate for an aircraft component is crucial in the design process since weight plays a crucial role in terms aircraft performance, mainly fuel consumption, range, endurance, load capacity and speed. A light but robust wing box is designed to withstand the maximum wing load. It is important that estimation of the weight of the wing box is accurate. According to design plans, the wing box consists of a total of 11 stringers, 12 stiffeners and 753 rivets. Since the wing box is shaped as a trapezoid, the stringers will have different lengths and therefore need to be calculated accordingly. Taking into account the geometrical property of a trapezoid, it can be deduced that the average length of the stringers can be found by summing the longest and shortest stringers and dividing it by two.

Now knowing the shape of the stringer, we can estimate its weight by using the average length, width of 20mm and thickness 3mm(considering a ã„´ shaped stringers as a bar when folded).

Since the stiffeners have same lengths, weight is relatively easy to calculate.

To find the net gain/loss of the rivets and holes, we need to deduct the weight of sheet metal when drilled away for rivets and add the weight of rivets.

And finally the weight of the sheet metal will be calculated.

Cost estimates

To have an accurate estimation of the wing box structure, three things need to be taken into account, how much aluminum was used in the metal plating, the price of stringers/stiffeners and how many rivets are used. Also, we need a small surplus of rivets in order to buffer the human error involved during the manufacturing procedure.

In the wing box, 1, 65m2 of aluminum sheet metal is needed, however, the metal sheet needs to be big enough so that the 2D design of wing box can be cut out. Therefore the appropriate sheet metal has the dimension of 2, 5m X 1, 25m and costs 53, 19 euros (Metals4U).

In the construction of a wing box, a total of 17029, 5mm of stringer/stiffener was used. The price of 5000mm of stringer/stiffener is 12, 57 euros (Metals4U). Because it is not possible to purchase less than 5000 mm of stringer/stiffener, four 5000mm stringer/stiffener needs to be purchased. This will in total cost 50, 26 euros.

753 rivets are needed for the wing box. Because it is only possible to purchase rivets in bulk, 800 rivets will be bought for both practical reasons and as a buffer. One hundred 3mm diameter rivets cost 4, 43 euros per 100 rivets (Rivets Aluminium 4. 0 x 10 5985). For 800 rivets, the cost will be 35, 44 euros.

Excluding manual labor wages for the students, the total cost for manufacturing the group’s wing box is 138, 89 euros.

Conclusion

This report has discussed the design of a wing box. The objective of this report was to design a wing box that is able to withstand a tip load of 2, 5kN without buckling, a tip load of 5, 0kN without failure (buckling is allowed), with at least one intermediate stringer attached to the lower skin. The design has to be optimized with respect to weight and producibility.

From our calculations it was concluded that the final wing box will have 6 stringers, 5 stiffeners on the short web plate, 7 stiffeners on the longer web plate and 2 spar webs. The construction will be done through riveting, with a rivet spacing of 30mm all equidistant in order to meet criteria.

By calculating the weight of each individual part and adding them up altogether, the weight of the wing box could be calculated. The weight estimation showed a total weight of 5, 98 kg.

In a similar way, the cost estimation was done, showing a total cost of € 138, 89

A production plan has been produced describing the list of activities to be performed by a team of 11 people.

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List of figures

Figure 4 – Van den Bos, 2010, Tips and tricks for modelling a wing box