MATERIAL FLOW ANALYSIS - A COMPARISON OF MANUFACTURING, USE AND FATE OF CFRP- FUSELAGE COMPONENTS VERSUS ALUMINIUM-COMPONENTS FOR COMMERCIAL AIRLINERS

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INTRODUCTION

The world wide air traffic constantly increased during the past decades, a trend that is estimated to continue within the next 20 years. To cover the growing demand in air transportation, new airplanes with a sales volume of more than 1000 Billion Euro have to be produced in this period [1]. To reach the target market share of 40-50 %, the European aircraft industry is challenged to advance its technological competence towards aircrafts that can be produced cost effective and that are light weight and fuel saving. Besides the application of modern engines, the use of fibre reinforced materials as an alternative to conventional aluminium alloys seems to be path-breaking to achieve these goals. Fibre reinforced materials are lighter and – if fitted in adequacy to their anisotropic qualities – stronger than aluminium.

Particularly carbon fibre reinforced polymers (CFRP) seem to be suitable as construction materials for aircraft structures due to their excellent mechanical properties and low specific weight of 1.55 g/cm^3 (aluminium: 2.8 g/cm^3). Because of the expensive and elaborate production process the use of CFRP in larger passenger airplanes is still restricted to relatively small structural parts (e.g. vertical stabilizer, wing flaps, fairings). The development of innovative production technologies is currently pushed forward to allow cost effective serial production of large and complex modules like wing and fuselage. A fuselage structure made out of CFRP could save more than 25 % of weight compared to the conventional aluminium fuselage.

So far there is no information available about mass and energy flows related to the production, use and recycling of a CFRP fuselage and a conventional aluminium fuselage. This work was performed within the project “Schwarzer Rumpf” by the Institut für Technikfolgenabschätzung und Systemanalyse (ITAS). The comparison is based on the dimensions of an A320.

PROCEDURE

System boundaries and data collection

The investigations were focused on the main structural parts of the A320 fuselage (FIGURE 1), which are skin panels, stringers (longitudinal stabilizers) and frames (cross section stabilizers), furthermore on the required fasteners (aluminium or titanium rivets and connecting plates "clips") and surface coatings.

The conventional A320 fuselage is composed of several tubular sections, each section consists of three panels riveted to circular frames. The stiffened panel elements are constructed by riveting stringers to the skin in longitudinal direction.

For the comparison between the aluminium- and CFRP fuselage, a 1:1 transformation was chosen, i.e. the CFRP-fuselage was supposed to consist of roughly the same geometrical parts as the aluminium fuselage. New fuselage construction concepts that have been developed within the "Schwarzer Rumpf" project presently offer too little data to be taken into account for the mass balance.

For the analysis of the aluminium and CFRP production lines the main process steps from the mining of the raw materials to the final product were identified and connected to a process chain with modules, which contain single processes or accumulated processes representing a complete production step.

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The process analysis and data collection was the most elaborate part of the work, since the production processes even at Airbus Industry itself had not yet been analysed in detail. In order to detect the most important process steps with respect to energy and material consumption and to decide which processes had to be analysed in depth, the essential process steps had to be identified and described with respect to the technology applied.

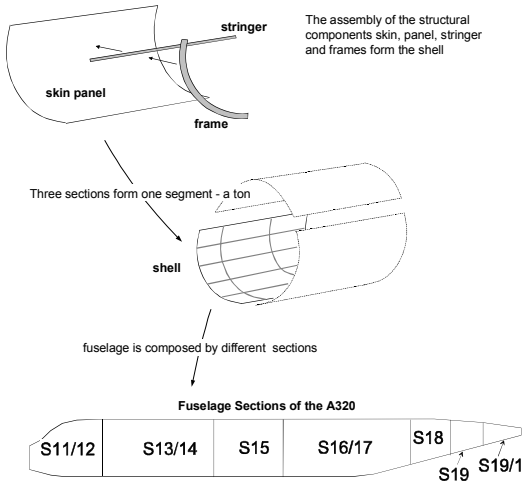

FIGURE 1: Simplified schematic depiction of the structural composition of an A320 fuselage

Data were collected from industry (e.g. raw material producers, Airbus Industries), industrial associations and scientific institutes. While for the production of primary aluminium and the semi-finished aluminium products actual studies could be used – in particular from the European Aluminium Association (EAA) [2], only inadequate data related to material and energy flows as well as production processes were available for the CFRP line. Therefore a completely new, improved database was built up for the production of fibres, resins and fabrics using actual data from relevant CFRP producers like Tenax Fibers and Saertex, which takes into account up to date production technologies. For data inventory and balancing the software tool GaBi 3.2 [3] was used.

