Design of a composite nose wheel for commercial aircraft

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Abstract. Innovative approaches for lightweight design of components can contribute significantly to reduced fuel consumption and emissions of future aircraft. Within the framework of the European aviation research program Clean Sky 2, an innovative design of an aircraft nose wheel for the A320 is developed using carbon fiber reinforced plastics (CFRP) in order to demonstrate a weight reduction potential of 27% compared to conventional designs. In the present paper, the approach of the development process and the final detailed design of the composite aircraft wheel as well as a manufacturing concept are presented, various design challenges are highlighted and the solutions developed to meet them are discussed. Within a concept phase different structural design principles for the wheel are analyzed, taking into account the challenging load cases during different phases of aircraft operation. The selected innovative design principle is further elaborated into a detailed design considering design challenges such as space, installation, and safety requirements, as well as integration of bearings, seals and joint solutions. Also, structural analysis of the composite components via FEA and experimental validation of the joints are discussed. In addition, the manufacturing concept for the complex wheel geometry via resin transfer molding (RTM) using carbon non-crimp fabrics is presented and an outlook on the future manufacturing and testing of wheel prototypes is given.

1. Introduction

Aircraft wheels are highly stressed components which have to endure static and dynamic loads that occur during different phases of aircraft operation. Conventional aircraft wheels for commercial aircraft are made of aluminum alloy and can weigh up to 100 kg depending on the type of wheel and aircraft [1]. They are usually designed as split hub wheels, allowing the assembly of the stiff tire by demounting two wheel halves. The wheel is seated on the landing gear axle via a taper roller bearing. This design principle is applied for nose wheels as well as main landing gear wheels. Based on research, it appears that there has been no major further development of this wheel design principle and material selection within the last decades. Due to their excellent mechanical properties, CFRP offer high lightweight potential and are increasingly being used in modern aircraft design. E.g. A350 XWB consists of 53% composite, mainly used in the fuselage and wing structures [2]. Within the automotive sector, CFRP wheels have successfully been introduced as serial parts, despite the manufacturing challenges due to the complex geometry, achieving a weight saving of 20 to 30% [3] [4] [5] [6] [7]. The objective of this research project is the demonstration of lightweight potential of composite wheels in aircraft sector, choosing the A320 nose wheel as first benchmark. This paper elaborates on the development process of the lightweight design. Other related topics such as material evaluation, fatigue and adhesive analysis, as well as manufacturing and testing of wheel prototypes may be presented in future publications.
2. Analysis of design principles
Apart from material selection, the structural design of the component is a key factor when it comes to lightweight design. Therefore, within a concept phase, different possible geometrical design principles are analyzed under the critical ultimate load condition and a preliminary topology optimization is carried out in order to identify the best structural design principle for the wheel.

2.1. Load conditions
The main function of the nose landing gear is the support of the fuselage and control of the rolling direction of the aircraft. Different radial and lateral loads occur during taxi operations, take-off and landing. Within Certification Specification CS-25 [8] the European Aviation Safety Agency (EASA) defines load factors representing the ratio of the occurring force component to the static force under maximum ramp weight of the aircraft, in order to define limit loads for each operating condition. Calculation of these load factors show that critical radial loads for the nose wheels occur in the braked roll condition. Due to the breaking torque at the main landing gear, high resulting vertical forces occur at the nose landing gear, which have to be supported by the two nose wheels. Critical lateral loads occur during turns. Within ETSO-135a [9] the EASA defines ultimate loads as 1.5 times limit load for forged aluminum wheels and 2.0 times limit load for cast aluminum wheels, under which aircraft wheels need to be tested for certification. Certification standards for composite aircraft wheels do not exist, therefore the load requirement of the composite wheel is defined as 2.0 times limit load as a conservative approach (see Table 1). With respect to fatigue evaluation, a radial load of 63.75 kN is calculated for roll tests according to ETSO, which needs to be endured for 3220 km.

