COMPENSATION OF PROCESS-INDUCED DISTORTIONS IN COMPOSITE WING SPAR

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Abstract. In this work, an attempt to decrease the process-induced distortions in composite C-sectioned spar was made. The distortions, arising during cure process due to elevated temperature, are problem even in case of low-temperature OoA prepregs. In order to predict distortions in cured part and redesign tool, so that the cured part has intended shape, a numerical analysis was carried out. Then experimental verification, by manufacturing C-sectioned component of carbon-epoxy OoA prepreg on aluminium tool and measuring it with use of CMM, was performed. The results of it were compared to results obtained from numerical calculations. The comparison showed, that numerical model was too simple to predict correctly amount of distortion. But, since it was able to predict nature of the effect, it seems, that development of the method will enable compensation of composite parts distortion.

Keywords: OoA prepreg, thermal expansion, process-induced distortion

1 Introduction

Carbon-epoxy composites are used in an increasing range in aerospace technology as a structural material, due to their high specific strength and design flexibility. But, because autoclave must be used in curing process of majority of these composites, they are not easily available for small companies. The solution may be use of prepregs for out of autoclave curing, that do not require buying any expensive installations. However, OoA technology also is a source of some problems that retard its development. One of them are manufacturing distortions and residual stresses in cured parts. Solving these problems will tend to speed up development of small aerospace companies.

Curing process of carbon-epoxy prepregs proceeds in elevated temperature. It may bring about process-induced distortions of the part and rise of residual stresses in cured parts. The main reason of such unfavourable effects are orthotropic properties of composite materials and tool-part interaction [4]. Difference between intended geometry and cured part shape may be source of problems, such as inability to maintain required tolerance, that may cause stresses in assembled structure or even costly rejection of a part.

It is advisable to perform tool correction to adjust cured part shape to intended geometry before curing, in order to avoid additional repeated production costs. Some authors, that set themselves a goal to understand and model cure distortion process have been publishing in recent years, but there are very few scientific papers, that tend towards compensation of manufacturing distortions. The present work is a trial to work out such a method that will enable effective compensation of process-induced distortions in parts made of OoA carbon-epoxy prepreg, by optimal design of tool. Scheme of the method is shown below *(fig.1)*.