Accounting for production residues

The total weight of the A320 aluminium fuselage structure of 4547 kg is the sum of 2196 kg skin panels, 598 kg stringers, 1399 kg frames, 238 kg clips and 116 kg rivets. The production of these structure components requires an initial input of some 12400 kg aluminium alloys, from which 3438 kg are recycled directly in the aluminium plant or rolling mill as pure alloys ("primary residue"). Therefore this amount of aluminium is only balanced with respect to the energy necessary for re-melting and is not subject of further steps within the mass balance.

The aluminium residues generated at the Airbus plants in the course of further processing the semi-finished parts sum up to 4670 kg. As these residues consist of a mixture of different alloys they can not be reused for the original products and thus can not be recycled within the system boundaries as it is the case for the "primary residues". They are therefore taken into account for the energy and mass balance. Figure 2 shows the estimated share of aluminium compounds for the production of the A320 aluminium fuselage: the largest share is the material for skin, stringers, frames and clips, followed by the primary residues from the aluminium plants and rolling mills, secondary residues like chips and cuttings arising in the airbus factories and residues arising from chemical and mechanical milling.

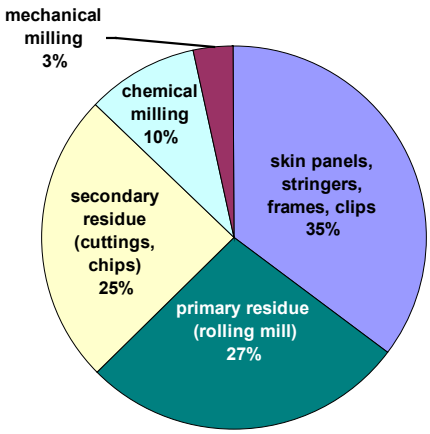

FIGURE 2: Estimated aluminium consumption for the production of the A320 aluminium fuselage

In the CFRP line, the balances are based on a 27 % weight reduction compared to the aluminium fuselage structure. The CFRP system consists of 60 % fibres (multilayer fabric made of several unidirectional layers) and 40 % resin. Production residues like cuttings and resins were estimated quantitatively for the different process steps and considered within the balance as wastes for recycling outside the system boundaries.

Analysis of the production process of the CFRP fuselage

Basic materials for the production of CFRP fuselage components are carbon fibres and resins. Carbon fibres are obtained from polyacrylnitrile (PAN) precursor fibres by different thermal treatment steps (stabilisation, carbonisation, and for special applications further graphitisation). The rovings are processed to woven fabrics or unidirectional tapes which form multiaxial fabrics used in composite production. The fabrics are incorporated into a polymeric matrix, in this case the commercial resin (Blendur™) which consists of 80 % diphenyl methane diisocyanate (MDI) and 20 % epoxy resin. It was chosen by the DLR within the project due to its good mechanical properties and processing features in the Single Line Injection method (SLI) [4], a new resin injection method for a cost effective production of large composite structures. This method is a combination of the RTM method and selected elements of the prepreg technology.

The operation sequence of the production of a CFPR fuselage with emphasis on the steps of processing the cured CFRP components (here: fuselage shells) is shown in a flow chart generated using the balancing software tool GaBi 3.2 (FIGURE 3). The modules (depicted as rectangular boxes) show the different process steps. For better clearness, some modules comprise several process steps, e.g. the module "production of CFRP" includes the all process steps of the composite part production described above. The CFRP shells are mounted with titanium-CFRP laminate clips, titanium bolts and steel screws, respectively. The final process step is the painting of the components. The total sequence of the production of semi-finished products (titanium and steel) as well as essential tooling steps like hole drilling, placing the bolts are included.

