Abstract

In the last decade the strong rise in oil prices has led to the increase of the needs to lighter aircrafts with efficient engines to reduce the kerosene consumption and the operating costs. Composite materials with their high specific strength and stiffness are widely used in the latest aircraft designs, but their intensive use is restricted to long-range aircrafts due to high manufacturing costs and low production rate. Integral designs and using dry fibre preforms overcome this drawback. Foam core sandwich structures combine the advantages of high bending properties with low manufacturing costs when liquid composite processes are used. Moreover, the high buckling stability of sandwich structures leads to the discard of stiffeners and thus the reduction of manufacturing steps. However, the use of foam core sandwich structures is not widespread in aircraft applications due to the better weight-specific performance of honeycomb cores and the susceptibility to impact loading. In this context, pin reinforcements are added to the foam core to improve its mechanical properties and its damage tolerance.

In order to enable the use of pin reinforced foam core in a primary aircraft structure, it is important to know its behaviour at different loading conditions and to predict its impact behaviour. This thesis contributes to the understanding of the damage mechanisms of pin reinforced foam core sandwich structures under different loading conditions. Quasi-static tests were performed and the micro-computed tomography was used to understand the damage occurrence under compressive, shear and indentation loads. The pins led generally to the improvement of the mechanical performance under static loading conditions. It was found out that a minimum pin volume fraction in the foam core is necessary to reach a remarkable improvement of the mechanical properties.

Since loading-carrying aircraft structures operate generally in extreme frost conditions, impact tests on pin reinforced foam core sandwich structures were performed at -55 °C and the damage behaviour was compared to the damage in panels impacted at room temperature. It was concluded that the residual stresses created in the vicinity of the carbon fibre pins during the manufacturing process and due to the thermal loading in operating condition lead to the degradation of the impact performance and create thermal cracks in the foam material. These cracks can dispread under further loading and endanger the integrity of the structure. Reducing the thermal stresses in the foam core by using fibre with high coefficient of thermal expansion like glass fibre or by modification of manufacturing parameters led to the delay of the thermal stresses to higher impact energies.

An FE-model simulating the impact behaviour of pin reinforced foam core sandwich panels was developed by using the simulation program Abaqus and following the building block approach. Two approaches to model the pin reinforced foam core were investigated and assessed. The homogenisation approach delivered more reliable results than the approach with discrete pin modelling. The simulation results were validated by using impact test results and an overall good agreement was achieved. The proposed model allows predicting the impact behaviour of sandwich structures and is able to simulate impact on structures with complex geometrical features so that it can be used for design studies and thus reduces the testing effort. A further improvement of the simulation results can be achieved by considering the residual stresses due to manufacturing and thermal loading in the foam, and by considering the damage of the pins if the pins are modelled.

Keywords: composite, impact, pin reinforced foam core, Tied-Foam-Core, sandwich, explicit FEM, micro-computed tomography.

Kurzfassung

In den letzten zehn Jahren hat der starke Anstieg der Ölpreise zur Verstärkung des Bedarfs an leichteren Flugzeugen mit effizienten Triebwerken geführt, um den Kerosinverbrauch und die Betriebskosten zu senken. Verbundwerkstoffe mit ihrer hohen spezifischen Festigkeit und Steifigkeit sind in den neuesten Flugzeugmodellen weit verbreitet, ihr intensiver Einsatz beschränkt sich jedoch aufgrund hoher Herstellungskosten und niedriger Produktionsraten auf Langstreckenflugzeuge. Integrale Designs und die Verwendung von Preforms aus Trockenfasern überwinden diesen Nachteil. Schaumkern-Sandwichstrukturen kombinieren die Vorteile hoher Biegeeigenschaften mit niedrigen Herstellungskosten beim Einsatz von Liquid-Composite-Moulding-Fertigungsverfahren. Darüber hinaus führt die hohe Knickstabilität von Sandwichstrukturen zum Wegfall von Versteifungen der Composite Schale und damit zur Reduzierung von Fertigungsschritten. Der Einsatz von Schaumkern-Sandwichstrukturen ist jedoch in Flugzeuganwendungen aufgrund der besseren gewichtsspezifischen Leistung der Wabenkerne und der Anfälligkeit für Stoßbelastungen nicht weit verbreitet. In diesem Zusammenhang werden dem Schaumkern Pin-Verstärkungen hinzugefügt, um seine mechanischen Eigenschaften und seine Schadenstoleranz zu verbessern.

