# The springback effect in thermoplastic composites for net-shape manufacturing

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## 1. Abstract

Thermoplastic composites remain challenging to process due to their high processing temperatures. This work proposes a net-shape manufacturing method for CFRTP structures using one-step springback molding. The resulting material combines consolidated skins with a lofted CFRTP springback core to produce lightweight sandwich structures. Different combinations of CFRTP fleece and organosheet preforms were processed, and the resulting sandwich materials were investigated using micrograph analysis, flexural testing, and interlaminar shear testing. The results show that organosheet preforms improve void distribution and mechanical performance compared to CFRTP fleece preforms. Organosheet skins increase flexural performance, while an organosheet core improves interlaminar shear strength. The work further discusses the trade-off between mechanical performance, manufacturability, and tooling complexity at the example of a curved panel with orthogonal stiffeners.

## 2. Introduction

Carbon fiber reinforced thermoplastic polymers (CFRTP) are attractive for lightweight structures due to their high toughness, weldability, recyclability, and suitability for automated manufacturing. However, thermoplastic composites remain challenging to process due to their high processing temperatures and matrix viscosities, making fiber impregnation and consolidation challenging [1].

A characteristic phenomenon observed during CFRTP processing is the springback effect, also known as deconsolidation. Upon heating and melting of the matrix, internal stresses from the reinforcement fibers are released, causing the material to expand in thickness when no external pressure is applied [2]. Previous research by Wan showed that this springback behaviour strongly depends on the fiber volume fraction and processing conditions [3].

Recent studies utilized the springback effect to manufacture lightweight sandwich cores. In these concepts, a lofted CFRTP springback core is combined with consolidated CFRTP skins during a processing cycle called the one-step springback molding, shown in Figure 2c). Previous research demonstrated improved bending stiffness, impact resistance, and energy absorption capability of springback sandwich structures. Furthermore, needle-punched CFRTP preforms were shown to improve trough-thickness reinforcement and reduce delamination [4]. A springback ratio of approximately 1.7 was found optimal for mechanical performance [5].

The principle of one-step springback molding has previously been applied at the coupon level. To extend the process toward net-shape manufacturing of lightweight high-performance structures, further understanding of material selection, void formation, and process limitations is required. This work therefore investigates one-step springback molding using endless CFRTP. Different CFRTP fleece and organosheet preforms are compared regarding performance and processability. Finally, the process is applied to the net-shape manufacturing of a curved stiffened demonstrator structure.

## 3. Materials and Specimen Manufacturing

Material selection was driven by the objective of net-shape manufacturing of high-performance CFRTP structures. Both the core and the skins used a carbon-fiber reinforced polyetherimide (PEI) matrix system. Based on the findings of Xiao, needle-punched material preforms were selected due to their favourable springback behavior. In this work, the materials were investigated both as drapable CFRTP fleeces and as organosheets.

The springback core material is commercially available as KyronTEX C44/R/500 from Mitsubishi Chemical Advanced Materials GmbH (Germany). The material consists of 44 wt.% fully recycled chopped carbon fibers combined with a PEI fleece to a total areal weight of 500 g/m$^2$. The skin material is commercially available as KyronTEX C55/1/440, consisting of 55 wt.% woven carbon fibers (0/90°) combined with a PEI fleece to a total areal weight of 440 g/m$^2$.

The one-step springback molding process combines woven CFRTP skins with a springback core to form a sandwich structure, schematically shown in Figure 1: the skins are fully consolidated with minimal void content, while the springback core lofts during springback molding to form a low-density layer with an approximate void content of 40%.

All springback sandwich specimens used the same layup consisting of three woven CFRTP skin layers on each side and four nonwoven CFRTP core layers. The specimens were one-step springback molded using 4 mm spacers to set the springback ratio and final specimen thickness. The 4 mm spacers equal a springback factor of 1.7, as recommended by Zhang [5]. After mold closure, the laminates were heated to 360 °C, held for 6 minutes, and subsequently cooled to room temperature.