| Load condition                        | limit load  | ultimate load |
|---------------------------------------|-------------|---------------|
| Critical combined radial and lateral load condition | $F_R = 82.7 \, kN$ | $F_R = 165.3 \, kN$ |
|                                       | $F_L = 38.9 \, kN$ | $F_L = 77.8 \, kN$ |
| Critical radial load condition        | $F_R = 132.2 \, kN$ | $F_R = 264.4 \, kN$ |
|                                       | $F_L = 0$     | $F_L = 0$     |

Unlike main landing gear wheels, nose wheels are not equipped with breaks, therefore only torque of inertia during spin up of the wheel leads to axial momentum, which is considered negligible after calculation. Temperature requirements are defined within the range of ambient temperatures from -50° C to 60° C. Tire pressure for static tests is defined as 12.3 bar [9].

2.2. FE-model of design principles
The design principles contain different geometrical structures of the cross-sectional profile of the wheel, such as the I-, Z-, V-, trapezoid-, C-, A- and X-profile, as well as the combined profiles trapezoid+A, trapezoid+X and trapezoid+Z (see Figure 2 top) and therefore create different load paths from the load introduction area to the bearing seat. For comparison, all cross-sections are designed to possess the same mass and can therefore differ in their wall thicknesses, depending on the size of the cross-sectional area. Only the wheel rim area is constant for all models, so that any bias in the comparison due to different flange stiffnesses is avoided.

Figure 1. Shell model of exemplary design principle with boundary conditions [10].
Shell models with a quasi-isotropic material model are created in order to evaluate the deformation under the different load cases such as tire pressure, radial load, and lateral load (see Figure 1). Tire pressure is applied all over the outside of the cylindrical wheel rim and flange area. Ultimate radial and lateral loads are introduced at the semicircular contact area between wheel and tire in the form of a parabolic load distribution. Cylindrical supports simulate the bearings of the wheel.

2.3. Evaluation of design principles

Figure 2 shows the evaluation of the maximum deformations of the different design principles under the described loads, which always occur at the outer rim flange position.

Figure 2. Analysis of design principles showing the trapezoid+A profile as best design principle with the least deformation [11].

The evaluation shows that the largest deformation under all loads of 4.84 mm occurs within the C-profile due to the low structural resistance to both radial and lateral loads. In contrast, the trapezoid profile shows only little deformation under radial loads due to the direct load path between load introduction area and bearing seat, but low resistance against lateral load. The smallest deformation under all loads of 0.47 mm occurs for the trapezoid+A profile, which is thus identified as the best structural design principle. Here, the lateral load is supported by the additional diagonal elements, creating a stiff geometrical structure overall. Furthermore, the analysis shows for all design principles that pure tire pressure only results in very little deformation compared to the radial and lateral loads.
2.4. Topology optimization
Independently from the analysis of the shell models, a simplified topology optimization is carried out, using Ansys Workbench. Starting from a basic material layout, the model is optimized for the given design space and boundary conditions, using the finite element method. The objective of the optimization is the maximization of structural stiffness under a given mass requirement. The analysis also identifies the trapezoid+A profile as the most suitable for the load transmission (see Figure 3).

![Figure 3. Simplified topology optimization.](image_url)

3. Detailing of the wheel design
In the following, the overall wheel design is presented and selected design details are elaborated.

3.1. Overall wheel design
The overall wheel design consists of two detachable wheel halves in order to allow mounting of the tire. The joint is sealed by a circumferential seal ring (see Figure 4). Each wheel half consists of three main components: a composite disk, a composite drum and a metal hub element (see Figure 5).

