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Investigation of the temperature dependent impact behaviour of pin reinforced foam core sandwich structures

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ABSTRACT

Dry carbon and glass fibre bundles were inserted into a ROHACELL® 71HERO Polymethacrylimide (PMI) foam core under a specific inclination angle and pin pattern in order to improve the impact damage tolerance and the fracture toughness of foam core sandwich. Impact tests were performed on pin-reinforced foam core sandwich panels with different pin-configurations at impact energies between 35 J and 70 J. X-ray computed tomography and ultrasonic C-scan were used to determine the damages in the foam core. At room temperature no cracks were observed in the foam core. Using carbon fibre pins led to the creation of thermally induced cracks in the foam core after impacts at −55 °C, which is critical for the integrity of the structure. The modification of the manufacturing process parameters and the use of glass fibre pins are two solutions to improve the impact behaviour at −55 °C by delaying the thermal cracks to higher impact energies.

1. Introduction

The aircraft industry is driven by high pricing pressure. That's why economic effectiveness of manufacturing processes plays an important role. Beside this, fuel saving and resource conservation are driving the research and development. In this contest sandwich structures present a smart solution that combines the light weight properties with the economical manufacturing process.

Foam core sandwich structures made of two stiff and strong face sheets bonded to a closed cell foam core exhibit high specific stiffness and strength as well as superior buckling stability compared to monolithic composite structures [1]. Thanks to the use of closed-cell rigid foamcores of Polymethacrylimid (PMI), the issue of moisture take up and the related material degradation, usually observed in honeycomb sandwich structures, have been solved. The acoustic damping and thermal isolation is also improved. Moreover, using resin infusion processes for the manufacturing of foam core sandwich panels and reducing the part count enable a more cost effective manufacturing of large panels compared to traditional with stringer stiffened composite shells [2]. In addition, the good energy-absorbing properties of foam core sandwich make it interesting to be used as crash absorbers in automotive and aerospace industries [3–5]. However, foam core sandwich structures are prone to impact loading. Invisible cracks can initiate, propagate in the core and peril the integrity of the structure [6]. In order to integrate foam core sandwich in a primary aircraft structure, the developed sandwich should be damage tolerant and the integrity of the structure after low-velocity impact should be maintained.

With the aim to improve the damage tolerance and the fracture toughness of foam core sandwich, many innovative through the thickness reinforcement solutions like pin reinforcement [7,8], double-T reinforcement [9], hierarchical and foam filled corrugation structure [10] and stitch bonded sandwich structure [11] have been proposed. Stanley and Adams [3] studied the feasibility and potential benefits provided by through the thickness stitching of sandwich structures. They investigated the effect of stitch density on the low-velocity impact response and CAI-behaviour. They performed impact tests and investigated the damage occurrence. They concluded that the damage surface decreases and the CAI-strength increases with the increase of stitch density. While only core crushing without cracks was the main failure mode in the unstitched specimens, multiple cracks were observed in the stitched specimens. Lascoup et al. [12] investigated the behaviour of angled stitched sandwich under impact loading. They focused on the effect of stitching and stitching density on the damage behaviour of the foam core sandwich structure. An important improvement of the maximum effort and rigidity was reached. Moreover, compared to unstitched specimens the face sheet debonding was suppressed as the stitches go through both skins and improve the connection to the foam core. Baral et al. [13] compared the structure response of foam core sandwich with PMI foam core and pultruded carbon fibre pins under water impact loading to the response of a

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honeycomb sandwich structure with the same areal weight and the same facing. They found out that the pin-reinforced foam core sandwich delays the damage to higher impact energies compared to honeycomb structure traditionally used for racing yacht hulls. While most of the available studies reported only benefits of the pin-reinforced foam core sandwich structure compared to the unreinforced foam core sandwich, Nanayakkara et al. [14] concluded that there was nearly no improvement of the impact and post-impact compression properties of the tested z-pinned sandwich. They tested foam core sandwich composite material with orthogonal pins made of carbon fibre under low-velocity impact und quasi-static flatwise compression loading. On the one hand, the through-thickness stiffness, strength and energy absorption were significantly increased. On the other hand, only small improvement of the low-velocity behaviour at low impact energies and nearly no enhancement of the post-impact properties were registered. Generally, the impact behaviour of foam core sandwich structure is improved when using pin-reinforcement [15,16], but the effectiveness is strong dependent on the material combination (foam/pin), the pin-configuration (pin-angle, -pattern and density) and how the pins are inserted into the foam core (pinning-technology).

The Tied Foam Core (TFC) technology is a new manufacturing process to produce pin reinforced foam cores automatically, with flexible pinning parameters. The aim of the TFC-Technology is to improve the damage tolerance and the fracture toughness of the interface of the foam core composite, as well as to reduce manufacturing time and cost compared to other pinning-technologies [17]. John et al. [18] determined the critical energy release rate G_{Ic} under peel loads of the interface between the core and the facings for different pin-reinforced sandwich specimens made with the TFC technology. They concluded that the critical energy release rate G_{Ic} increases with the increase of the pin-volume fraction in the core. In previous study [19], shear tests were performed to investigate the effect of the TFC-pinning on the crack propagation and structure integrity. It was found out that a minimum pin-volume fraction is necessary to improve the structure integrity significantly.

