Investigation of the influence of fuselage door surrounding structure’s geometric parameters on the weight and mechanical response of the fuselage

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Abstract

A great challenge in aeronautic industry is to reduce weight in aircraft, which can be accomplished through the study of new materials and the configuration of the airplane. One inevitable part of a fuselage are the cut-outs. Depending on their dimensions, they interrupt the loads path in the structure, forcing a redistribution of the loads in their vicinity. Consequently, there is a need for reinforcement, mainly around the cut-out. In this study, we are interested in the passengers’ door surrounding structure. A parameterized model of a half-fuselage section with a cut-out is done using the Finite Element software ANSYS and the influence of variations in its geometry on the weight of the fuselage is investigated through a Sensitivity Analysis based on parametric studies and “what-if” analyses.

Keywords: door surrounding structure, Sensitivity Analysis, ANSYS, metallic fuselage

1. Introduction

The fuselage is a very efficient structure for its thin-walled and aerodynamic shape. The problem arises when an opening is needed. In an aircraft it is called a cut-out. Big cut-outs are main contributors to failure of fuselage shells. They interrupt the load path of the skin and stiffeners and induce high concentrated stresses in the region around them. This demands for reinforcement on that region, which by itself increases the weight and cost of the aircraft. Entries for fuel tanks do not influence the structure as much as the ones for passengers and cargo.

The minimisation of weight is one of the main objectives in aircraft design and investigation is being done on what would make a commercial aircraft lighter and, being the stress level on the structure one of the factors for the increase of material, there must be a lot of study on the parts where they are biggest, such as in the cut-outs’ corners. Seeger and Wolf [1] used Evolutionary Algorithms to optimise the model ALCAS, a CFRP-made fuselage structure developed by Airbus. It is an example of optimisation that does not depend on derivative information of the Interest function, which has advantages when there are more than one discipline in the optimisation process (MDO). Dexl [3] studied the parameters that most influenced the static behaviour of this model using the tool GEOpS², developed in Technical University of...
Dresden. One limitation of this model is the difficulty in varying the stringer spacing. In this work an attempt to solve it is made. Many other authors studied the influences of different members in plates and cylinders with and without cut-outs, which is interesting to consult [4-8].

2. Literature Review

2.1 Fuselage Structures

2.1.1 Material

Although there is an increasing use in composite materials for their excellent properties and weight, there are still some research going on. The alloy AA 2024-T3 makes the majority of Airbus airplanes fuselage skin, so this is the material used in the developed model. Alloys with copper have good fatigue life and fracture toughness.

2.1.2 Structural Members

The actual airframe is of the type Semi-Monocoque. The compression loads are supported and the skin is protected, as well as the fuselage’s shape. The members are:

- **Skin**: a panel designed to withstand tensile loads caused by pressurization. It carries shear loads and handles the fuselage torsion.
- **Frame**: circumferential stiffeners that keep fuselage’s shape and are axially loaded due to hoop stress from cabin pressurisation;
- **Stringer**: axial stiffeners that support the skin in compressive loads due to bending;

2.1.3 Cut-outs and Surrounding Structure

The aspect ratio of a cut-out is defined as the ratio width-height, $b/h$. In Niu [2] the preliminary sizing of a plug-type door is based on an aspect ratio of 0.6. The generic reinforcing members are [4], [8] (Figure 1).

- **Sill**: a longitudinal stiffener that limits the cut-out above and below; sometimes two sills are considered – a main sill and an auxiliary sill;
- **Intercostal**: a short beam that makes a bridge between a main frame and the edge frame at the laterals of the cut-out;
- **Doubler**: an inside reinforcement around the cut-out, especially in the corners;
- **Door-stop**: fixed structural members of the doorframe that limit the door’s movement and transmit the internal pressure applied on the door to the edge frames.
- **Edge frame**: are attached to the right and left sides of the door; are axially loaded due to hoop stress, but are additionally subjected to bending due to the presence of the door;

![Figure 1 - Generic fuselage structure with a cut-out](image)

Due to the eccentricity of the loads from the door-stops relatively to the shear centre of the edge frame, there is a twisting moment on the latter. The frame generally has an open-section and low torsional stiffness. The intercostals, which are perpendicular to the frames, have high bending stiffness and can carry their torsion [4, 10].
The skin around the cut-out has tension in two directions due to pressurisation and carries large shear loads due to redistribution of loads caused by the cut-out. It is locally subjected to high bending stresses also due to the cut-out [4]. Near the corners of the cut-out, it is commonly thickened, forming the doubler.

The sills and the skin-stringer-panel form the upper and lower "bending-beams", essential to carry the fuselage torsion in the surrounding of the cut-out and to act as tension and compression members in fuselage bending. Also the cut-frames create tensile loads that result in additional bending of the sills [10].