![Figure 4. Overall wheel design consisting of two detachable wheel halves and a circumferential seal.](image_url)

![Figure 5. Main components of the wheel half: composite drum and disk with metal hub element.](image_url)

When assembled by a bolted connection, the two wheel halves create the desired trapezoid+A cross section, resulting in a stiff overall structural design (see Figure 6). Main function of the metal hub element is the reliable integration of the taper roller bearing by realizing a precisely machined bearing seat. Due to its conical shape, a large bonding area is achieved so it can be integrated in the composite drum by an adhesive joint, secured by a retaining ring. The disk is joined with the hub element by bolting at the inner diameter. The large outer diameter allows an adhesive joint with the drum, creating an additionally form-fitted and stiff double walled structure at the rim flange.
3.2. Analysis of deformation

A finite element model of the overall design is created as a linear-elastic solid model within the Ansys ACP software. The composite parts are modelled as multi-layered non-crimp fabric using ply-wise material data from characterization of unidirectional specimens made of high performance carbon fiber and epoxy based resin. Analysis and iterative optimization of the components, taking into account parameters such as fiber layup, wall thickness, and material distribution under the given manufacturing limits, result in a final wheel design with 27% mass reduction compared to the conventional aluminum wheel while still achieving sufficient strength of the components and joints. Figure 7 shows the analysis of the overall deformation under ultimate loads. Due to the structural design and high stiffness of the composite parts, 0.85 mm max. deformation occurs in the ultimate radial load case and 1.9 mm in the combined load case, which is considered acceptable to avoid critical tire leakage.

![Figure 6. Sectional view of the assembled composite wheel creating a stiff geometrical cross-section.](image)

![Figure 7. Analysis of deformation of overall wheel design under ultimate combined load case (left) and ultimate radial load case (right).](image)

3.3. Composite analysis

In order to identify a suitable fiber lay-up for the composite parts, the force and moment resultants in different areas of the wheel during a 360° wheel rotation are analyzed. After optimization of the lay-up, FE-analysis of the parts are done, evaluating the inverse reserve factor (IRF) of first ply failure according to Puck’s failure criterion [12]. The Puck criterion distinguishes fiber failure and three different inter-
fiber failure modes, referred to as modes A, B, and C. The analysis shows that critical fiber failure, as well as critical inter-fiber failure mode B and C, are not to be expected. The expected failure in the critical areas is inter-fiber failure mode A (see Figure 8), which occurs under positive transverse stresses of the individual ply. The critical areas are located in the radius area of the composite drum (IRF of 1.6) and radius area of the disk (IRF of 2.2). For the interpretation of these values, it should be kept in mind that the applied ultimate load (UL) is conservatively chosen as twice the limit load. For metal wheels under the same load, it would be acceptable to significantly exceed the yield limit, according to ETSO [9]. Much like yielding in metals, inter-fiber failure mode A is not per se critical in terms of the integrity of the composite wheel. Whether subsequent redistribution of stresses triggers more severe damage mechanisms under UL is to be investigated by the tests, since progressive damage simulation is outside the current project’s scope. Under roll-test loads, the computed IRF for the same mode A would be in the vicinity of 1, which is predominantly due to thermal residual stresses for the effective difference in temperature assumed here. This effective difference, however, is notoriously difficult to estimate so that further strengthening of the part may lead to an overly conservative design. At the present prototype stage, the computed values are therefore considered acceptable.

![Figure 8. Stress analysis of composite wheel parts under ultimate radial load case showing critical areas with inter-fiber failure mode A according to Puck [12].](image)

3.4. Evaluation of center joint
The wheel halves are connected via bolted joints in the center plane which can be accessed through the cut-outs in the disk components (see Figure 9 left).

![Figure 9. Bolted center joint with accessibility through cut-outs in disk component (left); form fitted sleeve design (center); experimental investigation of bolted specimen (right).](image)

The analysis of the force resultants between the wheel halves show that the most critical bolted joint is loaded with a shear force of up to 17 kN under static ultimate radial load. Within fatigue loading in roll test the bolted joint is loaded with a shear force of up to 4 kN. In order to compensate these high shear
forces, the joint is realized with a male-female sleeve design (see Figure 9 center). The form fit between the sleeves transmits the shear forces. As a benefit, the bolt diameter can be reduced by a factor of 3. The evaluation of the bolted joint is done experimentally. A specimen designed as a single shear lap joint between two composite parts and featuring the form-fitted sleeves is realized (see Figure 9 right) similar to the design in the wheel. The joint withstands fatigue loading at 4.25 kN, 6.125 kN and 8.5 kN for 3×10⁶ load cycles each, without failure or significant decline in stiffness. A residual static test on the specimen shows final failure of the joint at 23 kN. At this point the metal sleeves show plastic deformation.

