# EXPERIMENTAL STUDY OF THE INDENTATION BEHAVIOUR OF TIED FOAM CORE SANDWICH STRUCTURES

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**Abstract**
Foam core sandwich structures have a high potential to be integrated in a primary aircraft structure owing to the good ratio of bending stiffness and strength to weight. However closed cell foam cores are susceptible to damage if subject to local loading, such as tool drop, hail strike and indentation loads. In order to improve the mechanical properties and enhance the damage tolerance of foam cores CFRP- and GFRP-pins are inserted into the foam using the Tied Foam Core technology. Pin-reinforced sandwich panels and a reference configuration without pins, supported on a rigid base and tested under quasi-static indentation loads were investigated in this work. The effects of pin material and pin volume fraction on the load-indentation response were investigated. The global shape of the load-indentation curves is similar for all configurations with differences in face sheet rupture load and stiffness. Increasing the pin volume fraction enhanced the structure stiffness and the face sheet rupture load. The failure modes of the sandwich structure were determined using X-ray computed tomography at different load levels. It revealed that the collapse of the pins was only due to pin bending failure at the curved pin foot nearby the indentation area.

## 1. Introduction

Foam core sandwich structures made of two stiff and strong composite face sheets separated by a lightweight closed cell foam core, such as PMI foams, offer a high specific bending stiffness with superior buckling stability compared to stiffened monolithic shell structures [1]. Using this concept production efficiency would be enhanced if one-shot integral manufacturing method of sandwich parts is applied, since parts number and production time are extremely reduced [2]. Moreover using PMI foam cores, commercially known as Rohacell®, overcomes the issue of moisture take up of honeycomb core materials and provides an advantageous thermal insulating and acoustical behaviour [3]. Nevertheless, closed cell foam cores have a lower stiffness and strength compared to those of honeycomb cores and invisible shear crack could occur after impact loading and degrade the load carrying capacity of the structure [4]. With pin-reinforcement of the sandwich structure like X-Cor™ and K-Cor™ [5] the out-of-plane properties could be improved and the shear crack propagation could be stopped [6]. Due to the pre-defined pin-extensions that lie in the interface between the foam core and the monolithic skins, the studied pinning technology improves the mode I fracture toughness of the interface and the damage tolerance [7].
To enable the use of sandwich materials in a primary aircraft structure, the designed sandwich structure should be impact tolerant. That means the impact-induced damage should be visible, so that it could be repaired after a visual inspection, or the invisible cracks should be stopped and the integrity of the structure should be maintained until the next main inspection, at which the damage could be removed. The similarities in local damage occurrence during a low velocity impact event and a quasi-

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static indentation loading make the quasi-static indentation method suitable to investigate and understand the damage behaviour of a locally loaded pin-reinforced sandwich structure.

In early studies, no results were reported on the quasi-static indentation response of z-pinned foam core sandwich manufactured with the tied foam core technology (TFC). In this paper, the mechanical behaviour of TFC-Sandwich under quasi-static indentation loads was studied with the aim to investigate the effects of the pin material and pin volume fraction on the indentation response and to determine the pin failure modes using X-ray computed tomography.

## 2. Material and Manufacturing

Sandwich panels made of two thin carbon-epoxy skins separated by a closed cell PMI-foam core were manufactured with the Modified Vacuum Infusion (MVI) system as described in [8]. The dry fibre pins in the foam core were co-cured with the face sheets. The face skins consisted of four layers Toho Tenax HTS40 carbon fibre Non-Crimp Fabrics (NCF) [9] impregnated by Hexcel RTM6 epoxy resin [10]. The NCF-layers had the layup (45/0/-45) and were symmetrically stacked, which led to a face sheet thickness of about 1.5 mm. The PMI foam ROHACELL® 71 HERO [11] with a density of 75 kg/m$^3$ and a thickness of about 25.7 mm was used as core material. Two fibre materials were used for the pin-reinforcement: T800H carbon fibres from TORAYCA [12] and 1383 Yarn glass fibres from PPG Fiber Glass [13]. After curing, the pins had a diameter of about 1 mm. After the manufacturing of the panels, the test specimens were cut using a diamond cutting disc saw.

The pins were inserted into the foam core using the Tied Foam Core technology developed by Airbus Group. The automatic pinning process is very efficient and provides high accuracy regarding the pinning parameters. More information about the pinning process could be found in [14].