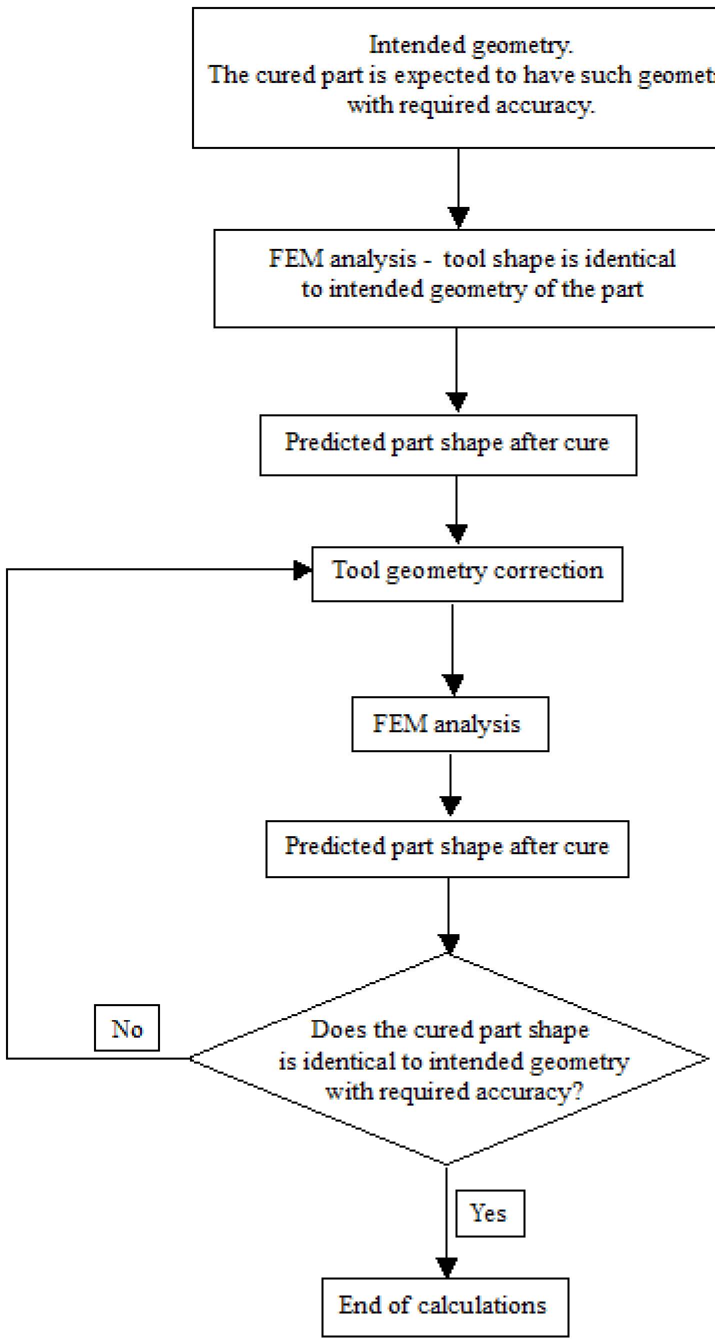

Fig.1 Scheme of the tool correction method

Start point of the calculation process is an intended geometry, that cured part is supposed to have. It is impossible to achieve part shape identical in mathematical sense to the required geometry, as a result of engineering calculations, so an accuracy of shape, that must be accomplished is assumed in the beginning. In first step of the process, shape of the tool is identical with the intended geometry of the cured part. Then FEM analysis is carried out. As a result of the analysis, predicted cured part shape is calculated. On the ground of it, there is correction of the tool shape performed. A FEM analysis is carried out again and the resulting part shape is compared to intended part geometry. If the difference between geometries is within required accuracy, the calculation process ends and corrected tool geometry is a result of it. If not, calculations are repeated until the accuracy is accomplished.

2 Process-induced distortions

The most significant source of process-induced distortion of C-shaped composite spar is an effect known in literature as a spring-in [1]. It occurs only in curved composite parts and result of it is a decrease of angle between areas attached to the curved part *(fig.2)*.

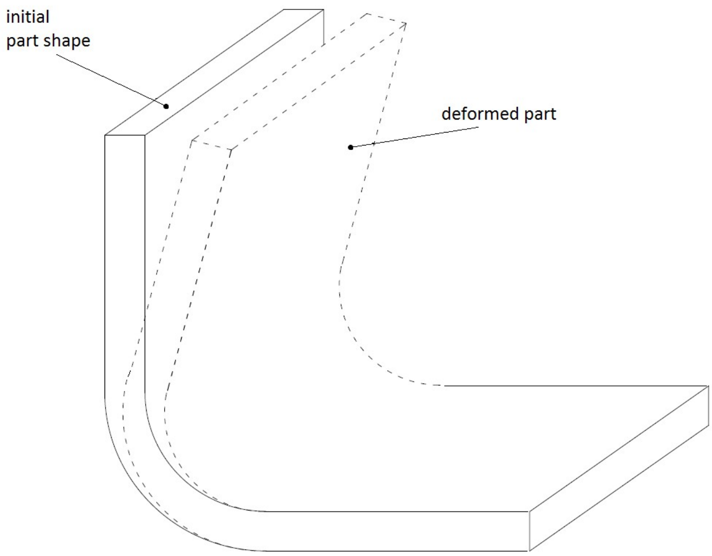

Fig.2 Spring-in effect in composite angular

Among the most significant reasons, why spring-in occurs, are counted different in-plane and through-thickness coefficients of thermal expansions (CTE), chemical shrinkage of the resin and tool-part interaction.

