# HIGH-RATE, SPRING-IN COMPENSATED, NET-SHAPE MANUFACTURING OF RTM MADE COMPOSITE FRAMES WITHIN THE EU PROJECT MAAXIMUS

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**Abstract**
Curved composite Z-frames have been manufactured within the MAAXIMUS project while its ambitious cost-saving goals have been conscientiously pursued. The frames are part of the project's wide-body side-shell demonstrator. A ready-for-high-rate RTM manufacturing process scenario has been established. It features net-shape preforming and iso-thermal curing. Moreover, prediction-based tool compensation has been applied in tool design in order to compensate for inevitable process-induced distortion (PID) of the composite frames. Therefore, the p-approach has been applied which stands out for its efficiency in terms of modelling and parameter efforts. The geometric evaluation of the frame cross sections shows that the prescribed angle tolerances of ±0.25° are consistently met. The results even indicate that more tight tolerances of ±0.10°are realistic.

## 1. Introduction

High performance composite structures are increasingly used in today's airframes due to their excellent weight-specific mechanical performance. The announced ramp-up for next generation aircrafts demands for taking the next step in composite manufacturing in order to fabricate parts with excellent dimensional fidelity in high-rate processes. Within the European FP7 project MAAXIMUS[1] a side shell structure was chosen as demonstrator. Its dimensions are similar to today's wide-body fuselage configurations. The majority of the frame components as well as the outer skin are made of carbon-fiber composites. The present paper is focussed on the advanced manufacturing of the C73 frames which are shown in Figure 1. The work reported in this paper addresses the ambitious goals of the MAAXIMUS project. Amongst others, those are the significant reduction of recurring (RC) and non-recurring (NRC) costs on various levels of the development chain.

## 2. RTM manufacturing of C73 composite frames

The frames are shown in figure 1(b). They have a Z-shaped cross section and a chord length of approximately 950 mm. The inner and outer flange widths are in the range of 15 mm up to 45 mm. The upper

[1]**M**ore **A**ffordable **A**ircraft through e**X**tended, **I**ntegrated and **M**ature n**U**merical **S**izing

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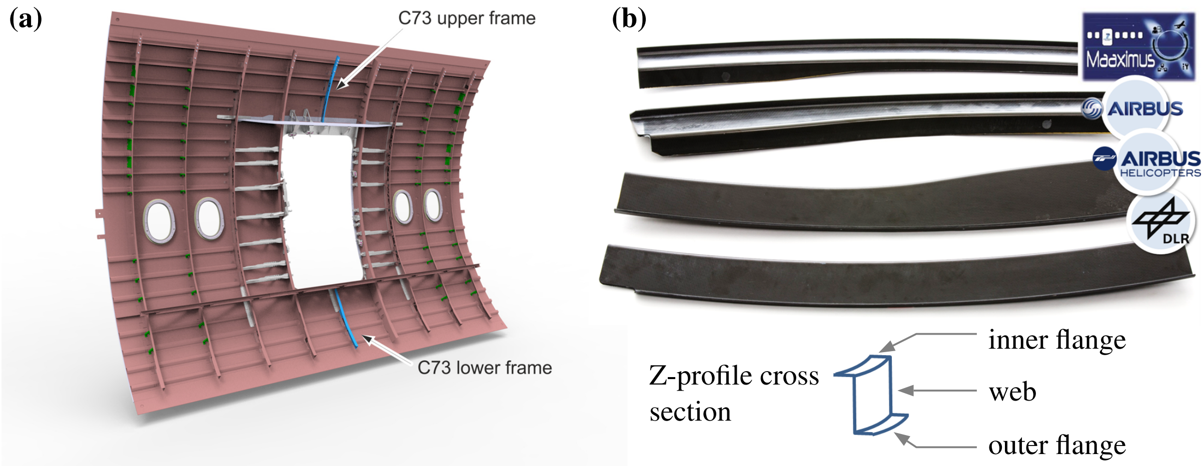