Four different pin configurations with pins and a reference configuration without pins were tested. The pin-pattern (Fig. 1) and the stitching angle of 50° were the same for all configurations. Glass fibre and carbon fibre pins were used. The distance between pins was modified to change the pin volume fraction, which is the volume of the pins divided by the volume of the core. For the calculation of the pin volume fraction the geometry of the test specimen and only full-embedded pins were considered. The parameters of the tested configurations are summarized in Table 1.

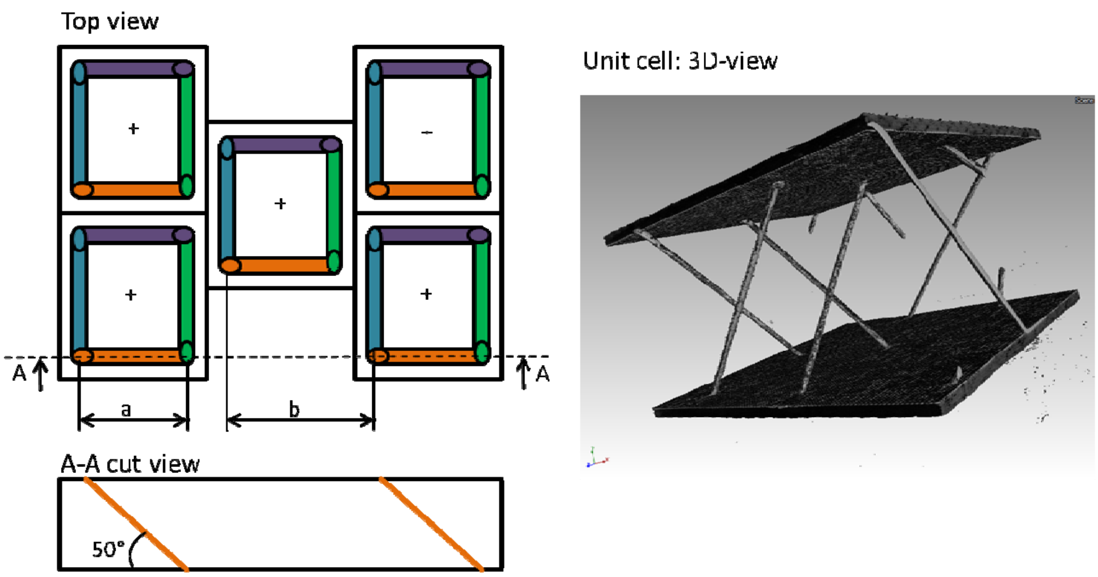


**Figure 1.** Different views of the unit cell and pinning pattern.

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**Table 1.** Parameters of the tested configurations

| Configuration | Pin material | Unit cell width (a) [mm] | Distance between two unit cells (b) [mm] | Pin volume fraction [%] |
|---|---|---|---|---|
| CFRP.10 | CFRP | 10 | 20 | 0.74 |
| CFRP.20 | CFRP | 20 | 40 | 0.20 |
| GFRP.10 | GFRP | 10 | 20 | 0.74 |
| GFRP.20 | GFRP | 20 | 40 | 0.20 |
| H.71 | Reference configuration with unreinforced foam core | | | 0 |

## 3. Quasi-static Indentation Test

### 3.1. Test Methods

The tests were performed based on DIN 53291 standard. The specimen dimensions are about 100 mm x 100 mm x 29 mm. The lower face of the specimen was supported by a rigid steel plate to prevent the specimen bending. The indentation load was applied using a hemispherical steel indenter with a diameter of 25.4 mm. A constant displacement rate of 1 mm/min was maintained until 12.5 mm indenter displacement was reached. The tests were conducted in a 250 kN Zwick Roell universal testing machine. The reaction force and the crosshead displacement of the indenter were continuously recorded. Five samples from each configuration were tested. The test setup is depicted in Figure 2.