2.1 Orthotropic coefficients of thermal expansion

The most significant reason, why spring-in occurs during cooling after cure cycle, is orthotropic nature of composite materials. In case of curved part made of isotropic material the effect does not occur, because the part shrinks uniformly in all directions. Owing to this, angle between areas attached to curved part, is preserved [2]. If the part is made of fibre reinforced carbon-epoxy composite, CTE in fibre direction (longitudinal) is lower than through-thickness (transverse) CTE - dominated by resin. CTE of the resin in virtue of literature [2,3,7] can be assumed to be on 30 – 45 $\mu\varepsilon/^{o}C$ level. CTE of carbon fibres is known to be very small, in comparison with this of resin, or even slightly negative [1,2,3,7]. In stage of cooling, after curing in elevated temperature, composite material contracts more in through-thickness than in fibre direction. In curved part it causes increasing of inner radius and decreasing of outer. As a result fibres laying closer to the inner radius are extended and those closer to outer radius – compressed. These stresses cause bending moment that decreases angle between areas attached to curved part *(fig.3)*.

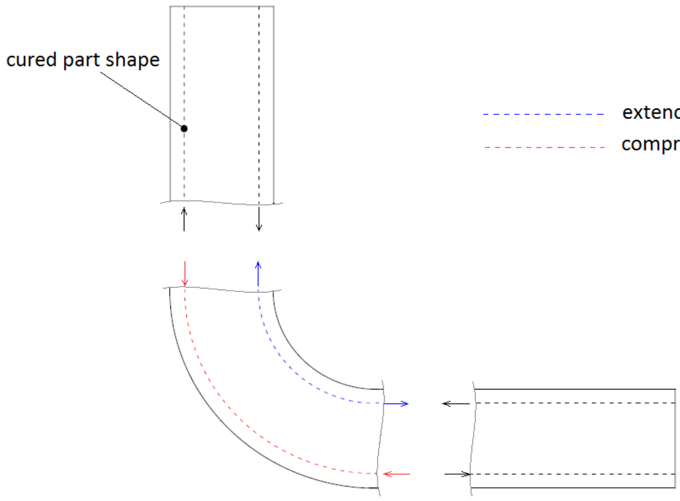

Fig.3 Spring-in mechanism

Ratio of change in angle magnitude before and after cooling to initial angle is given by equation [4]:

$$\frac{\Delta\theta}{\theta} = \frac{(\alpha_l - \alpha_t)\,\Delta T}{1 + \alpha_t\,\Delta T} \qquad (1),$$

where:

$\Delta\theta$ – change in angle magnitude [°],

θ – initial angle [°],

α_l – in-plane CTE [με/°C],

α_t – through-thickness CTE [με/°C],

ΔT – temperature change [°C].

Since this mechanism is caused by thermal contraction of the material, it may be count among thermoelastic phenomena. It means that with growth of the material temperature, change in angle of cured part decreases to disappear in cure temperature. If the spring-in effect disappears in temperature higher than cure temperature, it is unquestionable, that to the distortion, apart from orthotropic CTE, contributed also non-thermoelastic effects.

2.2 Chemical shrinkage

Similar influence on orthotropic properties of carbon-epoxy composite as CTE of fibres and resin has chemical shrinkage of resin. It occurs in thermosetting resins during polymerization and can have significant value of 7% of volume, typical for epoxy resins [1]. In the same way as in case of CTE, shrinkage causes contraction mainly in through thickness direction, increasing spring-in effect. In order to take chemical shrinkage into account, to *eq. (1)* additional component was added [4]:

$$\frac{\Delta\theta}{\theta} = \frac{(\alpha_l - \alpha_t)\,\Delta T}{1 + \alpha_t\,\Delta T} + \frac{(\varphi_l - \varphi_t)}{(1 + \varphi_t)} \quad (2),$$

where:

ϕ_l - in-plane chemical shrinkage [-],

ϕ_t - through-thickness chemical shrinkage [-].

Majority of the shrinkage occurs before vitrification of resin, when material is in rubbery state [6,8] and has low stiffness. That makes plies able to move in relation to each other, not causing change in shape of part. Thanks to this fact, chemical shrinkage of the resin does not contribute significantly to spring-in and can be neglected in analysis. However, some scientific papers on process-induced distortions take chemical shrinkage into consideration [3,7].