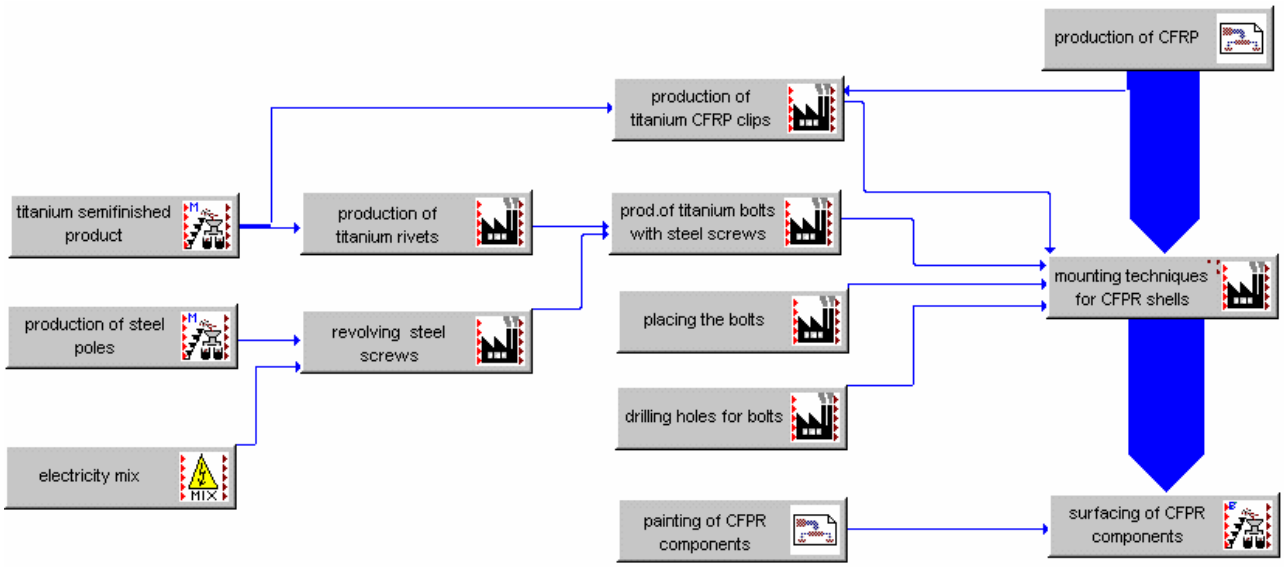

FIGURE 3: GaBi 3.2 flow chart of production, mounting and connection of CFRP components to a CFRP fuselage

RESULTS

The primary energy consumption was calculated to 2300 GJ for the production of the aluminium fuselage and to 2100 GJ for the CFRP fuselage (FIGURE 4). Taking into account various uncertainties related to the data quality for several process steps, it can be stated, that for the current situation the energy demand for both process chains is roughly on the same level. In figure 4 – figure 8 the different parts of the columns have the following meaning:

- production of raw materials and semi-finished products: **aluminium alloys** and rolling plates, **carbon fibre** fabrics; **titanium** alloys (aluminium fuselage) and **resins** (CFRP fuselage) are shown separately
- the **production** process for the further treatment of the semi-finished products: e.g. milling of frames and solution annealing for the aluminium parts, autoclave based resin injection (**SLI**-technology) for CFRP-parts
- **mounting** and connecting techniques: rivets and clip mounting incl. phases of operation for the aluminium fuselage (e.g. drilling of rivet holes), connecting of different parts in the CFRP-fuselage using titanium plates.
- **painting**: surface-treatment and -coating including special pre-treatments like e.g. anodic oxidation for the aluminium fuselage, excluding the finish coating since this can be considered to be similar for the aluminium- and CFRP-fuselage.

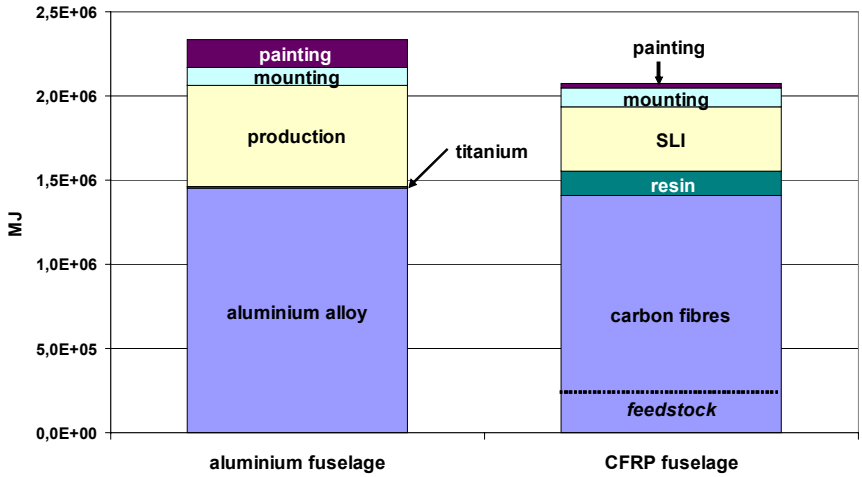

FIGURE 4: Primary energy consumed for the production of the aluminium and CFRP fuselage