**Figure 1.** MAAXIMUS side-shell demonstrator (a) with C73 upper and lower frames (b)

**Table 1.** Selected project goals and corresponding measures applied in the C73 frame context

| | |
|---|---|
| **Optimized composite fuselage:** | |
| Goal: | 50% reduction of fuselage assembly time |
| Measure: | *Reduction of PID due to tool compensation aiming for a no-shim assembly* |
| Goal: | 10% reduction of manufacturing costs |
| Measure: | *Application of multi-processing strategies, Avoidance of tool-rework loops due to effective compensation* |
| **Faster Development:** | |
| Goal: | Reduce by 10% the non-recurring cost of aircraft composite structures from preliminary design up to full-scale test |
| Measure: | *Efficient PID prediction methods allows for consideration early on in the design process* |
| **Right-First-Time Structure:** | |
| Goal: | Reduce the airframe development costs by 5% compared with the equivalent development steps in an industrial context |
| Measure: | *Reliable PID prediction enables the reduction of tool costs and prototypes* |

frame has a constant web height of around 80 mm. The web height of the lower frame increases from 80 mm to 115 mm along the profile. The upper frame has a nominal laminate thickness of 2.38 mm for the web and the outer flange. The inner flange thickness is 2.68 mm. A thickness tolerance of -6% up to +10% was prescribed in the project. The web laminate is quasi-isotropic while an additional UD ply is added at the inner flange area which is aligned in hoop direction. Laminate drop offs are located at the curved junctions between the web and the flanges.

### 2.1. Preform technology and manufacturing tool concept

The frame layup is composed of Hexcel's G0926 (5H satin) and G1157 (UD) carbon fabric [1] materials and RTM6 resin. Both sides of the frame were covered by a single 0.08 mm thick ply of HexForce 00120 glass fabric [2]. Automated net-shape preforming has been established which utilizes previous experiences [3]. It pursues a ply-by-ply strategy in order to provide quality-controlled preforms. The full-stack preforms of both frames were fine trimmed to the nominal shape using an ultra-sonic-based cutting technology in order to fit the tool cavity at curing temperature. The modular metallic manufacturing tool is shown in figure 2 (b). It features a fluid-based temperature control while closing forces are supplied by

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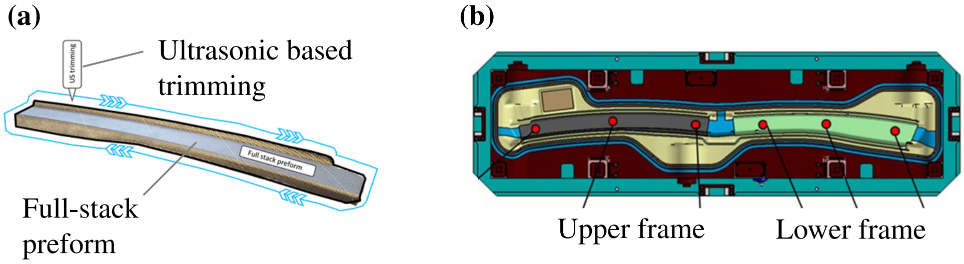


**Figure 2.** Ultrasonic-based full-stack fine trimming (a) and modular injection tool with geometrically compensated part cavities to counteract PID of the frames (b)

a hydraulic press. The inner-most tool modules, which form the part cavities, were made from aluminum. An isothermal RTM manufacturing strategy is pursued. The tool cavity geometries were compensated early on in the tool design on CAD level based on predictions of expectable process-induced distortion. This process is described in more detail within section 3 of the present paper.

### 2.2. Applied manufacturing processes and high-rate production concepts

Different certified RTM6 manufacturing processes have been investigated in the project. For the frame use case at hand an 155°C isothermal process represents the reference. It is a single-dwell process with a dwell stage length of 210 minutes. With respect to the MAAXIMUS project aims, focussing on high-rate composite manufacturing at low cost, multi-process sequences have been investigated in the project as well. This challenges the fact that a considerable fraction $\delta_{heat,cool}$ of today's manufacturing processes is dedicated to heating and cooling of the tool as can be quantified by equation 1. Those fractions can be saved for the most part when the tool is operated isothermally and multi processes are performed sequentially.

$$\delta_{heat,cool} = \frac{t_{total} - t_{dwell}}{t_{total}} \tag{1}$$

For the reference process 27% of the overall process time is dedicated for heating and cooling. Hence, a multi-process strategy promises significant cost savings on different levels. On the one-hand side energy costs are reduced as the tool cool down is saved. On the other hand side the overall process time is reduced, which is equivalent to a shortening of the tool occupancy and a reduction of labor costs. For sake of conciseness and due to the paper's focus on PID the results of the multi-process studies are excluded from the present paper.