2.3 Tool-part interaction

There is also influence on spring-in of tool-part interaction during autoclave processing considered in scientific literature [2,3,7]. The source of this effect is difference between CTE of composite and tool material. During heating tool, usually made of aluminium or steel, expands much more than composite part, that has CTE in fibres direction close to zero. Due to friction, caused by pressure, between part and tool, in early stage of cure occur stresses with through-thickness gradient in part material. After the part is released, the stresses cause bending. This mechanism occurs both in flat and curved parts. In the latter it influences spring-in angle of part: increases it in case of curing on convex tool and decreases in case of concave tool. However, in experiments with use of OoA prepregs, tool-part interaction phenomenon was not observed. In the author's opinion it can be explained by low force caused by vacuum in comparison with force possible to obtain in autoclave.

2.4 Other factors

Apart from the mechanisms mentioned above, there are several other factors, that influence spring-in effect in composite parts. Among these factors rank manufacturing defects [5,7] such as through-thickness volume fraction gradient and fibre wrinkling. These defects are particularly intensive in corners and their intensity increases with increasing curvature. Because of this, nevertheless part geometry does not influence directly spring-in magnitude, quality of specimens manufacturing is dependent on radius of curvature and it may cause contrary impression [4]. There was also noticed influence of laminate thickness on spring-in magnitude [2,3]. The thicker laminate is, the smaller spring-in effect occurs. Source of this effect may be temperature gradient that occurs in thick laminates during cure. In thinner specimens reduction of spring-in angle was not observed [9].

3 Resin properties evolution during cure

During cure process of carbon-epoxy prepreg, epoxy resin changes its properties. In the first phase it is usually described as a viscous fluid, that can distort freely without causing any stresses. In this phase layer consolidation and degasification take place. As the curing proceeds, gelation process occurs, that causes change of resin state from viscous fluid to rubbery state. In rubbery state resin can be treated as a solid with defined mechanical properties. The properties however, are much lower than those of fully cured composite. Viscoelastic model is usually used to describe them – stresses in material are relaxed after a certain time. Because of above, it can be assumed, that stresses induced in material in viscoelastic phase are not significant in further analysis, because:

1. are low, due to low material stiffness,
2. after certain time, shorter than viscoelastic phase in cure process, are relaxed.

During the cure cycle glass transition temperature T_g also changes. When the resin is in fluid and rubbery state, T_g is much lower than cure temperature. However, in certain point of cure process it suddenly starts to grow and becomes higher than actual material temperature *(fig.4)*. At the time, when it happens, rapid change of resin state from viscoelastic into elastic takes place. Stiffness grows significantly and relaxation time becomes so long, that residual stresses arising in material are not able to relax in curing cycle and cause part distortions. In contrary to resin, carbon fibre does not change its properties in time of curing.