In both production lines the major share of energy consumption results from the production of the raw materials (aluminium alloys and carbon fibre fabrics). Regard should be paid to the fact that the metal fuselage mainly consists of non-energetic resources whereas for the production of carbon fibres and resins mainly mineral oil based educts are used. Approximately 260 GJ of these educts remain in the fuselage material as the so-called feedstock energy. Feedstock energy represents the energy of the fuel that is taken into the system but used as materials rather than fuels.

Major energy consumptions for the further treatment of the semi-finished products can be assigned to the mechanical and chemical treatment of aluminium parts (in particular milling of frames and chemical milling of skin panels) and the autoclave process used in the SLI method. This technology uses an innovative resin injection management to embed the preformed carbon fibre fabrics with resin. Due to the fact that the autoclave has to withstand high pressures and temperatures required in the SLI-method, it is built out of massive steel walls which absorb much more heating energy than the CFRP part itself. Another large share of the energy is consumed by the production of nitrogen which is used as a protective gas in the autoclave.

While the production of the CFRP fuselage requires 10 % less energy compared to the aluminium fuselage (including the feedstock), the difference in CO_2 emissions amounts to some 25 % less (146 000 t for the aluminium fuselage production and 109 000 t for the CFRP fuselage production) as shown in figure 5. This is because – as mentioned above – the feedstock part of the energy balanced for the CFRP fuselage is not relevant with respect to emissions. Another reason is, that for the CFRP production the energy mix applied in this study involves a relatively high amount of nuclear energy as it is based on the situation in Germany, while for the production of the primary aluminium the energy mix of the European aluminium association has been taken into account which contains a smaller amount of nuclear energy and more CO_2 relevant fossil energy carriers. The EAA energy mix accounts for the fact that aluminium is a "global" product and the winning of bauxite and production of primary aluminium usually takes place in different countries using different mixtures of energy resources.

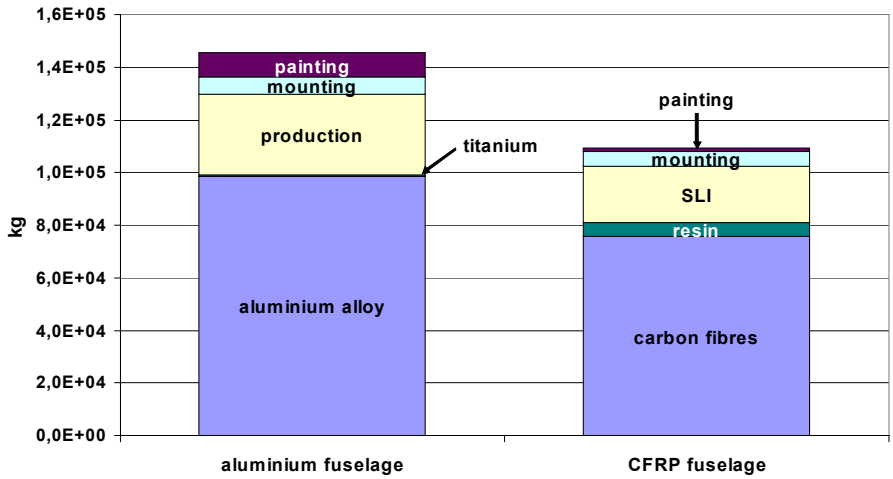

FIGURE 5: CO_2 emissions generated in the course of the production of the aluminium and CFRP fuselage

Some further examples for major emissions to air, residues from ore extraction and use of resources (gangue which mainly derives from brown coal mining is not included) related to the production and assembling of the aluminium

fuselage and the CFRP fuselage are shown in the following figures 6–8. It can be seen that in some cases significant amounts of emissions are related to energetically secondary processes: painting processes account for a large amount of non-methane volatile organic compounds (NMVOC), the production of titanium alloys used for mounting generates large amounts of residues from the extraction and preparation of the titanium containing ores. It should be emphasised in this context that the further processing of the semi-finished products contribute significantly to the mass and energy balances and have to be regarded carefully.