## 3. Applied tool compensation strategy

Composite materials have various advantageous aspects from a design point of view. They are light, they can be tailored to certain structural requirements by adapting the layup locally and they can be manufactured in almost any shape. However, the anisotropic properties of the single ply, being fiber dominated along the fiber directions and resin dominated in transverse directions, result in an anisotropic behavior of the full laminate. Combined with today's high-temperature manufacturing processes this anisotropy induces inhomogeneous strains inside the part due to curing and thermal dilation. In addition, tool dimensional change during heat up leads to residual stress build-up within the part [4]. Therefore, the subsequent conclusion can be drawn for all technically relevant composite structures made today.

> ***'The shape of a manufactured composite part inevitably deviates from the shape of the tool on which it has been processed.'***

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Three main mechanisms are distinguished in literature which induce PID. They are schematically illustrated in figure 3. Web warpage as well as geometrical scaling are classified as extrinsic sources for PID since they are dominated by the tool. In contrast spring-in is induced by the composite's anisotropy which explains its classification as an intrinsic source [5]. All three mechanisms affect part dimensions of technically relevant composite structures in aerospace applications, often causing the violation of geometric tolerances. As described in the preceding section the frame manufacturing strategy pursued in MAAXIMUS features isothermal curing. This implies that the tool dimensions do not change after the resin injection, which suppresses tool-part interaction due to tool stretching.

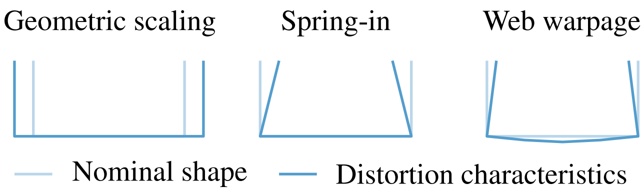


**Figure 3.** Distortion mechanisms typically relevant for composite frame structures [6]

Spring-in distortions occur widely independent from the tool properties [7]. Therefore, spring-in is considered as the most relevant mechanism affecting the manufactured shape of the frames at hand. Since those distortions are inevitable for the regarded manufacturing scenario it has been deemed necessary to compensate them by modifying the nominal tool shape. In addition, it has been necessary to account for geometrical scaling of the tool dimensions as the part is cured at elevated temperature while the nominal design refers to room temperature ($T_{cure} > T_{room}$). The part dimensions are scaled homogeneously within the CAD environment by applying equation 2.

$$L_{tool,manufacturing} = \tilde{L}_{nominal} \cdot p_{scale} \quad \text{with} \quad p_{scale} = 1 + \alpha_{eff} \cdot (T_{room} - T_{cure}) \tag{2}$$

Usually, the scaling parameter $p_{scale}$ is calculated utilizing an effective coefficient of thermal expansion (CTE) $\alpha_{eff}$ which is basically the difference of the tool CTE and an assumed average CTE for the composite $\left(\alpha_{tool} - \alpha_{composite}\right)$. For an 155°C process, an assumed room temperature of 22°C, a tool CTE $\alpha_{tool}$ of 12 ppm/K and an assumed CTE of the composite of 2 ppm/K the scaling parameter is calculated to $p_{scale} = 0.99867$. Even though this procedure is frequently applied in industry it should be noted that it implies an isotropic scaling of all part dimensions. While this is practicable for tools made from isotropic metals it is erroneous for anisotropic composites for two reasons. On the one hand side the CTEs differ significantly between the in-plane directions and the through-thickness direction. On the other hand side, locally varying layups along the part lead to a zone-to-zone CTE inhomogeneity. This induces shape changes of a whole part, such as a superposed global bending, when a temperature load is applied. The zone-specific laminate CTEs for the outer flange, the inner flange and the web are given in table 2. It can be seen that the web CTE of the frame in hoop direction ($\alpha_x$) exceeds the CTE of the inner flange by approximately 41%.