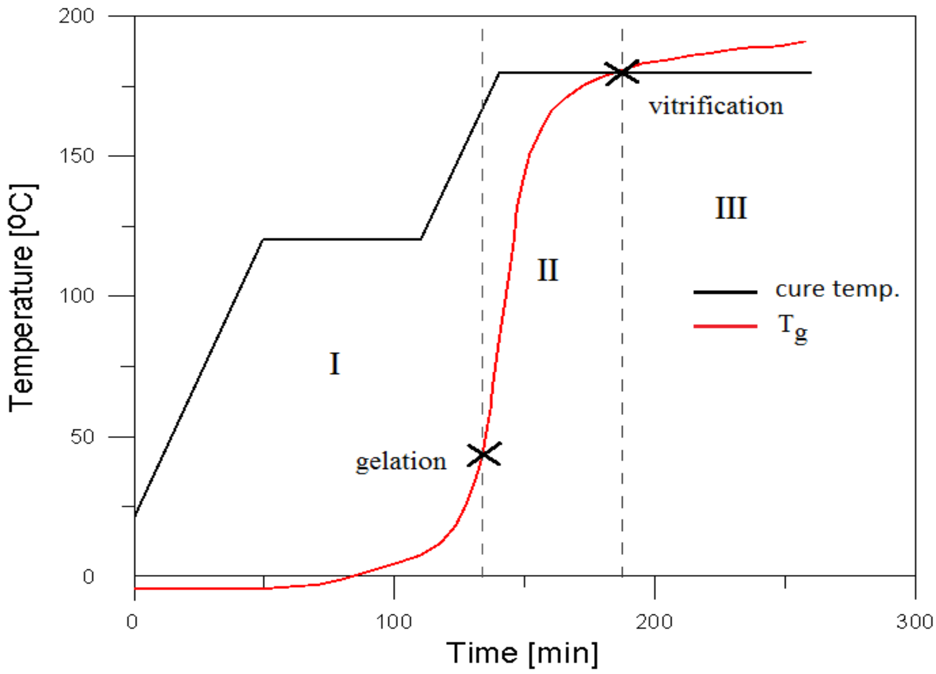

Fig.4 Exemplary cure cycle plot. I – viscous phase, II – viscoelastic phase, III – elastic phase

Due to complicated changes, to which resin is subjected during cure cycle, some simplifications have to be done in composite part cure modelling. One of the simplifications, that was employed in present work, is division of resin state into three phases during cure *(fig.4)* and assumption, that transitions between these phases are instantaneous. Within the phases material properties are assumed to be constant. None of these assumptions is fully true, but they were proved to be right by experimentally verified results of calculation models based on them [2,6]. Another assumption made, as a result of previous considerations, is that significant stresses arise in material only after vitrification, when resin is in elastic state [7].

4 Material properties

In order to verify numerical calculations, a C-sectioned specimen was manufactured of unidirectional carbon-epoxy prepreg Umeco MTM-46. The prepreg is assigned for low temperature OoA curing. Below its mechanical properties are shown *(Tab.1).*

Longitudinal Young modulus	E_1 = 128290 [MPa]
Transverse Young modulus	E_2 = 8760 [MPa]
In-plane Poisson ratio	ν_{12} = 0,288 [-]
In-plane shear modulus	G_{12} = 4720 [MPa]
Longitudinal CTE	α_1 = 0,8 [με/°C]
Transverse CTE	α_2 = 40 [με/°C]

Tab. 1 Material properties of Umeco MTM-46

Due to the fact, that longitudinal and transverse CTE were not given in material datasheet, their values for calculations were assumed on ground of literature [1,2,3,7]. The rest of material properties was adopted from the material datasheet. To calculate spring-in angle from *eq. (1)*, CTE for laminate are needed. They can be calculated from *eq. (3)*, derived from Classical Lamination Theory [12,13].

$$\{\alpha_L\} = -\frac{1}{\Delta T}\,[A]^{-1}\,\{N^T\} \quad (3),$$

where:

$\{ \alpha_L \}$ – laminate CTE vector,

[A] – laminate extensional stiffness matrix,

$\{N^T\}$ – thermal stress resultant vector,

ΔT – change of temperature.

5 Finite element model

Aluminium tool geometry, on which specimen for experimental verification was cured, is shown below *(fig.5)*. The specimen lay-up consists of 12 plies of MTM-46 prepreg with fibers in 0^o (x axis direction in *fig.5*) and 90^o (y axis direction in *fig.5*).