### 2.2 Review on Mechanics

#### 2.2.1 Static Behaviour

In a complex structure like in an aircraft, it is difficult to calculate the stresses and then verify if the strength of the material is enough to carry them. A common indicator of the static behaviour of the structure in a FEM analysis is the von Mises Stress:

$$\sigma_{eqv} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

#### 2.2.2 Stability

Considering a column compressed axially by $P$ and a transversal load is suddenly applied. If $P < P_{cr} = \frac{\pi^2 Et}{L_e^2}$, the column will restore its initial position after removing the transverse load; otherwise, it becomes unstable and may lead to failure. Two types of instability can occur: the primary, called the global instability, and the secondary (crippling), which occurs locally. Fuselages resist to in-plane tensile stresses and shear stresses, but may buckle for low compressive loads in the same plane. For that reason, the concept of shear web is used and the skin is reinforced by stiffening members.

Other quantities studied in this work were the Elastic Energy of Deformation, a measure of the stiffness of the material, and the Natural Frequency of the system, although it will only give an idea of how it changes with the geometry. Like the buckling factor, the full cylinder should be modelled to show a real value.

### 2.3 Fuselage Loads

The effects of cabin pressurization in the fuselage structure increase as the airplane goes up because of the decreasing air pressure. The pressure difference is maximum at the maximum operating altitude of the aircraft. In the case of A320, it is $h = 40000 \text{ ft} = 12192 \text{ m}$, giving a pressure outside of $p_{ext} = 18754 \text{ N/m}^2$. Humans cannot stand a value of pressure below a certain level for a long time. According to EASA CS-25 [10], the cabin altitude must be $h = 1800 \text{ m}$, although in Airbus a limit of 2400 m is used. The internal pressure will be chosen to be $p_{int} = 80285 \text{ N/m}^2$. The difference of pressures is then:

$$\Delta p = p_{int} - p_{ext} \approx 61500 \text{ N/m}^2$$

The pressure force transmitted to the surrounding structure through the door-stops is calculated from the internal pressure as:

$$F_{DS} = \Delta p \cdot A_{door}$$

Additionally, a force is applied in each bulkhead, that makes them go apart and exercise a longitudinal tension in the cylinder. It is calculated as:

$$F_z = \frac{1}{2} \cdot \pi \cdot \Delta p \cdot r_s^2$$
Other applied loads were taken from the study of van Tooren [7] and assumed as typical loads in the A320: a shear load, \( F_y = \frac{1}{2} \times 600\,000 \) N and a bending moment, \( M_x = \frac{1}{2} \times 4\,400\,000 \) Nm (half of a fuselage section). More specific values would mean a loads analysis, as there are different contributions to the calculation of loads in each part of a fuselage and a great amount of load cases; this was outside the scope of the thesis.

### 2.4 Sensitivity Analysis

A Sensitivity Analysis (SA) consists in studying the structural behaviour of a system with respect to changes in design parameters, such as its geometry, material and number of members. It is based on the computation of rates of change of the interest functions with respect to the design variables. The derivatives represent trends to help the designer make estimates and are important for an optimisation of the system.

#### Table 1 – Problem formulation

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>doors’ Width and Height ( x = (B, H) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest Function</td>
<td>structure’s Weight, ( W );</td>
</tr>
<tr>
<td>Design Constraints</td>
<td>material’s strength, ( \sigma_{\text{yield}} ), and maximum displacement, ( u_{\text{adm}} ).</td>
</tr>
</tbody>
</table>

### 3. Methodology and Implementation

The following softwares were used:

- **MATLAB**: creates the design space and calls ANSYS in a loop for each variation in the design space; then reads the results from the analyses, that stores in arrays of characters;
- **ANSYS**: an APDL script has all the information for the modelling of a fuselage structure; it performs all the structural analyses.

#### 3.1 Modelling

We consider a conventional transport aircraft (narrow body), and a section of the fuselage which does not change significantly in length; only half of a fuselage section is modelled, due to symmetry about the aircraft axial plane. Also, although a floor was not modelled, its location is fixed (and so it is the door sill height relatively to the ground). The number of frames is also fixed. Two versions were developed:

- **Version 1**: The structure is divided in parts: above and below the cut-out, and at the lateral another division; the number of stringers changes with the height of the cut-out. The spacing is calculated from the number of stringers below the cut-out, \( s_{\text{str}} = \beta / n_{\text{str}} \), as the floor height is fixed.
- **Version 2**: both the number of stringers and frames are fixed, their spacing changing with the part of the section – below \( (s_{\text{str}} = \beta / n_{\text{str}}) \), above \( (s_{\text{strU}} = \varphi / n_{\text{strU}}) \) and lateral to the cut-out \( (s_{\text{strC}} = \gamma / n_{\text{str}}) \). The number of stringers below and at the lateral were chosen to be the same. Above the cut-out the number of stringers is such that the spacing did not differ much from the other two.