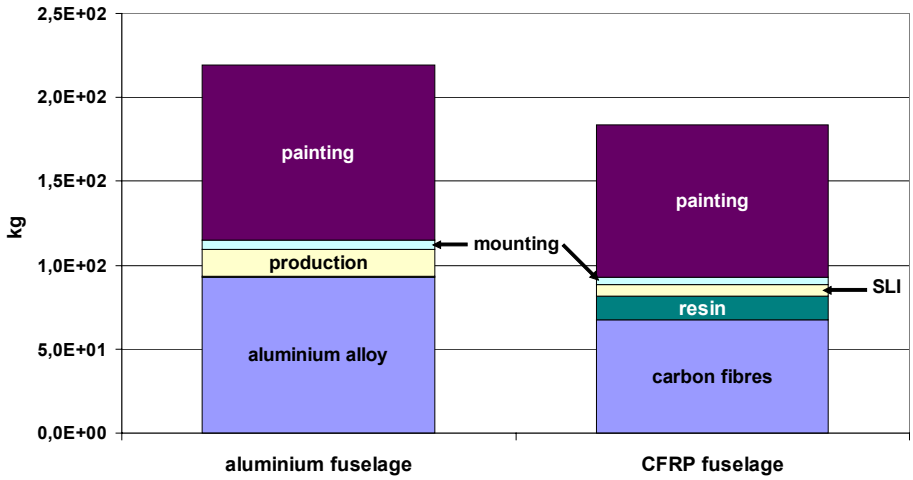

FIGURE 6: NMVOC emissions generated in the course of the production of the aluminium and CFRP fuselage

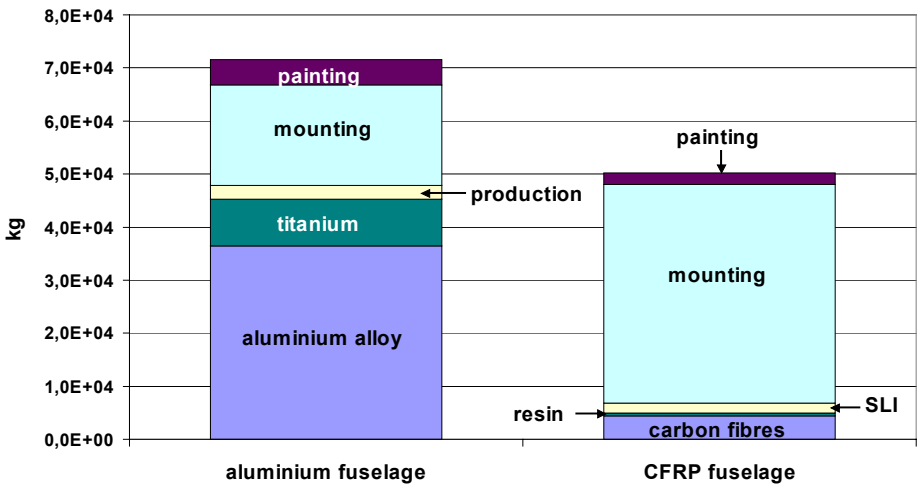

FIGURE 7: Residues from ore extraction

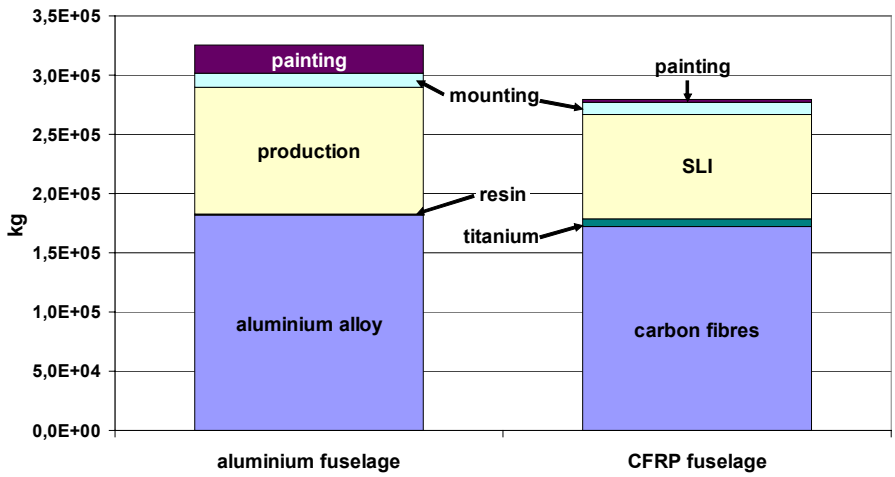

FIGURE 8: Use of non-regenerative resources (gangue which mainly derives from brown coal mining is not included)