*Figure 1. Schematic of the springback sandwich structure with consolidated skins and a porous springback core.*

Three material preform combinations were investigated as shown in Figure 2:

a) CFRTP fleece skins with a CFRTP fleece core
b) CFRTP organosheet skins with a CFRTP fleece core
c) CFRTP organosheet skins with a CFRTP organosheet core

The organosheets were manufactured from the corresponding fleece materials in a separate hot-pressing step. Due to the bulky structure of the fleece materials, larger tooling clearances and larger closing pressures were required compared to the organosheet configurations, as shown in Figure 2. Test specimens for mechanical characterization were cut from the manufactured plates using a circular saw. To benchmark the mechanical performance, a fully consolidated CFRTP reference laminate was manufactured from the woven CFRTP fleece in a conventional hot-press process (360 °C, 12 bar, 6 minutes).

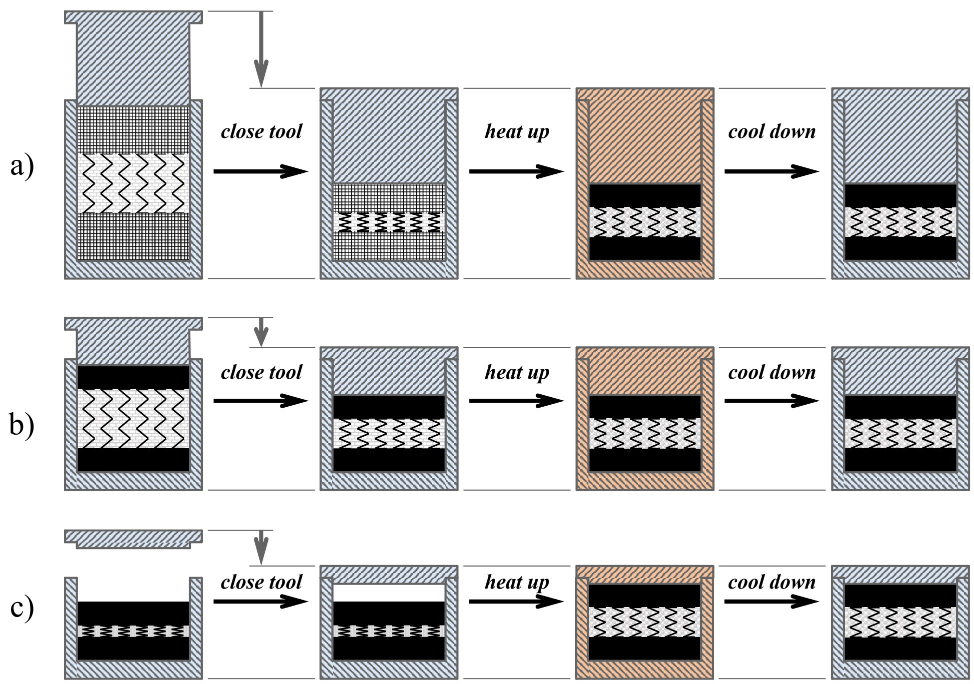



*Figure 2. One-step springback molding using different CFRTP preforms for skins/core: a) fleece/fleece, b) organosheet/fleece, c) organosheet/organosheet. The bulky fleece increases the tooling closing path and required tooling size.*