Um den Einsatz von Pin-verstärktem Schaumkern in einer primären Flugzeugstruktur zu ermöglichen, ist es wichtig, sein Verhalten bei unterschiedlichen Lastbedingungen zu kennen und sein Aufprallverhalten vorherzusagen. Diese Arbeit trägt zum Verständnis der Schadensmechanismen von Pin-verstärkten Schaumkern-Sandwichstrukturen unter verschiedenen Lastbedingungen bei. Quasi-statische Tests wurden durchgeführt und die Mikro-Computertomographie wurde eingesetzt, um das Schadensbild unter Druck-, Scher- und Eindruckbelastung zu verstehen. Die Pins führten im Allgemeinen zur Verbesserung der mechanischen Leistung unter statischen Lastbedingungen. Es wurde festgestellt, dass ein minimaler Pinvolumenanteil im Schaumkern notwendig ist, um eine deutliche Verbesserung der mechanischen Eigenschaften zu erreichen.

Da tragende Flugzeugstrukturen im Allgemeinen unter extremen Gefrierbedingungen arbeiten, wurden bei -55 °C Schlagversuche an Pin-verstärkten Schaumkern-Sandwichstrukturen durchgeführt und das Schadensverhalten mit dem Schaden von bei Raumtemperatur beaufschlagten Platten verglichen. Es wurde festgestellt, dass die während des Herstellungsprozesses in der Nähe der Kohlefaserpins erzeugten Eigenspannungen und aufgrund der thermischen Belastung im Betriebszustand zu einer Verschlechterung der Impactleistung führen und thermische Risse im Schaumstoff erzeugen. Diese Risse können sich unter weiterer Belastung ausbreiten und gefährden die Integrität der Struktur. Die Reduzierung der thermischen Spannungen im Schaumkern durch die Verwendung von Fasern mit hohen Wärmeausdehnungskoeffizienten wie Glasfasern oder durch Änderung der Herstellungsprozessparameter führte zur Verzögerung der thermisch induzierten Risse auf höhere Schlagenergien.

Ein FE-Modell zur Simulation des Aufprallverhaltens von Sandwichpaneelen mit Pin-verstärktem Schaumkern wurde mit dem Simulationsprogramm Abaqus und nach dem Baukastenprinzip entwickelt. Zwei Ansätze zur Modellierung des Pin-verstärkten Schaumkerns wurden untersucht und bewertet. Der Homogenisierungsansatz lieferte zuverlässigere Ergebnisse als der Ansatz mit diskreter Pin-Modellierung. Die Simulationsergebnisse wurden durch die Verwendung von Impact-Testergebnissen validiert und eine insgesamt gute Übereinstimmung erzielt. Das vorgeschlagene Modell ermöglicht die Vorhersage des Impactverhaltens von Sandwichstrukturen und kann die Strukturantwort von Strukturen mit komplexer Geometrie simulieren, so dass es für Designstudien verwendet werden kann und somit den Testaufwand reduziert. Eine weitere Verbesserung der Simulationsergebnisse kann durch die Berücksichtigung der Eigenspannungen im Schaum, die durch Fertigung und thermische Belastung erzeugt wurden, sowie durch die Berücksichtigung der Beschädigung der Pins bei dessen Modellierung erreicht werden.

Schlüsselwörter: Faserverbundstrukturen, Pin-Verstärkung, Sandwichstruktur, Impact, explizite FEM, Mikro-Computertomographie, Tied-Foam-Core.