There is not doubt that tool compensation is necessary in order to manufacture aerospace components within tight geometrical tolerances. Recalling the MAAXIMUS objectives, cost saving is enabled by improved manufacturing processes on the one-hand side. On the other hand side efficient PID prediction capabilities are the key to further significant cost reductions and development accelerations as costly prototype-tool-rework loops can be avoided and the overall part development process is shortened. Thus, composite manufacturing companies face a demanding challenge: They must be able to derive compensated tool geometries at lowest possible cost preferably without extensive prototype manufacturing . Due to high cost pressure in the market, methodologies are desired which require as little effort as possible to derive tool compensation measures which allow the fabrication of parts within tolerances provided by OEMs.

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### 3.1. Phenomenological-numerical prediction of process-induced distortions

Within MAAXIMUS the p-approach simulation strategy has been applied [8, 9] to predict the frames PID. This information is used for the compensation of the upper frame tool geometry. The p-approach basically combines phenomenological simulation parameters, in particular a measured L-angle distortion, with efficient numerical models basing on shell or solid finite elements. The suitability of the approach has been successfully demonstrated in recent publications [8, 10]. The generated finite element model of the frame was set up based on the nominal CAD data. Homogenized zone-specific material properties were assigned to the inner flange, outer flange and the web region. Three-dimensional laminate theory proposed by Chou et al. [11] has been used to calculate the necessary engineering constants. Selected values are listed in table 2. According to the p-approach a single composite L-angle has been

**Table 2.** Zone-specific engineering constants, CTEs and nominal laminate thicknesses of the upper frame

| Zone | $E_x$ [GPa] | $E_y$ [GPa] | $G_{xy}$ [GPa] | $\nu_{xy}$ [-] | $\alpha_x$ [ppm/K] | $\alpha_y$ [ppm/K] | $t_{lam}$ [mm] |
|---|---|---|---|---|---|---|---|
| Inner flange | 43.87 | 34.39 | 18.87 | 0.439 | 1.96 | 4.59 | 2.64 |
| Web | 35.47 | 35.47 | 20.49 | 0.441 | 2.76 | 3.62 | 2.38 |
| Outer flange | 35.47 | 35.47 | 20.49 | 0.441 | 2.76 | 3.62 | 2.38 |

manufactured. It is representative for the frame characteristics at hand in terms of fiber material, stacking, manufacturing process and preforming. The manufactured L-angle showed a spring-in distortion $\Delta\varphi$ of 0.963°.

$$\frac{\Delta\varphi}{\tilde{\varphi}} = \frac{\varepsilon_T - \varepsilon_R}{1 + \varepsilon_R} = \frac{-\varepsilon_R^*}{1 + \varepsilon_R^*} \quad \rightarrow \quad \varepsilon_R^* = \frac{-\Delta\varphi}{\Delta\varphi + \tilde{\varphi}} \tag{3}$$

According to equation 3, which has been developed by Radford [12], this corresponds to an equivalent through-thickness strain $\varepsilon_R^*$ of -1.06%. This value is utilized within the PID prediction process where it acts in laminate-thickness direction as documented in [13].

### 3.2. Results

Three different simulation runs have been performed: (a) spring-in + cool down, (b) cool down only, (c) spring-in only. The FE model was setup in ABAQUS. Eight-node brick elements (C3D8) have been used. Figure 4 shows the results of the three runs. It should be noted that the magnitudes of the illustrated node translations directly refer to the indicated coordinate system. The legend given on the left-hand side is valid for all three plots.

