Experimental study of the mechanical behaviour of pin reinforced foam core sandwich materials under shear load

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Abstract. Sandwich structures with a lightweight closed cell hard foam core have the potential to be used in primary structures of commercial aircrafts. Compared to honeycomb core sandwich, the closed cell foam core sandwich overcomes the issue of moisture take up and makes the manufacturing of low priced and highly integrated structures possible. However, lightweight foam core sandwich materials are prone to failure by localised external loads like low velocity impacts. Invisible cracks could grow in the foam core and threaten the integrity of the structure. In order to enhance the out-of-plane properties of foam core sandwich structures and to improve the damage tolerance (DT) dry fibre bundles are inserted in the foam core. The pins are infused with resin and co-cured with the dry fabric face sheets in an out-of-autoclave process. This study presents the results obtained from shear tests following DIN 53294-standard, on flat sandwich panels. All panels were manufactured with pin-reinforcement manufactured with the Tied Foam Core Technology (TFC) developed by Airbus. The effects of pin material (CFRP and GFRP) and pin volume fraction on the shear properties of the sandwich structure and the crack propagation were investigated and compared to a not pinned reference. It has been concluded that the pin volume fraction has a remarkable effect on the shear properties and damage tolerance of the observed structure. Increasing the pin volume fraction makes the effect of crack redirection more obvious and conserves the integrity of the structure after crack occurrence.

1. Introduction
Compared to stiffened monolithic shell structures sandwich panels offer a high specific bending stiffness with superior buckling stability, which could bring new design principles and make the assembly process more efficient [1]. Closed cell foam core materials combined with dry fibre preforming enable to manufacture integral sandwich structures with complex geometries using resin infusion technologies [2]. Nevertheless, foam core sandwich structures are vulnerable to concentrated impact loads, which could result in serious structure damages [3]. Core shear cracks with large damage sizes could occur and degrade the load carrying capacity of the structure [3]. With monolithic profiles reinforced foam cores or Z-pinned sandwich structure like the X-Cor™ and K-Cor™ sandwich [4] the out-of-plane properties are improved. The pins used in this study are cut with a pre-defined extensions on both pin ends that lie in the interface between the face sheets and the foam core, thus the Mode I fracture toughness of the interface and the damage tolerance are improved [5]. During the manufacturing process thermal stresses could arise in the interface between pins and foam material, which could lead in critical cases to early failure of the core material [6].
Using the TFC pinning technology reduces the production costs and time, and improves the damage tolerance as well as the fatigue behaviour of the sandwich structure [7]. The aim of this work is to study the shear crack stopping behaviour and the effect of the pins on the mechanical properties of the structure under shear loading.

2. Materials and manufacturing
The Modified Vacuum Infusion (MVI) system as described in [8] was used for the manufacturing of the studied sandwich panels. The sandwich structure consists of a pin-reinforced ROHACELL® HERO foam core and two CFRP face sheets made of Toho Tenax HTS carbon fibre non-crimp fabrics (NCF) impregnated by Hexcel RTM6 epoxy resin. The mechanical properties of the used materials are depicted in the manufacturers' data sheets [9–11]. The core has a thickness of about 25.7 mm and the face sheets consist of four triaxial NCF-layers, with the layup (45/0/-45), which makes a face skin thickness of about 1.5 mm.

Four different pin configurations with different pin distance, materials and same pin angle of 50° as well as a reference configuration without pin reinforcement were tested. The pins have a diameter of about one millimetre. T800H carbon fibre from TORAYCA [12] and 1383 Yarn glass fibre from PPG Fiber Glass [13] were used for the pins. Figure 1 shows the used pin pattern and a 3D-view of the unit cell.

The nomenclature of the tested configurations is depicted in table 1.

| Configuration | Pin material | Unit cell width (a) [mm] | Distance between two unit cells (b) [mm] | Pin Volume fraction [%] |
|---------------|--------------|--------------------------|----------------------------------------|------------------------|
| CFRP.10       | CFRP         | 10                       | 20                                     | 0.75                   |
| CFRP.20       | CFRP         | 20                       | 40                                     | 0.2                    |
| GFRP.10       | GFRP         | 10                       | 20                                     | 0.75                   |
| GFRP.20       | GFRP         | 20                       | 40                                     | 0.2                    |
| H.71           | Reference configuration with unreinforced foam core | | | 0 |

Figure 1. Different views of the unit cell and pinning pattern [14].
The pin volume fraction was calculated based on the test specimen geometry and the number of pins inserted in a test specimen. Only pins with fully constrained ends were considered.

3. Out-of-plane shear test

3.1 Test description and specimen preparation

To determine the shear moduli and strengths for the tested configurations, shear tests in accordance to DIN 53294-standard [15] were conducted. From every test configuration, four test specimens were tested. A test specimen has a length of 390 mm and a width of 100 mm. The test specimens were bonded to steel rigid plates by means of the adhesive epoxy system Scotch-Weld® 9323 B/A [16]. The tests were conducted with sandwich skins bonded to the rigid plates to enable a homogeneous load introduction to the pin-reinforced core. Figure 2 shows the test setup with all parts labelled.