CONCLUSIONS AND RECOMMENDATIONS

The analysis of the aluminium production chain revealed some major energy and material intensive steps that offer potential for more economic operations some of which are about to be applied in the near future. Some material- and also cost-saving improvements are:

- for the aluminium fuselage
  - Laser welding to substitute the highly work and weight intensive riveting technology,
  - New aluminium casting technologies which offer new possibilities for the construction of integrated aluminium parts
  - By a further improved scrap collection the major part of the aluminium scrap could be recycled for the original products
  - Anodic oxidation with chromic acid is highly energy intensive and causes highly toxic waste waters that have to be treated carefully
- for the CFRP fuselage
  - New installations for the production of carbon fibres will save more than 10 % of energy in comparison to conventional plants. Additional saving potential will come with an increasing demand for CFRP-products and consequently larger production sites [5]
  - Optimising blank forming will further reduce cuttings and thus material waste
  - Substitution of the highly energy consuming autoclave process used in the SLI technology for resin injection and hardening by alternative technologies. For the resin hardening process a new microwave-technology is currently investigated at the Forschungszentrum Karlsruhe [6]
  - Substitution of titanium which has to be produced with an extremely high energy consumption. Improvement of the integrative construction could help to substitute titanium plates that are currently used to connect the shells of the CFRP fuselage model developed by the Deutsches Zentrum für Luft- und Raumfahrt (DLR).

PHASE OF USE

The use of CFRP in the considered fuselage components of an A320 could reduce its weight by roughly 1000 kg. An extension of CFRP applications for the total fuselage could increase this reduction to 2500 kg, which means a weight reduction of 24.2 % in comparison to the conventional aluminium fuselage and of 4.5 % related to the take off weight of an Airbus A320. Based on mission performance calculations, the resulting fuel saving amounts to 3.7 % during a 5300 km flight and 4.1 % during a 1900 km flight. Assuming a life time performance of an A320 of five 1900 km-flights per day over 20 years this results in a reduction of fuel consumption of 8100 t and a reduction of CO_2 emissions of 25000 t (TABLE 1). For the reduction of emissions in the altitude range below 1000 m in the surrounding of the airport the reductions amount to 3.5 % for NO_x, 1.2 % for CO and 2.3 % for hydrocarbons.

TAB. 1: Reduction in weight, fuel consumption during life time and resulting CO_2 emissions for a CFRP fuselage in comparison to a conventional aluminium fuselage type Airbus A320

Weight reduction	Reduction of fuselage-structure weight	Reduction of aircraft weight	Reduction of take off weight
2.5 t	24.2 %	6.1 %	4.3 - 4.5 %
Fuel consumption during service life time			
Aluminium alloy	CFRP	Reduction	Reduction
221 700 t	213 600 t	8 100 t	3.7 – 4.1%
CO_2-emissions during service life time			
Aluminium alloy	CFRP	Reduction	Reduction
700 000 t	675 000 t	25 000 t	3.6 %

MAINTENANCE AND REPAIR

While in the military field CFRP meanwhile is a standard structural material e.g. for tactical aircrafts, CFRP parts for commercial airliners are only used to a relatively small extend (e.g. flaps, vertical stabilizers, engine fairings). Information on the behaviour of CFRP in practice can thus only refer to these special parts. The following statements are mainly based upon information from the German Lufthansa Technik AG and refer to their experience with respect to the maintenance and repair of CFRP aircraft components.

New publications by Boeing [7], [8] report that world's airlines spend more than $40 billion on airplane maintenance each year – that is about 17 % of all airplane-related operating costs (FIGURE 9). Approximately 56 % of the accidents of commercial jet airplanes occur during landing approach or landing phase [9]. The share of damages – not accidents –

that takes place on ground is certainly higher. This general statement is approved by a statistical evaluation of Lufthansa [10]. From the analysed 168 damages, which occurred during January and February 1994, 67 affected the fuselage and more than 70 % belonged to the category 'foreign object damage' (FOD) on ground (FIGURE 10). Aircrafts operating in short or medium range were affected mostly because of their smaller height above ground. Another reason is that they have up to eight flights a day whereas aircrafts operating in long range distance touch down 1.5 times a day in average. Many of the damages on ground are caused during the embarking or disembarking phase by service vehicles, fork-lift trucks, passenger bridges, etc (FIGURE 11). They affect very often the area around passenger doors, cargo doors, fuel or other servicing inlets. It seems to be an important advice to the designers that within these areas monolithic structures should be preferred to sandwich panels with thin outer skins.