Run (b) shows the effect of the zone-specific CTE inhomogeneity. In-plane CTEs were prescribed in the model only. It can be seen that the CTE inhomogeneity leads to considerable warping of the whole part. It illustrates that the widely applied tool-scaling procedure described above, which assumes an homogeneous average CTE for the composite, is erroneous for parts with different laminate zones. Run (c) considers $\varepsilon_R^*$ only while in-plane CTEs are set to zero. Changes of the flange-to-web angles as well as a global warping of the part were observed. The bending is directed in opposing direction as it was found for run (b). Run (a) represents the superposition of the runs (b) and (c), where in-plane CTEs and $\varepsilon_R^*$ are considered simultaneously. It can be seen that the corresponding distortion mode is dominated by spring-in, even though magnitudes decreased compared to run (c). It is an important finding that there is a significant coupling between spring-in, which is mainly generated in the curved transition zones between web and flanges, and a global warpage of the frame. It seems reasonable to conclude

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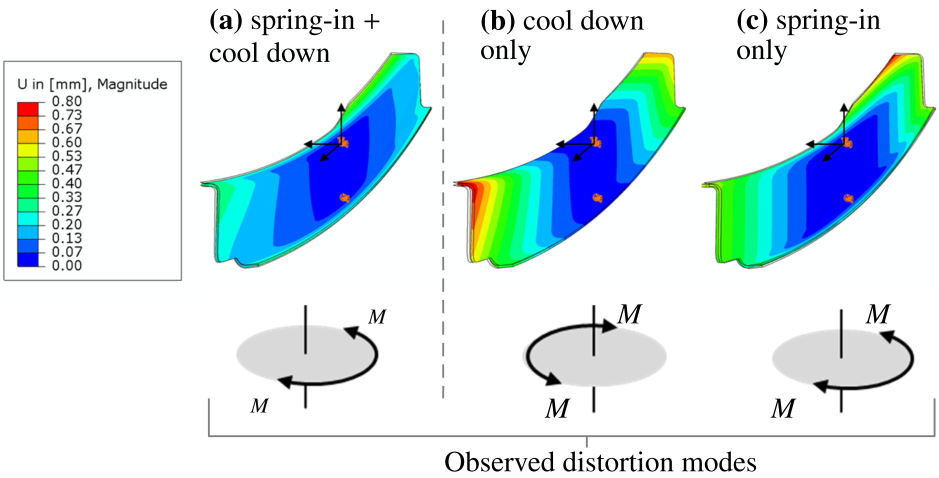


**Figure 4.** Predicted distortions of the upper frame. Contributions due to cool down and spring-in counteract each other. *M* indicates a bending moment which illustrates the observed global distortion.

that this effect is relevant for all typical curved frame geometries, independent whether they have Z- or C- shaped cross sections. It is basically founded by the fact that the frame-surface does not represent a developable surface. Figure 5 shows the calculated distortions of run (a) in a vectorized form. It can be seen that tipping of flanges due to spring-in gives the highest deformations. These distortions were used for the compensation task of the frame geometry. They have been inverted analytically and the CAD model has been updated based on a field of the node coordinates. Within the MAAXIMUS

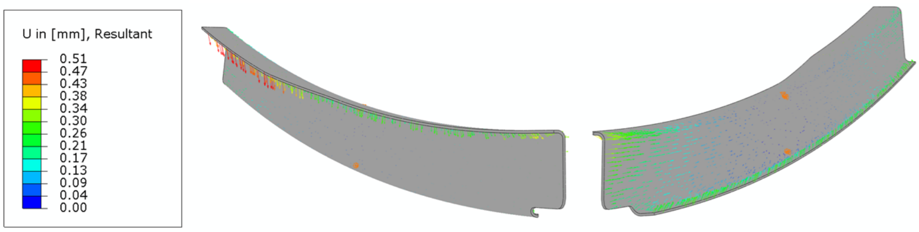


**Figure 5.** Distortion magnitudes and directions used for the tool compensation. Flange areas show highest deformations.

project a one-step compensation ($n = 1$) has been applied. However, it should be noted that in theory tool compensation is a nonlinear problem, as indicated by equation 4. Therein, $X$ and $n$ denote a specific manufactured configuration and the number of iterative compensations, respectively. $\Delta x_{PID,n}$ denotes the shape deviation of the manufactured part from the nominal design after $n$ compensation steps. Without any compensation ($n = 0$) the parameter $\Delta x_{PID,0}$ is equal to the distortions shown in figure 5.