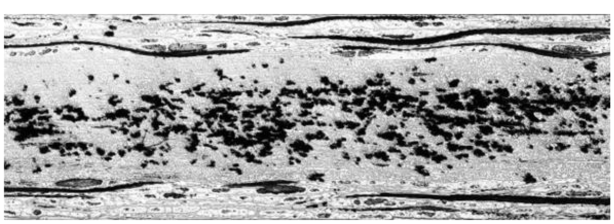
## 4. Void analysis

In this study, void content was evaluated via optical microscopy on a Keyence VHX-7000 digital microscope. Two specimens measuring 24 mm x 3.5 mm each were analysed for each processing method. A greyscale brightness threshold was applied in ImageJ across all specimens to distinguish voids. Based on the micrographs shown in Figure 3, void content in the specimen was analyzed qualitatively and quantitatively. The hypothesis was that the springback sandwich has a high, uniformly distributed void content in the core from the springback lofting and that the skins are fully consolidated with a low void content. Void content in the skins was quantified, as these carry the in-plane loads in sandwich structures. The micrographs show that the void content and void distribution strongly depend on the used material preform.

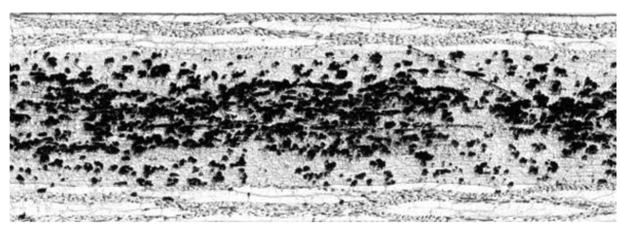
For the springback sandwich processed from fleece skins and a fleece core shown in Figure 3a), the micrographs show a high void content in the skins of 16.6 % (± 3.8%). This is a lot higher than expected and more than what is accepted in high-performance applications. The void content in the core, on the other hand, was concentrated in the middle of the core, with lower void content towards the interface with the skin layers.

The high void content in the skins can be attributed to poorly impregnated fibers. This is mostly due to two effects: the first one is that the springback pressure from the core is not sufficient to consolidate the fibers. The second effect, maybe more important, is that the springback CFRTP layup is heated from the top and bottom, i.e., the PEI in the skins melts before the PEI in the core melts. As a result, the molten PEI from the skins flows into the core, which is still in the form of a fleece. This matrix flow from the skins into the core explains the reduced void content in the core close to the outer skins. Having a high void content in the skins is undesirable, as performance in CFRTP is strongly reduced with increasing void content. The matrix flow from the skins into the core could potentially improve the bond between the layers, while the high void content in the middle of the core poses a weak point in the upcoming interlaminar shear test.

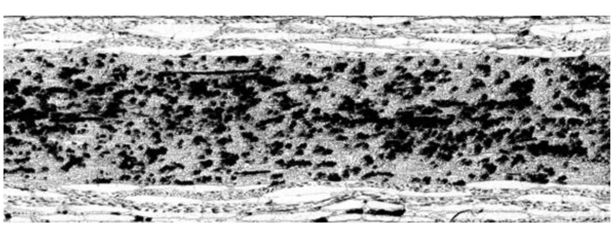
For the springback sandwich processed from organosheet skins and a CFRTP fleece core, shown in Figure 3b), the micrographs show a low void content in the skins of 0.8 % (± 0.4 %). This indicates a significant reduction in void content in the skins compared to the springback sandwich manufactured entirely from fleece material preforms. Consequently, the void content in the core is higher overall. Also, using an organosheet for the skins in one-step springback molding leads to a more uniform void content distribution in the core with only a slightly increased void content in the middle of the core.



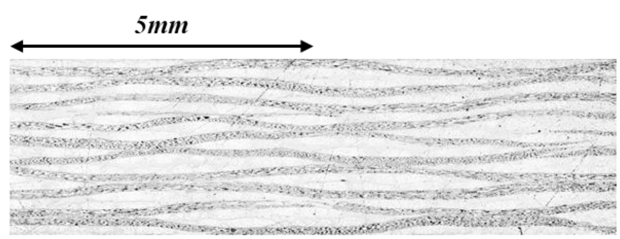
*a) One-step springback moulding with CFRTP fleece preforms*



*b) One-step springback moulding with CFRTP organosheet skins and CFRTP fleece core*