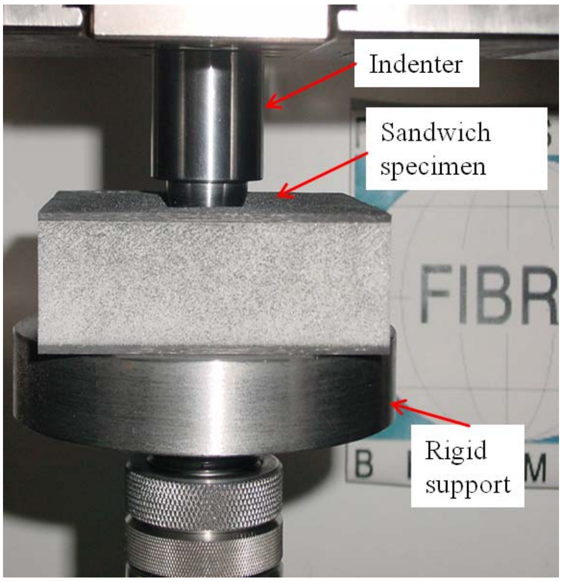


**Figure 2.** Test setup: Sandwich specimen under indentation Load

In order to investigate the failure behaviour and to determine the failure occurrence at different load levels, test specimens were loaded to specific load levels and then unloaded. Afterwards the X-ray computed tomography was used to inspect non-destructively the damage in the test specimen. The tomography computer Phoenix-x-ray Vtome X m (research edition) was used (Fig. 3). The program Volume Graphics was used to analyse the generated 3D data.

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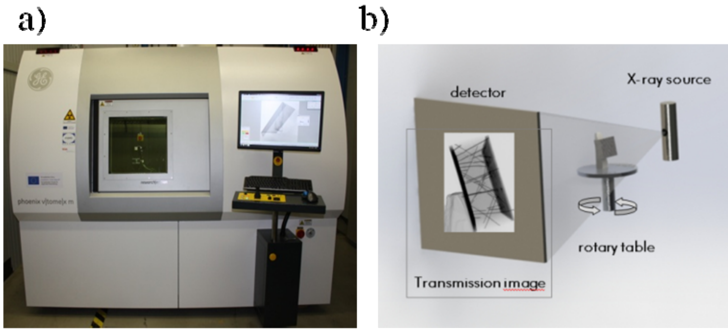


**Figure 3.** a) The tomography computer Phoenix-x-ray Vtome X m, b) CT-operation principle: inspected specimen placed between an X-ray source and an X-ray detector and rotated stepwise

### 3.2. Test Results

The average indentation load-displacement response of each configuration are depicted in Figure 4. The overall shape of the indentation curves of the pin-reinforced specimens is similar to the shape of the indentation response of the non-reinforced reference configuration (H.71). Four characteristic regions can be identified in the indentation load-displacement curves:

1. Initial linear elastic region: At this stage, the structure behaviour is linear elastic. After loading, the deformation is totally recovered. This elastic region continues until reaching a load between 900 and 1100 N, at which the stiffness begins to decrease. This stiffness drop is a sign of damage initiation in the structure. The damage at stiffness degradation was investigated with X-ray computed tomography and will be discussed in the next section.
2. Invisible damage propagation: the load continues to increase quasi linearly until face sheet rupture begins. In this region, invisible damages propagate in the indenter region. It is assumed that delamination, interface debonding and pin-breakage are the main failure modes in this region. Small fluctuations in load-indentation curves of pin-reinforced specimens could be identified. Acoustic emissions were also registered.
3. Visible damage propagation: In this region the fibres of the face sheet layers begin to break. This region is characterised by a sharp load drop and loud acoustic emission. After complete penetration of the face sheet the load increases slightly.
4. Plateau region, damage propagation in core material and interlaminar face sheet zone: In this region, the indenter has already penetrated the face sheet and the indentation load is only carried by the core material. The indenter continues to penetrate at nearly constant load. At this stage core crushing in the indentation area, delamination propagation in the face sheet and pin collapse are the main failure mechanism.

The stiffnesses of the tested configurations in the initial elastic region (region nr. 1) are not the same; the specimens with pin-reinforcement are stiffer than the reference configuration (H.71). The damage initiation occurred almost at the same load level (between 900N and 1100N). A significant difference in the indentation response is observed in the second region (region nr. 2). The configurations with pin-reinforcement have higher stiffness compared to the reference configuration. The stiffness increases with the increase of the pin volume fraction and the stiffness of the pins. The pins carry partially the indentation load, create an alternative load path and increase the stiffness of the core. The use of the pins increases also the load at face sheet rupture (region nr. 3) and the load in the plateau region (region nr.4). Configuration GFRP.10 with glass fibre pins and 0.74% pin volume fraction induced the highest augmentation in region three and four. This is based on the highest maximum stain to rupture of glass fibres compared to carbon fibres.

The use of pin-reinforcement leads to the improvement of the quasi-static indentation response of sandwich materials. The stiffness and the load at face sheet rupture are increased especially when enough glass fibre pins are used. The effect of pin material on the indentation response was first observed at a pin volume fraction of 0.74%; at lower pin volume fraction the effect of pin material is minor. While carbon fibre pins led to the highest increase of the sandwich stiffness, led the glass fibre pins to the highest augmentation of the load at face sheet rupture.