$$X_{part,n} = X_{part,nominal} + \Delta x_{PID,n} + \begin{cases} 0 & \text{, for } n = 0 \\ -\sum_{j=1}^{n} \Delta x_{PID,j-1} & \text{, for } n \geq 1 \end{cases} \tag{4}$$

This nonlinearity of a compensation task basis on the fact that compensation measures are derived from PID predictions or measurements of a certain configuration $K_i$. If this compensation measure is added to $K_i$, an new configuration $K_{i+1}$ is created. This new configuration produces a different amount of distortions which deviates from the distortion of configuration $K_i$. Thus, a full compensation is not achieved and additional steps become necessary. Even though, a one-step compensation works fine for many parts the preceding fact should be kept in mind. When part scale and complexity increases a multi-step procedure can become necessary to improve compensations. The manufactured frames have

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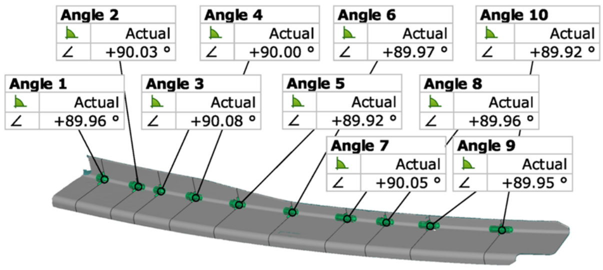
been evaluated in terms of laminate thickness, global shape deviation as well as cross-section shape. Representative for all manufactured upper frames figure 6 shows results of a cross-section evaluation. It can be seen that the provided angle tolerance of ±0.25° is met for the whole frame where the nominal flange-to-web angle was 90°. An even more strict tolerance of ±0.10° is achieved, which is in the range of typical part-to-part scattering observed on L-angle level [14]. The evaluation of the global part shape revealed a slight bending of the overall frame. It has a maximum amplitude of 0.6 mm and its distortion mode is identical to the one observed for simulation run (c). Even though the magnitude is of low relevance for the assembly, further investigation is necessary to elaborate its source. It needs to be verified whether a simultaneous or a sequential consideration of cool-down and spring-in is practicable.




Angle tolerance : 90° ± 0.25°

**Figure 6.** Inner flange-to-web angle measurements verify tolerance conformance

### 3.3. Robustness of the applied compensation strategy

Process robustness is a vital aspect in high-rate manufacturing scenarios. The applied compensation measures for the upper frame have been calculated for the 155°C reference process. Thus, the L-profile has been manufactured accordingly, as its distortion is used for the prediction of the frame PID. One essential question, in context of a tool compensation is, whether the compensation is robust even when process boundaries are changed, such for example the dwell temperature is elevated from 155°C to 180°C. As known from Radford [12] spring-in is composed of a reversible thermal and an irreversible chemical fraction $\Delta\varphi = \varphi_{thermal} + \varphi_{chemical}$. It is assumed here, that dwell temperature elevation mainly affects the thermal fraction of spring-in. Thus, the effect of a dwell temperature change on the final part shape can be estimated using equation 5, as shown by Huang and Yang [15].

$$\Delta\varphi_{thermal} = \tilde{\varphi} \cdot \frac{(\alpha_T - \alpha_R)\Delta T}{1 + \alpha_R \Delta T} \approx 90° \cdot \frac{-60\ ppm/K \cdot (-25K)}{1 + 64\ ppm/K \cdot (-25K)} \approx 0.13° \tag{5}$$

The corresponding parameters, in particular the in-plane CTE $\alpha_T$ and the through-thickness CTE $\alpha_R$ have been measured using thermo-mechanical analysis, while the necessary specimens were cut from the available L-profile. The parameter $\Delta T$ refers to the definition of Radford $\Delta T = T_{RT} - T_{cure}$. Hence, the increase from 155°C to 180°C results in $\Delta T = -25$ K. The corresponding spring-in angle is calculated to 0.13°. This result indicates tha the compensation is rather robust for the frame at hand, since even a remarkable process change leads to moderate spring-in changes below the tolerance threshold.