*c) One-step springback moulding with CFRTP organosheet preforms*




*d) Reference CFRTP organosheet*

*Figure 3. Micrographs of the springback sandwich specimens and the reference organosheet used for void content analysis. The spatial resolution of the micrographs was 2.1 µm per pixel.*

Using an organosheet for the skins shows effective in reducing the void content in the skins. Unlike for the fleece, which led to a high void content, carbon fibers were already impregnated in the material preform before the one-step springback molding, proving effective in keeping the matrix in the skins. As a result, matrix flow from the skins into the core is reduced. While this should lead to improved mechanical performance, organosheets are stiffer compared to the drapable CFRTP fleece. This is a drawback in the net-shape manufacturing of structures, where materials are placed in shape before the process.

For the springback sandwich processed from organosheet skins and organosheet core, the micrographs show a low void content in the skins of 2.1 % (± 0.6 %). This is higher than for the springback sandwich processed using a fleece core. Also using an organosheet for the core in one-step springback molding leads to the most uniform void content distribution in the core with no visible gradient in void content in the middle of the core, as shown in Figure 3c).

Remarkably, using an organosheet core leads to a higher void content in the skins compared to processing a fleece core. This can be explained by the fact that when all layers are in the form of organosheets, the layup is slightly thinner than the final springback sandwich. The lofting to the final thickness mostly comes from the springback effect in the core. However, since the layup is heated from the top and bottom in the one-step-springback molding, the PEI in the skins melts before the PEI in the core. Only the melding of the PEI in the core should unlock the springback effect. Until then, there is a gap between the tool and the skins, which have melted polymer. This gap leads to the voids in the skins for the process with an organosheet core. On the other hand, using an organosheet core for the one-step springback molding reduces matrix flow from the skins into the core, as the organosheet offers less space for matrix flow from the skins than a fleece core. This explains the more homogeneous void distribution in the core. Finally, the reference organosheet, processed from the woven fleece material preform as used in the skins, in a hot press process, a void content of 0.3 % was achieved.

## 5. Flexural performance

Three-point flexural tests were conducted in accordance with DIN EN ISO 14125 to evaluate the flexural performance of the springback sandwich specimens. For each processing method, six specimens were tested to determine the mean values and corresponding standard deviations. Further details, including specimen dimensions and loading speeds, are provided in Table 1.

*Table 1. Specimen geometry and testing parameters for flexural testing (3-P-Fl) and interlaminar shear strength (ILSS) testing.*

| Parameter | Unit | 3-P-Fl | ILSS |
|---|---|---|---|
| Specimen length | mm | 200 | 24 |
| Specimen width | mm | 15 | 8 |
| Span length | mm | 100 | 16 |
| Loading speed | mm/min | 10 | 1 |
| Loading nose radius | mm | 5 | 3 |
| Support radius | mm | 5 | 3 |

From the flexure test, the flexural modulus ($E_f$) and flexural stiffness (EI) were evaluated for the springback sandwich and the reference organosheet. The flexural stiffness (EI) captures the effect of specimen thickness, while the flexural modulus ($E_f$) is a material property and does not depend on thickness. While keeping the weight identical (4640 g/m$^2$), the springback sandwich specimens had a larger thickness than the fully consolidated reference specimen (3.4 mm vs. 2.9 mm).

Figure 4 shows the results for the flexural modulus (left) and the flexural stiffness (right). The springback sandwich processed from fleece skins and a fleece core exhibited the lowest flexural modulus at 31000 MPa. The springback sandwich processed from organosheet skins achieved a flexural modulus of approximately 44000 MPa, independent of the core preform type (fleece or organosheet). The reference organosheet, which uses only woven fibers, reached a flexural modulus of 47000 MPa.