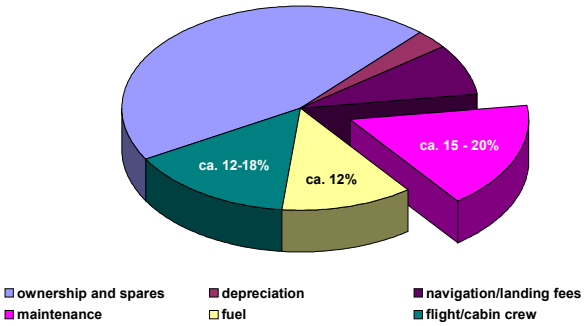

FIGURE 9: Airplane-related operating costs [7], [8]

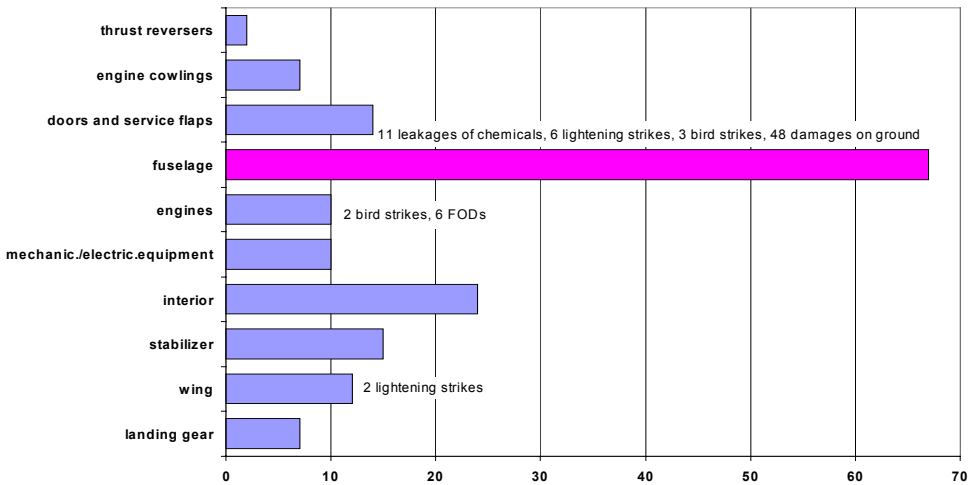

FIGURE 10: Analysis of the damage claims of Lufthansa within the period of January to February 1994 [10]

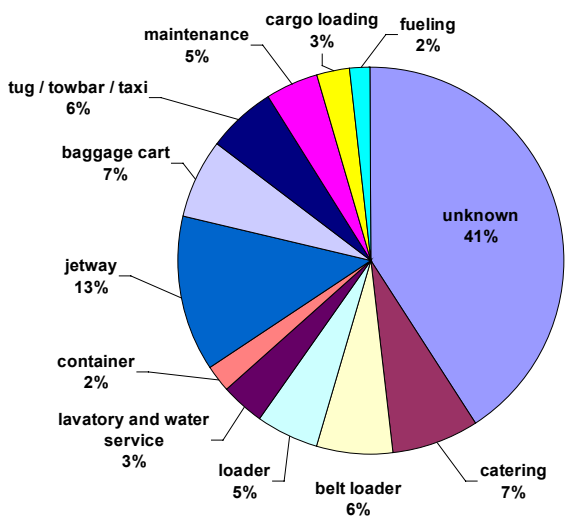

FIGURE 11: Causes of ground damage to aircraft [11]

Very often damages in CFRP parts cannot be detected by visual checks as it is possible for aluminium parts. The detection of those hidden damages requires non-destructive inspection technologies like ultrasonic or x-ray procedures. Once detected the surrounding area of the damage has to be inspected as well to make sure that no fluid ingress (water, de-icing fluids, hydraulic oil, etc.) or delamination had occurred. Not just delamination between the different single layers of sandwich components but also between fibres and resins may occur.

Normally the effort for the repair of *small damages* in aluminium structures or monolithic CFRP structures is relatively small. The repair of complex CFRP sandwich structures is more skilful. The repair of *large damages* is usually less expensive for CFRP than for aluminium components, as they mostly can be repaired in the workshop of the airline company, whereas larger repairs in aluminium structures often have to be placed externally which causes higher repair costs and longer aircraft downtimes.