1 Introduction

1.1 Motivation

Due to their high specific strength and stiffness Fibre Reinforced Polymer (FRP) composites are widely used where structures with high mechanical performance combined with lightweight are needed, e.g. in the maritime, wind energy and aerospace industries. In the last decade the use of high performance carbon fibre reinforced composite materials has proven its effectiveness in the aerospace industry. Composite materials have even substituted most of the metallic structures in the latest civil aircrafts to reach more than 50% of the structural weight in the Boeing 787-Dreamliner and the Airbus 350 XWB. In addition to weight reduction, composite materials offer many advantages like environmental durability, superior fatigue properties, life cycle costs and service life extension. However, due to the complex mechanical behaviour and using conventional design approaches that are based on metallic design approaches, manufacturing costs are very high compared to metal manufacturing processes and the full potential of these materials has not been used yet. The high materials and manufacturing costs limit the use of composite materials to high-end products with strict lightweight requirements.

The combination of innovative composite design with efficient manufacturing techniques would lead to a better exploitation of the potential of composite materials and to the reduction of manufacturing costs. Integral manufacturing of composite parts improves the mechanical performance of the structure and reduces the material and manufacturing costs as the parts count and the assembly time are extremely reduced. Sandwich composite structures consisting of two strong and stiff composite face sheets bonded to a rigid core offer the possibility to manufacture integral composite parts while having good mechanical performance. Sandwich structures with a closed cell foam core offer many advantages compared to stiffened monolithic shells and to the in aircrafts widely used honeycomb sandwich. It combines the high specific bending stiffness and superior buckling stability [1] with the possibility to manufacture sandwich panels with complex geometries using cost effective resin infusion technologies [2]. Moreover, closed cell foam core overcomes the issue of moisture take up of honeycomb sandwich, has excellent acoustic damping and thermal insulation properties, which makes the foam core sandwich attractive for the integration in primary aircraft structure. In addition, foam core material has good energy-absorbing properties with nearly a constant crushing load level [3], which makes it interesting for crash absorbing applications in automotive and aerospace industry [4-6]. However, sandwich structures are susceptible to external localised loads normal to the face sheets, like low-velocity impact and inappropriate load introduction. Such kind of loading could lead to face sheet rupture, local core crushing, interface debonding and microcracks, as well as in worst case shear cracks [7]. These failures could degrade the load bearing capacity of the panel, propagate under further loading and threaten the integrity of the structure.

In order to enhance the compressive properties of foam core sandwich and its damage tolerance, many innovative through the thickness reinforcement solutions like pin reinforcement [8, 9], double-T reinforcement [10], hierarchical and foam filled corrugation structure [11] and stitch bonded sandwich structure [12] have been proposed. In order to enable the use of this kind of hybrid sandwich composites in primary aircraft structure, it is essential to understand and assess the damage behaviour at different loading conditions and to provide reliable simulation methods to design the structure. On the one hand, the experimental investigation provides an understanding of the mechanical behaviour and the damage modes, which enables to know the limits of the used materials. On the other hand, simulation methods enable a faster structure development with reduced scrap rates and engineering effort.

1.2 Objective

The first main objective of this PhD thesis is to investigate the influence of pins on the mechanical performance and the damage behaviour of pin-reinforced foam core sandwich structures. The pins are embedded in the foam core under a specific inclination angle and predefined pattern using the Tied Foam Core (TFC) pinning technology. Different quasi-static tests were performed, namely flatwise compression, shear and indentation tests. X-ray computed tomography was used as well to identify the damage modes under static loading. The main effects and influencing parameters should be detected and the gathered findings should be compared to the published results of similar pin-reinforced foam core sandwich structures; differences and similarities should be identified.

The second objective is to investigate the temperature dependent impact behaviour of the pin-reinforced foam core sandwich structure. Low-velocity impact tests were performed at room temperature and very low temperature (-55 °C). The damage behaviour was investigated by using ultrasonic C-scan and X-ray computed tomography. In this work the influence of the very severe frost conditions on the impact damage occurrence should be thoroughly investigated and analysed.

The last main objective of this work is to develop a simulation model to describe the damage behaviour of the studied structure under low-velocity impact. The model should be capable of predicting the different damage modes and the load-displacement response with good accuracy, so that it can be applied to large sandwich structures with real boundary conditions.

Finally, it is expected that this PhD thesis will contribute to a significant understanding of pin-reinforced foam core sandwich structures, which would widespread the use of these materials in aerospace applications.