The differences in flexural modulus can be explained by the void content in the skins, as found during the void analysis. The springback sandwich processed from fleece skins had a significantly higher void content in the skins than the other specimens, leading to inferior flexural performance. In contrast to the skins, the core layer with chopped recycled carbon fibers appears to have only a minor influence on the flexural modulus, as the springback sandwich can achieve values similar to the reference organosheet despite having a porous, nonwoven core.

Unlike the flexural modulus, the flexural stiffness depends on material thickness. Despite high void content in the skins, the springback sandwich processed from CFRTP fleece preforms matched the reference organosheet in flexural stiffness at 1.50 Nm$^2$, mostly due to its increased thickness. Using organosheet skins, however, resulted in higher flexural stiffness values of 2.22 Nm$^2$ and 2.28 Nm$^2$, respectively.

The obtained flexural stiffness results show sandwich effects associated with increased material thickness at equivalent weight. Due to the springback core, the springback sandwich specimens match and exceed the performance of a fully consolidated specimen at equivalent weight, as expected from the literature. Comparing the springback configurations shows that the skin preform (fleece vs. organosheet) has a strong influence on flexure performance, whereas the core preform has only a minor effect. The core preform was expected to have a major effect on the interlaminar shear strength as described in the next subsection.

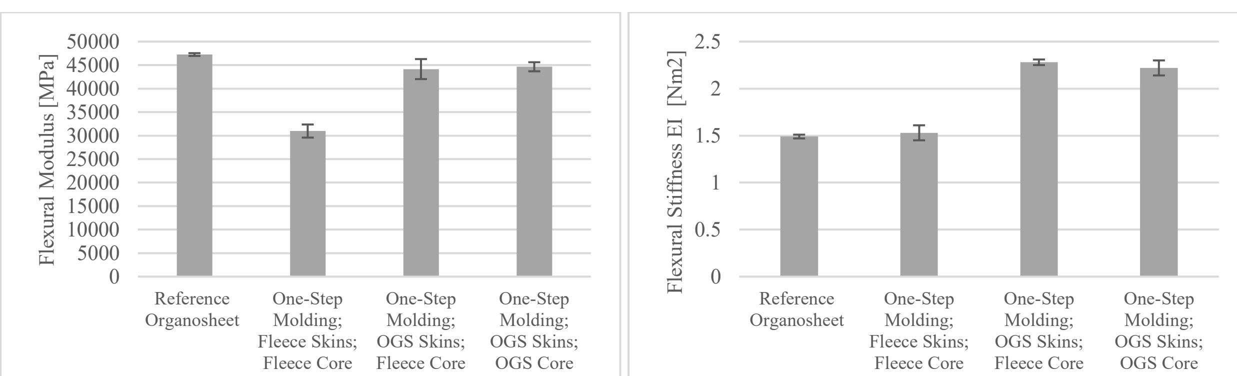



*Figure 4. Flexural modulus (left) and flexural stiffness (right) of the springback sandwich specimens processed from fleece and/or organosheet (OGS) preforms as well as the reference organosheet. All specimens have an area weight of 4640 g/m2.*

## 6. Interlaminar shear testing

Short beam shear tests were conducted in accordance with ASTM D 2344 to evaluate interlaminar shear strength (ILSS). For each one-step springback molding method, six specimens were tested to determine the mean values and corresponding standard deviations. Further details, including specimen dimensions and loading speeds, are provided in Table 1. ILSS was evaluated for the springback sandwich configurations and the reference organosheet in both longitudinal and transverse directions. ILSS is highly sensitive to voids and other defects and should therefore provide insight into the influence of the porous springback core [6]. Figure 5 shows the obtained ILSS values for the springback sandwich specimens and the reference organosheet.