4. Manufacturing concept

4.1. Selection of material and manufacturing process
Resin Transfer Moulding (RTM) is chosen as manufacturing process for the composite parts due to the complex geometry of the wheel. Also, the components require a defined geometry on both sides, which is achieved by the closed mold process in RTM. Standard composite material certified for aircraft application is specified for the design, using non-crimp-fabrics with Tenax® HTS carbon fiber and Hexflow® RTM6 epoxy as resin system.

4.2. Manufacturing of composite drum
The complex geometry of the composite drum requires a preforming concept which enables the two-dimensional fabrics to be draped into a complex three-dimensional shape without faults such as wrinkling. Therefore, a sectorial preforming concept is developed as shown in Figure 10 and Figure 11. The 360° geometry is divided into 30° sectors in which the cut-out pattern of the fabric can be draped flawlessly. In order to avoid weak lines between the patterns, the layup is realized with overlapping primary and secondary sectors as shown in Figure 10 and Figure 11. By alternating ±90° fabrics and ±45° fabrics, a quasi-isotropic layup can be realized. Also, with this preforming concept a homogeneous fiber volume content can be achieved in the whole part.

![Figure 10. Preforming concept: sectorial stack-up with overlapping NCF cut-out pieces.](image)

![Figure 11. Manufacturing concept of composite drum.](image)

4.3. Manufacturing of the composite disk
Due to its simple flat-shaped geometry, the composite disk can be realized by stacking up large pieces of non-crimp fabric. The fiber orientation is 0°/90°, ±30° and ±60°. After the RTM process and water jet cutting of the component, this results in continuous fibers in the radial direction of each spoke.
5. Conclusion and outlook
The analysis of design principles shows, that a wheel cross section in form of a trapezoid+A profile is most suitable for a lightweight wheel design. It provides a direct load path from the load introduction area to the bearing seat, thus supporting the high radial loads. Lateral loads are supported by the diagonal elements, creating a stiff overall structure.

Further development of the design principle into a detailed wheel design considering various requirements such as structural durability, mountability and manufacturability results in an innovative composite wheel design with 27% mass reduction compared to the conventional aircraft nose wheel. A manufacturing concept is developed, which allows the preforming of the complex composite drum by using a sectorial lay-up approach.

Further steps of the Clean Sky 2 project include further improvement of the manufacturing process and the realization of several wheel prototypes which are planned to be tested in ultimate static load tests as well as roll tests according to ETSO [9].

References
[1] Niu M C 1988 Landing Gears Airframe Structural Design (Conmilit Press Ltd).
[2] FAST (Flight Airworthiness Support Technology) 2013 June Special Edition Airbus Technical Magazine.
[3] Ireson N 2018 May 4 The Future of Carbon-Fiber Rims Automobile.
[4] Sloan J 2017 Feb 10 Porsche and the braided carbon fiber wheel Composites World.
[5] Mubea Carbo Tech cited 2020 8 22 www.carbotech.at/en/.
[6] BMW-M 2016 cited 2020 8 22 www.bmw-m.com/en/topics/magazine-article-pool/every-gram-counts.html.
[7] Schweizer N, Giesel A et al 2012 Development of a composite wheel with integrated hub motor ECCM 2012 - Composites at Venice, Proceedings of the 15th European Conference on Composite Materials.
[8] Agency EASA 2016 Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25).
[9] Agency EASA 2010 Large Aeroplane Wheels and Wheel and Brake Assemblies (ETSO-135a)
[10] Seip J 2019 Numerische Beanspruchungsanalyse eines Flugzeugrads aus Faser-Kunststoff-Verbund Masterthesis TU Darmstadt.
[11] Brinek M 2018 Konzeptionelle Entwicklung eines Flugzeugrads aus Faser-Kunststoff-Verbund Masterthesis Hochschule Darmstadt
[12] Puck A 1996 Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis (München: Hanser Verlag)

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