1.3 Structure of the work

This PhD Thesis consists of six chapters. In this chapter an introduction into the work including its motivation, objective and structure is provided.

The second chapter starts with a general overview about the state of the art of sandwich structures, its applications and manufacturing technology as well as the fundamentals of the sandwich theory and standard damage modes. Then the failure modes under low-velocity impact are explained and an analytical model to predict the impact behaviour of foam core sandwich structures is presented. The chapter is concluded with a literature review about through-the-thickness reinforcement of composite sandwich structures and a detailed presentation of the used pinning technology (TFC-technology).

The third chapter focuses on the characterisation of the used pin-reinforced foam core. Different quasi-static tests were performed in which four pin configurations were investigated. Concerning the compressive properties, an analytical model to predict the compressive strength and stiffness was assessed and applied to the tested materials. In addition to visual inspections X-ray computed tomography was used to determine the damage modes at every loading condition investigated in this work.

The following chapter four covers the impact response of TFC-sandwich at low temperature and discuss the influence of very low-temperature on the damage behaviour. Test procedure and results for impact tests at room temperature and -55 °C are presented. The damage modes were investigated using ultrasonic C-scan and X-ray computed tomography. An investigation of the influence of the manufacturing process and the pin material on the damage mode at -55 °C is provided and the results are analysed.

In chapter five, the development of a numerical model to simulate the impact behaviour of pin-reinforced foam core sandwich structure is presented. In a first part the fundamentals of explicit simulation are given and the used assumptions, material models and modelling approach are explained. In the second part, a numerical model for impact on foam core composite sandwich structure, which is the basic of the model of the pin-reinforced foam core sandwich, is introduced. The last part of the chapter deals with the simulation of the low-velocity impact on pin-reinforced foam core sandwich structure. All simulation results were compared to the experimental results for validation.

In the last chapter, the results are summarised, limitations and recommendations for an efficient implementation of the results are given and prospects to improve the presented findings of this work are proposed.

2 State of the art

Chapter 2 is giving an overview about the state of the art of composite sandwich structures. In the first part an insight into the fundamentals of composite sandwich structures is presented with focus on applications, material combination and manufacturing. In the second part, the low-velocity impact behaviour of foam core sandwich structures is considered, where the impact failure modes and the analytical method to predict the impact response of foam core sandwich structures are discussed. The third section provides a critical review about available through-the-thickness reinforcement methods of foam core sandwich structures. The motivation behind using the through-the-thickness reinforcement, the properties and the manufacturing processes are highlighted. The impact behaviour of foam core sandwich structures and the effects of through-the-thickness reinforcement on the mechanical properties of sandwich composites provide the basis of the performed research work. Lastly, the tied foam core (TFC) pinning technology investigated in this work is thoroughly described and its advantages compared to other technologies are outlined.

2.1 Fundamentals of composite sandwich structures

2.1.1 Definition

There are different tales about the origin of the word sandwich, which describes a tasty snack consisting of two slices of bread with a filling of e.g. meat and cheese. One of these tales recounts that John Montagu (1718-1792) the 4th earl of Sandwich and British first lord of the Admiralty during the American Revolution gave his name to this dish. He was a devoted Cribbage-player and spent hours playing at his table without any food except his sandwiches. Sandwich structures are built in similar manner to the sandwich dish, the two bread slices are replaced by two skins of high performance materials like metal sheets or composites and the filling is replaced by a hard lightweight core [13].

Industrially used sandwich structures have three main components (Figure 1): two thin, strong and stiff skins separated by a thick, hard and lightweight core with negligible strength compared to the face sheet material. Both components are bonded to each other by adhesive medium to ensure structural integrity and load transfer. The sandwich functional mode is similar to that of an I-beam with more material efficiency, as different materials are used and the mechanical potential of the face sheets is better exploited. The rigid core maintains the distance between the skins constant, resists shear and out-of-plane compression and provides support to face sheets, which increases the resistance against bending and buckling. The face sheets work together and resist in-plane loads, namely tensile and compression stresses resulted from bending loads. The adhesive layers bond the face sheets and the core together and ensure the load transfer between them. As the sandwich concept works only when all elements are bonded together it is important that the adhesive joint has enough strength to withstand the shear and tensile stresses set up between the skins and the core. A huge variety of materials exists for the sandwich elements, which makes the design of sandwich structures very time consuming, but it offers the possibility to tailor the mechanical properties of the sandwich to the specific application. Moreover, every material combination should separately be investigated as the damage behaviour and the mechanical properties depend strongly on the used sandwich constituents and the manufacturing process.