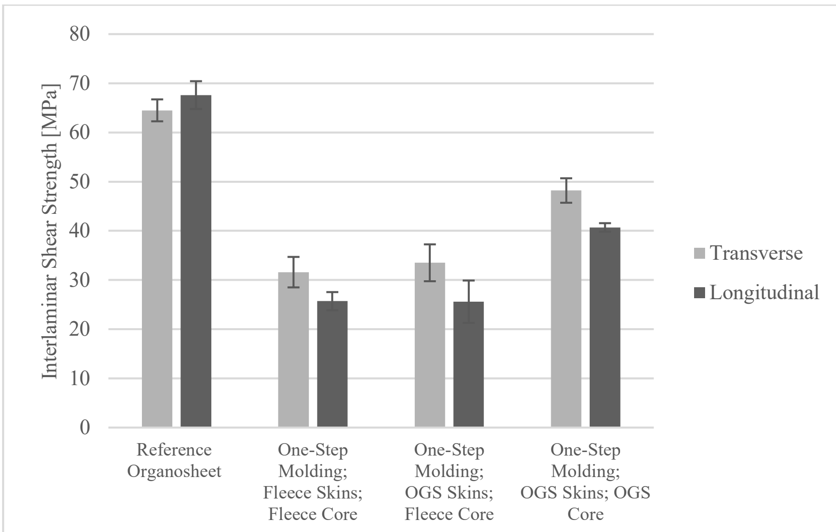



*Figure 5. Interlaminar shear strength of the springback sandwich specimens and the reference organosheet in longitudinal and transverse directions.*

The reference organosheet achieved the highest ILSS values, reaching 67.6 MPa in the longitudinal direction and 64.5 MPa in the transverse direction. Among the springback sandwich configurations, the specimen processed from CFRTP fleece preforms achieved the lowest ILSS values at 25.7 MPa and 31.6 MPa in longitudinal and transverse direction, respectively. Replacing the fleece skins with woven CFRTP organosheet skins resulted in only a marginal improvement, yielding 25.6 MPa in longitudinal direction and 33.5 MPa in transverse direction. In contrast, using organosheet preforms for both the skins and the core significantly improved the ILSS, reaching 40.7 MPa in longitudinal direction and 48.2 MPa in transverse direction. All springback sandwich specimens failed through interlaminar shear in the center of the core layer.

Independent of the material preform used, the ILSS in the transverse direction was consistently 6 to 8 MPa higher than in the longitudinal direction for all springback sandwich configurations. This behavior is attributed to the nonwoven carbon fibers in the core. According to the material supplier, Mitsubishi Chemical Advanced Materials GmbH (Germany), the fibers are not distributed fully randomly and exhibit a slight preferential orientation in the transverse direction.

The ILSS results indicate that interlaminar shear performance is governed primarily by the core preform and the resulting void distribution. Using an organosheet preform for the core improved the ILSS by more than 50% compared to using a fleece preform. Two main effects are considered responsible for this improvement. First, the organosheet preform led to a more homogeneous void distribution within the core, reducing local void concentrations that promote interlaminar failure initiation. Second, the carbon fibers were already fully impregnated prior to springback molding, suggesting that the high-viscosity thermoplastic matrix adhered more effectively to the fibers and hindered crack initiation and propagation. Nevertheless, the springback sandwich specimens remained significantly below the ILSS of the fully consolidated reference organosheet due to the high void content within the core. Comparing the springback configurations further shows that the core preform (fleece vs. organosheet) has a strong influence on ILSS, whereas the skin preform has only a minor effect.

## 7. Process-performance relations

The micrograph analysis and mechanical testing showed that material preform selection strongly influences both processing and performance in one-step springback molding. Needle-punched fleece preforms are attractive due to their low material cost, high drapability, and pronounced springback behavior. The high drapability facilitates the net-shape manufacturing of complex geometries, where the material must conform to the mold during layup. However, the results presented in Section 4 showed that fleece preforms lead to increased void contents, particularly in the skins. Furthermore, their highly bulky structure requires large tooling clearances, long mold closing paths, and high initial compaction forces.