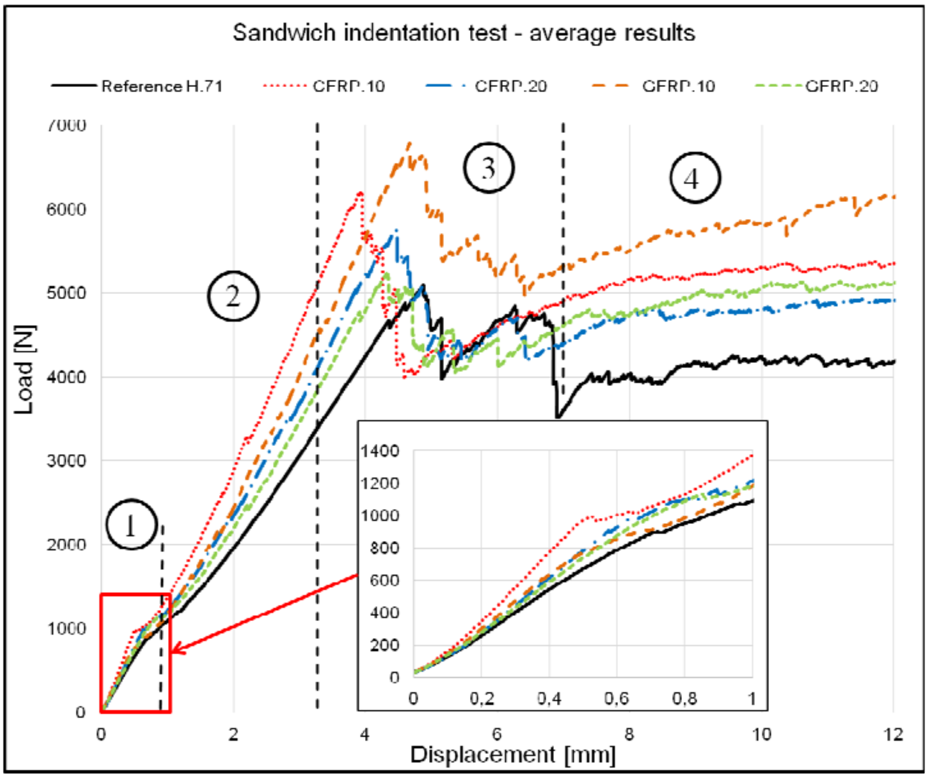


**Figure 4.** Average indentation response of the tested configurations **[15]**

With the aim to identify the failure mechanism at characteristic load levels, three test specimens were loaded to different load levels, afterwards they were inspected using the X-ray computed tomography (one H.71-specimen and one CFRP.10-specimen were loaded to about 2000N and a CFRP.10-specimen was loaded to about 4000N) .

Figure 5-a and 5-b show delamination in the top face sheet of sandwich specimens in reference configuration H.71 and CFRP.10 after reaching the 2000N indentation load. No other failure types were found, which means that the face sheet delamination is responsible for the first load drop in the load-indentation curves. This would explain why the first load drop occurred almost at the same load level independent of the tested configuration.

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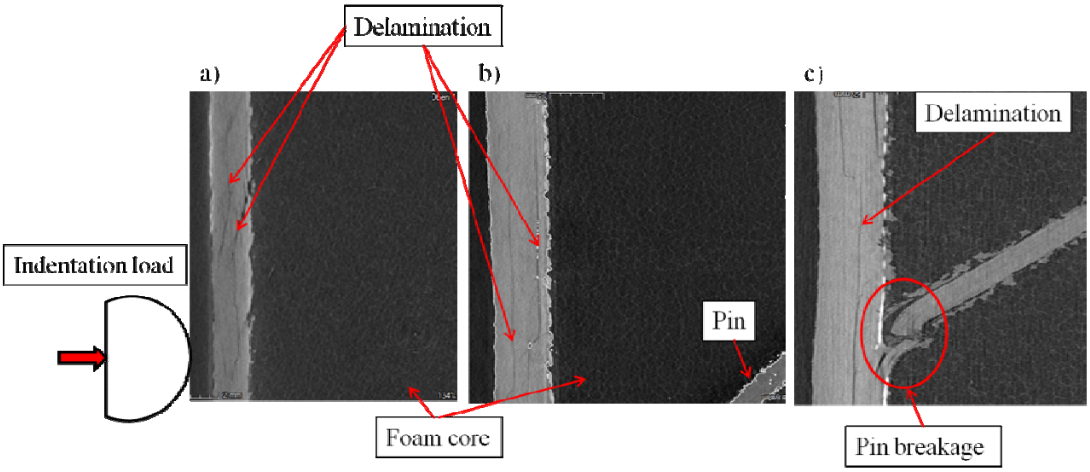