John et al. [20,21] investigated different influencing effects that can in- or decrease the residual stresses in a pin-reinforced foam core of a sandwich structure made by vacuum assisted infusion process. Depending on the pin-pattern parameters, for instance pin size, distance and pin angle, and the preparation conditions the residual stresses can be minimized. An important role are playing the pin material as well as the thermal process parameters. The relaxation behaviour of the PMI foam core material should also be considered. Residual stresses left in the sandwich structure can be estimated at least of about 15% of the overall residual strength left in the foam core, when pins are implemented [20,21].

To date, no work can be found in the open literature about the effects of very low temperature on the impact behaviour of pin-reinforced sandwich structures. As the impact behaviour at very low temperature would extremely differ from the behaviour at room temperature, it is important to keep the damage occurrence under control. Hence, in this work impact tests on TFC-reinforced sandwich specimens at −55 °C were performed. The impact energies varied between 35 J and 70 J. Ultrasonic C-scans and micro computed tomography (CT) were used to determine the damage modes. Two solutions were proposed and validated to avoid crack propagation in the core at −55 °C. Although low-velocity impact incident are rare at −55 °C for an aerospace sandwich structure, it was assumed that this temperature would represent a possible in service temperature and a worst case temperature for the impact loading.

2. Materials, manufacturing and testing

2.1. Sandwich specimens

Sandwich panels consisting of two thin carbon-epoxy skins and a closed-cell PMI foam core have been manufactured using the Vacuum Assisted Resin Infusion (VARI) process as described by Zahlen et al. [22]. This process enables the co-curing of the pins, since the dry fibre roving are impregnated and cured simultaneously with the impregnation and curing of the face sheet layers. The sandwich facings are made of Toho Tenax HTS40 carbon fibre Non-Crimp Fabrics (NCF) impregnated by Hexcel RTM6 epoxy resin. The skin faces are made up of four triaxial NCF-layers, with the layup (45/0/−45), symmetrically stacked, which results in a face sheet thickness of about 1.5 mm. The closed cell PMI foam ROHACELL® 71 HERO [23] with a density of approximately 75 kg/m^3 and a thickness of about 25.7 mm has been used as core material. For the reinforcement of the foam core, glass and carbon fibre roving have been used. The cured pins have a diameter of about one mm. The specimens for the impact test were cut using a diamond cutting disc saw with a reduced feed velocity to avoid excessive pins and foam damages at the cutting surfaces.

2.2. Tied foam core technology

In this work, the Tied Foam Core technology developed by Airbus Group was used to insert the pins into the foam core. Dry glass and carbon fibre bundles are inserted into the foam core under pre-defined angle and pattern, which can be changed depending on the required mechanical properties. The automatic pining process consists of four main steps [24]: a needle stitches through the foam and hooks in the roving, which is already on the other side of the foam plate. Then the needle is pushed back and the fibre bundle is cut with predefined extensions. The different steps are depicted in Fig. 1. In finished sandwich

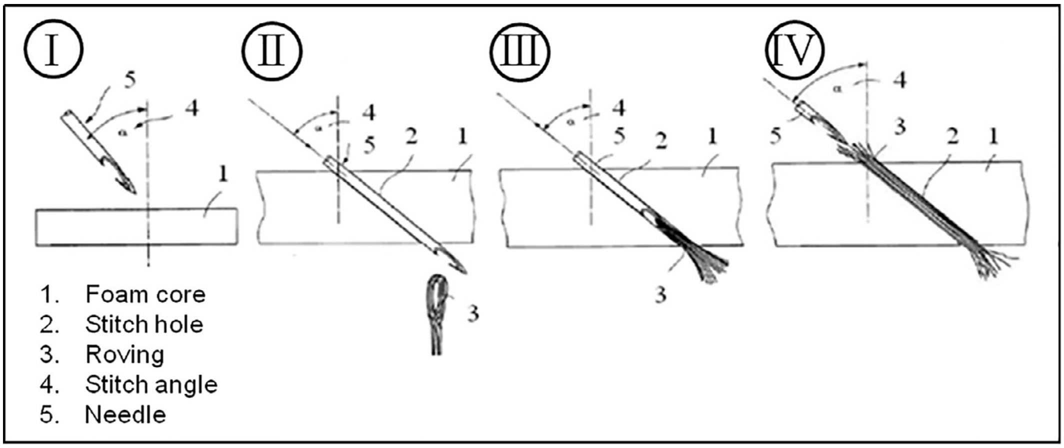

Fig. 1. TFC-technology pinning process [25].