In contrast, organosheet preforms achieved the desired void distribution with consolidated skins and a porous core, resulting in improved mechanical performance. Due to their preconsolidated nature, organosheets require little mold closing paths and compaction force, simplifying tooling design and reducing initial compaction requirements. These advantages come at the cost of higher material prices or an additional processing step. Furthermore, organosheets are stiffer and less drapable than fleece preforms, limiting their suitability for complex net-shape manufacturing.

Consequently, material preform selection represents a trade-off between cost, drapability, tooling requirements, and mechanical performance.

## 8. Demonstrator manufacturing

Finally, the one-step springback molding process was applied to net-shape manufacturing of a part for the first time. The curved CFRTP panel shown in Figure 6 measures 800 mm x 525 mm with a 10° curvature and has two I-frames and three Ω-stringers, similar to an aircraft fuselage. The demonstrator was manufactured in a rigid mold consisting of 31 components with a total weight of 420 kg. Compared to simple coupons, the curved and stiffened geometry required significantly more tooling considerations. Based on the previous findings, organosheet material preforms were used for both the woven skin and the nonwoven springback core.

The demonstrator was net-shape manufactured in a one-step springback molding step using a hot press for heat conduction. During processing, the Ω-stringers were supported by wash-out salt-cores. The successful manufacturing of the curved, orthogonally stiffened panel demonstrates the use of the one-step springback molding for CFRTP structures. However, increased structural complexity also increased tooling complexity and handling effort, confirming the trade-off between manufacturability, tooling complexity, and mechanical performance discussed in the previous section 8.


*Figure 6. Curved CFRTP demonstrator panel with orthogonal stiffeners manufactured using one-step springback molding.*

## 9. Discussion of manufacturing potential

The one-step springback molding process enables the net-shape manufacturing of CFRTP structures using metallic molds. This reduces labor, minimizes material waste, and eliminates secondary joining such as riveting, bonding, and welding. Unlike welded thermoplastic structures, the process allows continuous fibers between structural elements, such as Ω-stringers and skins. In addition, the springback core uses recycled carbon-fiber nonwovens combined with a recyclable thermoplastic matrix, resulting in a lightweight and recyclable composite structure.

Using CFRTP organosheet preforms reduced void content in the skins, leading to improved mechanical performance. However, this requires either more expensive CFRTP organosheet materials or an additional hot press step. The ability to combine fleece and organosheet preforms within one thermoplastic structure offers flexibility in balancing drapability, tooling size, and performance.

Despite the demonstrated manufacturing of parts from coupon level to demonstrator scale, several limitations became evident. The high void content within the springback core remains difficult to control and strongly influences interlaminar performance. In addition, increasing structural complexity significantly increased tooling complexity, size, and handling effort. These limitations should be addressed in future research.

## 10. Conclusion

This work investigated the one-step springback molding for the net-shape manufacturing of CFRTP sandwich structures using fleece and organosheet preforms. Void content and distribution, flexural performance, and interlaminar shear strength were evaluated and linked to material preform selection and tooling considerations. The process was applied to the manufacturing of a curved demonstrator panel with orthogonal stiffeners. The results showed that the selected CFRTP preform strongly influences void distribution and mechanical performance. Organosheet preforms were required to achieve the intended structure with consolidated CFRTP skins and a low-density springback core. Using organosheet skins increased flexural performance, while using organosheet cores improved interlaminar shear strength. In contrast, CFRTP fleece preforms provided superior drapability for complex geometries but resulted in higher void contents. Furthermore, the bulky nature of the CFRTP fleece increased tooling size and compaction forces compared to organosheet preforms. The curved demonstrator panel transferred the one-step springback molding process from the coupon level to a larger geometry, while revealing the high tooling complexity associated with net-shape manufacturing. Future work should therefore focus on combining the drapability of CFRTP fleece preforms with the mechanical performance of CFRTP organosheets, while reducing tooling complexity, weight, and cost.

## 11. Acknowledgements

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