## 4. Conclusion

A ready-for-high-rate RTM process has been established for composite Z-frames. It pursues the ambitious cost-saving goals of the MAAXIMUS project since net-shape preforming and manufacturing as well as prediction-based tool compensation are featured. Geometric inspections of the manufactured frames prove that the prescribed angle tolerance of ±0.25° is met for all frames. The conformance to an even more strict tolerance of ±0.10° could be demonstrated, which underlines the suitability of the

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p-approach, which has been applied to predict the frames' process-induced distortion. The numerical simulations also reveal a superposition of spring-in and thermo-elastic distortions during the cool down. Both effects counteract each other. A coupling between spring-in and a global frame warping is observed, which can likely be traced back to the fact that the frame geometry does not represent a developable surface. Consequently, this observation is relevant for all typical frame profiles used in aerospace applications. Moreover, it could be demonstrated that the often applied isotropic scaling of part dimensions, which is performed in the tool design process to account for elevated curing temperatures, is erroneous for composite structures with locally varying layups. Geometric inspections of the global frame shape reveal slight global warpage of the frames similar to the distortion mode found in a simulation which considers spring-in only. Even though this distortion mode is of minor relevance within the assembly due to its low magnitude, additional investigation is necessary to identify its source reliably. The assessment of the robustness of the compensation measure reveals that even a remarkable process change, in form of a dwell temperature increase from 155°C to 180°C, results in an estimated spring-in increase of 0.13° only, which is still below the tolerance threshold.

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## References

[1] HEXCEL. Hexforce and hexply aerospace selector guide, 02 2002.

[2] HEXCEL. Hexforce 00120 1200 z6040 e01 1f e glass fabric, June 2015.

[3] A. Hindersmann, W. Exner, N. Liebers, M. Opitz, T. Torstrick, and H. Ucan. Forschungsplattform fr endkonturnahe faserverbundbauteile im automatisierten fertigungsprozess. *Deutscher Luft- und Raumfahrtkongress*, 2012.

[4] G. Fernlund, A. Poursartip, A. Arafath, and C. Lynam. How to get the part dimensions right in composites processing. *Composites World*, 2015.

[5] C. Albert and G. Fernlund. Spring-in and warpage of angled composite laminates. *Composites Science and Technology*, 51:pp.1895, 2001.

[6] E. Kappel. Forced-interaction and spring-in - relevant initiators of process-induced distortions in composite manufacturing. *Composite Structures*, 140:217–229, 2016.

[7] E.Kappel, D. Stefaniak, and G. Fernlund. Predicting process-induced distortions in composite manufacturing a pheno-numerical simulation strategy. *Composite Structures*, 120:98–106, 2015.

[8] E. Kappel, D. Stefaniak, D. Holzhüter, C. Hühne, and M. Sinapius. Manufacturing distortions of a cfrp box-structure - a semi-numerical prediction approach. *Composites: Part A*, 51:89–98, 2013.

[9] E. Kappel. *Process Distortions in Composite Manufacturing*. PhD thesis, Otto-von-Guericke University, Magdeburg, Germany, 2013.

[10] E. Kappel, N. Liebers, M. Buggisch, P. Hilmer, M. Kleineberg, and C. Hühne. Holistic quality approach for autoclave-injection composite manufacturing. *JEC Composites Magazine*, 96, 2015.

[11] P.C. Chou, J. Carleone, and C.M. Hsu. Elastic constants of layered media. *Journal of Composite Materials*, 6:80–93, 1972.

[12] D.W. Radford. *Shape Stability in Composites*. PhD thesis, Rensselaer Polytechnic Institute, 1987.

[13] E. Kappel, D. Stefaniak, and G. Fernlund. Predicting process-induced distortions in composite manufacturing: A pheno-numerical simulation strategy. *Composite Structures*, 120:98–106, 2015.

[14] E. Kappel, D. Stefaniak, and C. Hühne. Process distortions in prepreg manufacturing an experimental study on cfrp l-profiles. *Composites Structures*, 106:615–625, 2013.

[15] C.K. Huang and S.Y. Yang. Warping in advanced composite tools with varying angles and radii. *Composites Part A*, 28A:891–893, 1997.

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