For the repair of CFRP parts a large amount of different expensive materials (tapes, prepregs, resins, different foils, bonding material, etc.) has to be kept in stock, as the prescriptions for the repair of different parts and damage-types are very strict and specific and an exchange of similar materials is not yet allowed. Many of the CFRP repair materials - in particular temperature sensitive prepregs – can only be stored for a restricted time (maximum 6 months) at -18°C and have to be disposed when they have exceeded their date of expiry. In contrast for the repair of aluminium parts aluminium sheets with about 10 different strengths for the two most common alloys (Al-Cu-Mg and Al-Mg-Zn alloys) are stored. Another costly aspect is that instead of the formerly projected cost reduction for CFRP, the prices for CFRP spare parts have increased strongly in comparison to those for aluminium spare parts.

Well engineered and designed CFRP parts have the advantage to be extremely fatigue proof, so that almost no cracks and fractures emerge during normal flight operations. Furthermore CFRP is non corrosive which makes elaborate protection against corrosion redundant. On the other hand the very small electrical conductivity of CFRP parts requires a coating with special antistatic coatings, metal foils or nets for the protection from damages caused by lightening strikes.

An advantage of aluminium parts is their damage tolerance in case of minor damages like small dents or scratches. Unlike CFRP parts which have to be repaired immediately (in worst cases by expensive transport of exchange parts to the respective airport), the repair of slightly damaged aluminium parts in many cases can be postponed until the aircraft is back in the port of registry or until the next scheduled maintenance.

Above all it can be resumed that because of its minor weight and good properties concerning stiffness, corrosion resistance and a lack of fatigue behaviour CFRP has excellent chances to be an important structure material for future aircraft. At the moment there are no principle advantages or disadvantages of the two considered materials in respect to maintenance and repair. Unless it is very important that even during the design phase people from the maintenance and repair departments of leading airlines (for example Lufthansa Technik) participate with their experience in developing maintenance and repair friendly components with good accessibility for inspection and repair procedures.

RECYCLING OF ALUMINIUM AND CFRP PRODUCTION RESIDUES

In the context of this study only the production residues are considered, the recycling of new parts rejected due to defect, exchange spare parts or the fate of the complete fuselage are neglected up to now, a subject for further research activities. The production of the aluminium fuselage generates metal losses like cuttings and chips. A large part of this scrap arises from the production of the semi-finished products in the aluminium plant and rolling mill and can be fully recycled without quality losses with just a trickle of the energy required for the production of primary aluminium.

Scrap from processing the semi-finished parts at Airbus facilities usually consists of different aluminium alloys. Although it must not be reused for the original parts, it is a valuable material for high quality secondary aluminium products. An improved scrap collection could provide this amount to be reused for the production of the original products.

On the other hand, no residues from the production of CFRP can be recycled into the process chain to be reused for the original products. Due to the chemical composition of the carbon fibres and the resins they cannot be recycled as it is possible for aluminium, they can only be "down-cycled" to products of minor quality, consequently loosing their value for production of the original (aircraft) parts.

Mostly CFRP residues are deposited. Recycling technologies for residues of CFRP, fibres and resins are still in the beginnings. At present the material is normally shreddered to particles of defined size and used as admixture in secondary polymeric products like e.g. sheet moulding compounds. This is also practised for CFRP residues from the Airbus production site in Stade, which are delivered to a specialized recycling firm (Hadeg Recycling GmbH, Stade) located nearby. Besides particle recycling Hadeg investigates thermal processes to recover the carbon fibres by simultaneously using the heating value of the resins in a pyrolytic process. In this process the material is shreddered too prior to pyrolysis.

It can be stated that currently particle recycling and pyrolysis seem to be the most interesting ways for the recycling of CFRP residues. Nevertheless there is still no market for processed CFRP residues. This is because of too small amounts of residues existing for effective recycling, limited fields of applications, insecurities on the side of producers

concerning long performance behaviour of CFRP-parts containing recycled material and an in many cases negative image of recycled materials, particularly if admixed to high performance compounds. An improvement of this situation requires enforced efforts to find new, interesting applications for recycled CFRP residues. The image of the recycled material has to be improved in order to overcome the resistance of engineers to use it as a fully qualified material. New research activities in the field of recycling technologies and advanced systems analysis have to be performed.

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