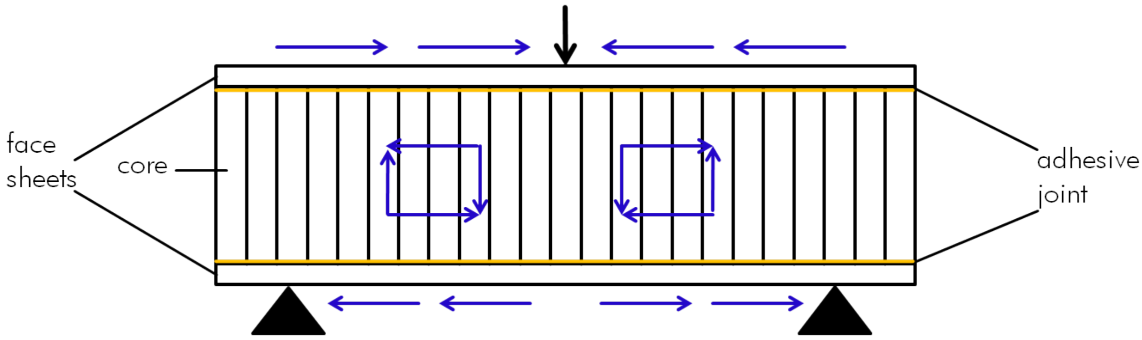

Figure 1. Main elements of a sandwich construction

2.1.2 Application of composite sandwich structures

The first discussion about the advantages of sandwich constructions is associated to Duleau who, in 1820, tested the bending performance of two beams assembled with a constant distance to each other. He concluded that the bending stiffness increases by the third power of the distance between the beams [14]. The sandwich concept was firstly adopted by Fairbairn, in 1849, who built bridges with sandwich elements made of steel sheets and corrugated steel core [15]. Due to the lack of high performance materials and suited structural adhesive, it took 110 years to use the concept of sandwich structure commercially [13]. The earliest serial application of composite sandwich structure was the British aircraft De Havilland Mosquito that was produced during the Second World War. Sandwich made of veneer faces and balsa core was mass produced [2]. Some years later, in 1943, the American military aircraft Vultee BT-15 was developed with a sandwich fuselage made of glass fibre skins and balsa core [16]. Balsa was the first core material to be industrially used and is still in use in applications where the weight is not critical like in cruising yachts or rotor blades for wind turbine.

Research and development of sandwich structures started in the 1940´s and continues nowadays with the aim to improve the damage behaviour and the weight efficiency creating new materials and concepts. Honeycomb cores were already developed in 1905 in Germany, but they were used as core material first at the end of the 1940´s mainly in aerospace structures [17]. Honeycomb cores are produced with different forms and materials, for instance aluminium and aramid paper, and offer the best weight specific material properties. However, due to their high costs, their use is limited to aerospace applications.
In the early 1940´s, the first polyvinylchloride (PVC) was developed in Germany. But it took about 15 years to be used in industrial applications due to the softness of the first developed foams. Due to the improvement of manufacturing processes and material properties of the PVC and polyurethane (PU) core materials, they are today commonly used in many low and medium cost industrial applications. In addition to the further development of core and adhesive materials, the use of composite materials as skins has given an important push to the sandwich structure to be used in different sectors.

Nowadays composite sandwich structures find a broad range of applications in commercial aircraft and satellite structures. While almost all satellite structures are made of honeycomb sandwich constructions [16], the use of composite sandwich structure in commercial aviation is limited to secondary structures [2]. Due to the strict safety requirements, it is important to understand the structure behaviour after damage occurrence. Therefore, every structure should prove that every in-service damage occurrence doesn´t lead to failure or excessive structural deformation until the damage detection. Due to the lack of ma-