![Figure 2 - Dimensions of model (versions 1 and 2)](image-url)
3.2 Mesh

The skin and doubler are areas meshed with SHELL181, a plane (2D) shell type with 4 nodes and 6 degrees of freedom in each node, following Mindlin-Reissner Theory; the thickness, $t_s$, and the offset from the nodal coordinate system are the inputs. The stiffeners (frames, stringers, etc.) are discretized using BEAM188, 3D beam element with 2 nodes and 6 degrees of freedom at each node, formulated by the Timoshenko theory. Z-profiles are chosen for every stiffener, with exception for the edge and adjacent frames and the upper and lower sills, which have C-profile (Figure 3).

![Meshed model (versions 1 and 2) with the shell and beam elements in colours](image1)

3.3 Load Cases

Three load cases were implemented:

- Case 1: Internal Pressure ($x$1,33) [10]
- Case 2: Internal Pressure + Shear load, $F_y$
- Case 3: Internal Pressure + Bending Moment, $M_x$

The application of forces and moments is done using Multipoint Constraint (MPC) elements, a common method in FEA. In this method a node is created at some point – the masternode –, and connected to nodes that belong to the structure and then the load is applied in the masternode. A macro from PADT, Inc. [11] was used. The elements created by this routine are of the type MPC184, an element that creates a rigid connection between two deformable regions and transfers loads (forces and/or moments) between them. In the case of the longitudinal and shear forces, MPC184 were created at the right end of the model between a masternode at origin of axes and the nodes of the shell at the same z-location (Figure 4).

For the door-stop loads, $F_{DS}$, the same method was used, but using the RBE3 element. This element asks for a masternode with some mass. The most common is to mesh a KP with the type MASS21, a unit mass that provides also rotational inertia. A masternode was created at the centre of the cut-out and linked to the nodes at the end of the intercostals, which simulate the door-stops (Figure 4). Then the contribution of the pressure at the door to the force was applied at the masternode in the respective components.

![Figure 4 – Left: Pressure on the door transmitted to the door-stops; Right: Axial force due to bulkheads](image2)

3.4 Boundary Conditions

There is only a door along the fuselage part, so a constraint in axial direction in one of the edges is added, in this case the left one ($z = b_s$). The other extremity of the half cylinder is subjected to the loading. At the other side of the section we consider an emergency exit with the same dimensions. With both symmetry conditions, the loads and the rigid
body motion in mind, two groups of contraints were considered:

\[ \begin{align*}
1: & \quad z = b_z \rightarrow U_z = 0 \\
& \quad y = \pm 90^\circ \rightarrow U_z = 0, \; ROTZ = 0, \; ROTY = 0 \\
& \quad y = 90^\circ \rightarrow U_y = 0 \\
2: & \quad z = b_z \rightarrow U_z = 0, \; U_y = 0 \\
& \quad y = \pm 90^\circ \rightarrow U_z = 0, \; ROTZ = 0, \; ROTY = 0
\end{align*} \]

4. Convergence Analysis

4.1 Static Behaviour

Making in the first place a convergence study to see if the model converges, the plots of maximum displacement and maximum von Mises Stress were obtained (Figure 5). The number of elements created is in accordance with the mesh size. It is then expected that when varying the element size, the number of elements will not always change. An element is only created if its line’s length reaches the value of the input, size.

Figure 7 shows the distribution of stresses in model 2 for a mesh with size = 30 mm.

4.2 Buckling

In all experiments, the values of \( b_f \) are negative, meaning that the sum of loads will not instabilize the whole structure. This type of instability, known as crippling, appears in the areas near the constrained edges or the application of forces. A way of minimising this effect is to insert additional members, which reduce the effective length of the area. The fuselage’s section is also not sufficiently large in length for the results of these analyses to be an evidence of the real stability of the structure.

5. Parametric Studies

5.1 Reference geometries

The tables of Figure 8 show the ranges of variation of each design variable and the increment, as well as the design constraints. The plots of each quantity taken with Matlab are shown in Figures 9-16.
5.1.1 Internal pressure

- **Version 1**: variation of \(B\) (\(H=1850\) mm):

  Figure 9 – Variation in model 1 with the cut-out’s width

- **Version 1**: variation of \(H\) (\(B=810\) mm):

  Figure 10 – Variation in model 1 with the cut-out’s height

The calculation of the Buckling factor was not done, otherwise none of the other quantities would be written in the file with the results because for some analyses ANSYS hung.