![Test specimen under shear load.](image)

The load was applied to the ends of the rigid plates in compression through a knife-edge bearing at a constant movement rate of the testing machine cross head of 1 mm/min. The load-shear displacement curves were automatically recorded and used to calculate the shear modulus and strength of the core material. Only specimens with shear failure mode were considered for the evaluation. The shear strength was calculated as follow [15]:

\[
\text{Shear strength} = \frac{\text{Load}}{\text{Area}}
\]
\[ \tau_s = \frac{F_B}{A_0} = \frac{F_B}{l_1 \cdot b} \]  

where \( F_B \) is the load at shear failure in N, \( l_1 \) the length of the specimen in mm and \( b \) is the specimen width in mm.

The shear modulus is determined as follow [15]:

\[ G_S = \frac{\Delta \tau}{\Delta \gamma} = \frac{h}{l_1 \cdot b} \frac{\Delta F}{\Delta \vartheta} \]  

where \( h \) is the thickness of the core in mm and \( \frac{\Delta F}{\Delta \vartheta} \) is the slope of initial linear portion of load-shear displacement curve in N/mm. Since the used standard doesn’t contain an explicit definition of \( \frac{\Delta F}{\Delta \vartheta} \), it was calculated by using a best fit to the linear region of the load-shear displacement curves.

3.2. Test results

The stress-shear strain curves of the tested configurations are depicted in figure 3.

**Figure 3.** Stress-shear strain response of the tested configurations.

Mx-y is the identifier of the test specimen where x is the configuration number and y is the number of the test specimen in the tested configuration. In every configuration test results of four test samples were considered except the configuration CFRP.10 where the specimen M1-3 failed due to debonding of the adhesive layer and was not considered in the interpretation.

Comparing the different stress-strain curves shows that using pin-reinforcement increases the non-linearity at the initial portion of the curve. This makes the determination of the shear-modulus of pin-
reinforced test specimens more complicated. Moreover, the response of pin-reinforced specimens shows higher results scatter and a reduced shear strain at failure compared to the reference configuration.

The obtained values for shear strength and shear modulus for the tested configurations are summarised in bar graph-form in figure 4. First observations of the shear properties show that an improvement of shear behaviour is only reached for the configurations CFRP.10 and GFRP.10, which have about four times higher pin volume fraction than the configurations with 20 mm unit cell width. While the configurations CFRP.10 and GFRP.10 led to an increase of shear modulus of about 35% and shear strength of about 15%, the configurations CFRP.20 and GFRP.20 decrease the shear properties. Considering the pin material, CFRP and GFRP-pins led nearly to the same results when maintaining the pin-pattern unchanged. The latter finding leads to the conclusion that an improvement of the mechanical properties could also be reached when using low-cost pins made of glass fibres.

![Figure 4](image)

**Figure 4.** Average values and standard deviations of the calculated shear properties of the tested configurations.

### 3.3. Crack propagation

When the shear strength of a specimen is reached, a shear crack with an angle between 35° and 45° arises and propagates in upper and lower interfaces between the core material and the skins thus the test specimen is divided in two parts. Figure 5 shows an example of a shear crack.

![Figure 5](image)

**Figure 5.** Under shear load failed specimen-close-up view.
Regarding the crack redirection and maintaining the integrity of the structure, observations from test execution and failed specimens investigations showed that only specimens with 10 mm unit cell width prevented the abrupt failure and the collapse of the tested specimen. With high pin volume fraction the expected effects of crack redirection and alternative load path are reached. After crack initiation, the crack propagation is slowed down and the load is mainly carried by the pins. Figure 6 shows the crack redirection effect of two different pin volume fractions. Test specimens with unit cell width of 20 mm showed only a minor effect of the pins on the crack propagation and they had nearly no residual load carrying ability, while the specimens with 10 mm unit cell width showed a change of the direction of the crack propagation and the pins at the fracture surface assured the integrity of the test specimens.

![Figure 6](image.png)

**Figure 6.** Top view of tested specimens after removing the skins.

4. Conclusions
This study is a baseline about the influence of pin-material and pin volume fraction on the shear properties and crack propagation of TFC-sandwich. From the results presented above an enhancement of the shear properties and crack redirection are only possible when a sufficient pin volume fraction is existent. It was expected that the low pin volume fraction of the configurations CFRP.20 and GFRP.20 would lead to a minor improvement of the shear properties compared to the reference configuration without pin reinforcement, but the test results showed that a pin volume fraction of about 0.2% led to a slight degradation of the shear properties of the foam core. It is possible that the low pin volume fraction of the configurations CFRP.20 and GFRP.20 was not sufficient to create an additional load path to carry the shear loads and the inserted pins created local stress concentrations in the foam core that led to an early collapse of test samples. Considering the pin-material, GFRP-pins showed, as expected, the same improvement of the shear properties like the CFRP-pins, which would reduce the material cost. To get a full characterisation of TFC-sandwich, out-of-plane tension and compression tests are to be performed in further investigations.
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