**Figure 5.** Failure in indented sandwich specimens: a) Reference configuration at 2000N load, b) CFRP.10 at 2000N and c) CFRP.10 at 4000N

Afterwards the delamination continues to propagate in the top face sheet and the pins under the indenter begin to fail at the curved pin extension (Fig 5-c) on the loaded side of the specimen. Every pin collapse is reflected in a small fluctuation in the load-indentation curve. The load-indentation response of the reference configuration without pin-reinforcement has no fluctuations between 1000N and 4000N, which confirms the observation above. Core crushing under the indenter at this load level was not observed since the resolution of the X-ray computed tomography images was not high enough. Further loading of the sandwich specimen after face sheet rupture leads to delamination and face sheet debonding propagation, pin crushing and splitting under the indenter and pin collapse outside the indentation region (Fig. 6) due to the bending of the indented face sheet. The nearer to the indentation region, the more the pin crushes and splits. Outside the indentation region, no pin collapse was detected.

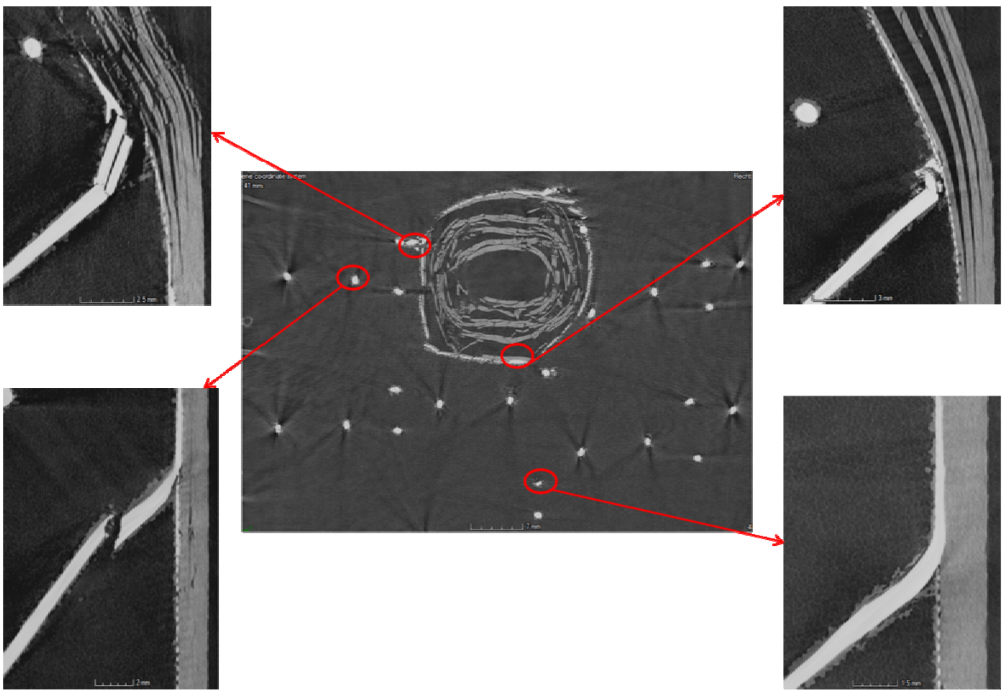

**Figure 6.** Failure occurrence in pin-reinforced specimen at the end of the indentation test

## 4. Conclusions

In this paper, the indentation response of pin-reinforced foam core sandwich manufactured with the Tied Foam Core technology was studied. The failure modes at different load levels were non-destructively investigated using the X-ray computed tomography. The overall shape of the load-indentation curve of pin-reinforced specimens is similar to that of unreinforced sandwich. The performed indentation tests showed that using pin-reinforcement improves the indentation response of foam core sandwich as the stiffness and the face sheet strength are increased. The effect of pin material is first at about 0.74% pin volume fraction evident. The carbon fibre pins led to the highest increase of the stiffness and the glass fibre pins led the highest improvement of the face sheet rupture load. After pin collapse initiation due to bending failure at the curved pin extension nearby the indenter, the pin begins to split and to crush with increased indenter displacement. A comparison of the failure development in pin-reinforced foam core sandwich under low-velocity impact will be performed in further investigations.

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