- **Version 2**: variation of \(B\) (\(H=1850\) mm):

  Figure 11 – Variation in model 2 with the cut-out’s width

- **Version 2**: variation of \(H\) (\(B=810\) mm):

  Figure 12 – Variation in model 2 with the cut-out’s height

Here, also the program stopped working before writing the results for heights over 1980 mm, so the plots show less points.

5.1.2 Internal Pressure + Shear Load

- **Version 2**: variation of \(B\) (\(H=1850\) mm):

  Figure 13 – Variation with the cut-out’s width (case load 2)
5.2 Modifications to initial model

An “what-if” analysis was done to both models, but only the important results are here commented.

- **Version 1:**
  - frame web height decreased to 50 mm;
  - edge frame web height decreased to 100 mm;
  - frame flange width decreased to 20 mm;
  - sill’s thickness decreased to 1,2 mm.
  - number of stringers below the cut-out, went from 10 to 5.

With these changes, the slopes in the plots of each quantity changed. An optimised configuration was chosen based on the parametric study of the height (Table 2). There was a decrease in the Weight of 531,80 N relatively to the same point in the reference structure.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, B</td>
<td>810 mm</td>
</tr>
<tr>
<td>Height, H</td>
<td>1880 mm</td>
</tr>
<tr>
<td>Weight, W</td>
<td>2080,64 N</td>
</tr>
<tr>
<td>Maximum Stress</td>
<td>277,73 MPa</td>
</tr>
<tr>
<td>Maximum displacement</td>
<td>17,78 mm</td>
</tr>
<tr>
<td>Total elastic energy</td>
<td>4005508,65 J</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>12,33 Hz</td>
</tr>
</tbody>
</table>
Doubler thickness decreased to 2 mm.

An optimised configuration was chosen based on the parametric study of the height. There was a decrease in the weight of 463.28 N relatively to the same point in the reference structure.

Table 3 – an optimised configuration for model 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, B</td>
<td>810 mm</td>
</tr>
<tr>
<td>Height, H</td>
<td>1700 mm</td>
</tr>
<tr>
<td>Weight, W</td>
<td>2022.70 N</td>
</tr>
<tr>
<td>Maximum Stress</td>
<td>278.30 MPa</td>
</tr>
<tr>
<td>Maximum displacement</td>
<td>13.90 mm</td>
</tr>
<tr>
<td>Total elastic energy</td>
<td>3 829.16 J</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>12.36 Hz</td>
</tr>
</tbody>
</table>

Even having optimized configurations, these were done for each of the parameters, fixing the other. The advantage of a Sensitivity Analysis to the design comes from varying more than one parameter at the same time and changing the configuration for each of the points (B, H) to satisfy the design constraints and evaluate the weight.

### 5.3 Sensitivity Analysis

The analysis was performed with version 2 of the model and for the 1st load case (Internal pressure), using the Forward Difference Scheme. It took 2 hours and 30 minutes in total, using a PC Intel® Core™ i7-4700MQ CPU @ 2.40GHz and 8Gb RAM. The plots are shown in figures 17 to 20.

Figures 17 to 20 are interpreted as the obtained derivatives \( \frac{dW}{dB} \) and \( \frac{dW}{dH} \) for each point (B, H). Observing the plots, one can conclude that the weight always decreases with an increasing variation in the width, but the same does not happen for the a variation in height with the same sign. In the range approximately between 800 and 1000 mm, for \( H = 1100 \) mm, the variation is positive, meaning that the weight is increasing.
6. Conclusions

A study was conducted using a fuselage section with a door cut-out with the goal of studying the sensitivity of the weight to the change in parameters of its surrounding structure. For the first model, as the number of stringers is not fixed, the functions have discontinuities with the variation of H. The sensitivity of each parameter using the Finite Difference method could be obtained more easily with version 2. The behaviour of the material concerning its strength is not straightforward and a more detailed study should be done. For a comparison between the weight of structures that fulfill the design constraints for each dimension of the cut-out, a manual or automatic optimisation based on adding or removing material to the structure should be done. It would be interesting to have the same study being implemented in a composite fuselage, ideally with a cut-out having round corners. Additionally, to model the floor, the door itself and auxiliary sills would certainly add value.

References


[8] Reinforcement of a Door-Cut-Out in a Pressurized Aircraft Fuselage: https://w3 mediapool.hm.edu/mediapool/media/fk03/fk03_lokal/temp/verschiedenes/rumpler_1/konws9900_1/konws9900.html


[10] EASA CS-25 Large airplanes, Sub-part C.