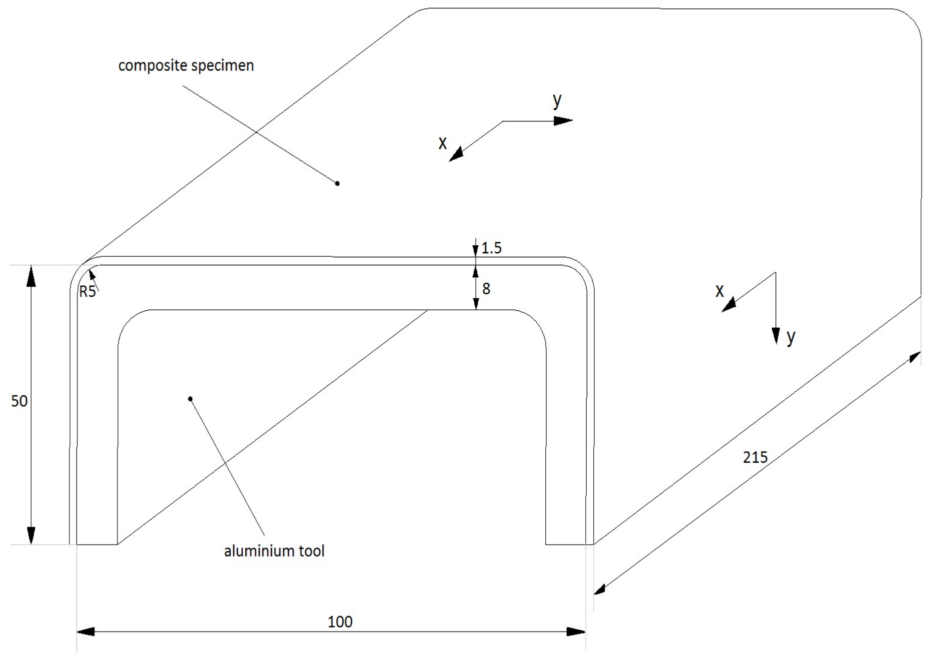

Fig.5 Tool and specimen dimensions in ambient temperature

The spring-in effect was modelled using ANSYS software. There were used solid 45 elements in tool modelling and solid-shell 190 elements, dedicated particularly for composite materials, in specimen modelling. There were placed contact 174 elements, between tool and composite part elements, in order to model interaction between them.

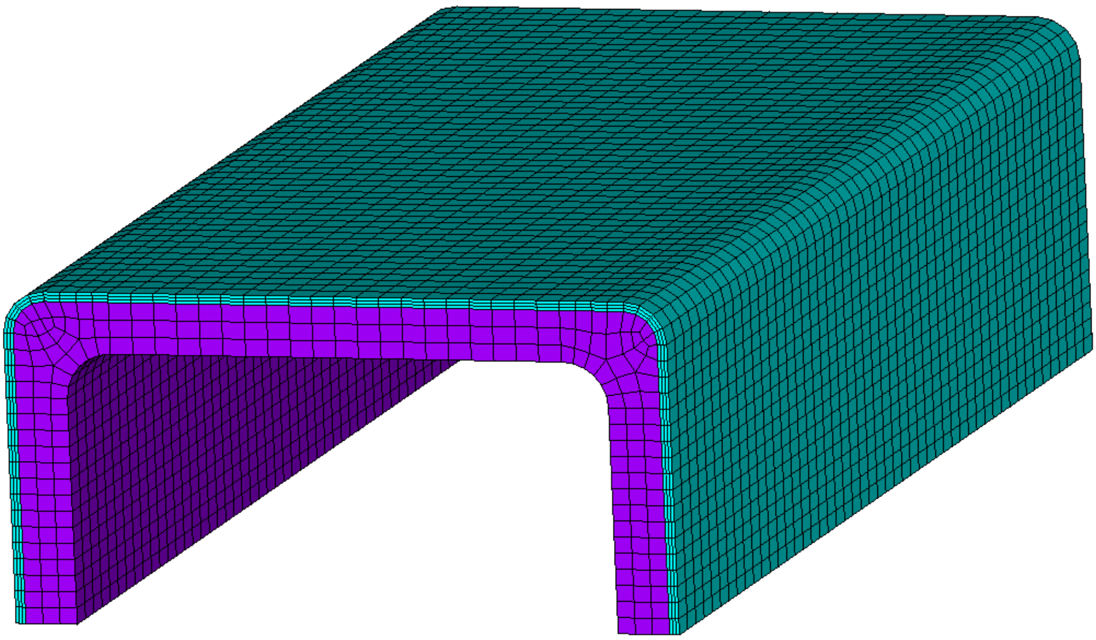

Fig.6 Finite element model

Although, during cure process resin properties change and the cured part is not elastic before reaching glass transition temperature, there were some simplifications, that let use of elastic material properties only *(tab.1)*, assumed. In consideration of the fact, that significant stresses occur only during cooling down of the part from cure to ambient temperature (see section 3), in FE model only this phase of cure cycle was taken into account. It can be assumed, that part material is elastic within it, because its temperature is lower than T_g. Cure cycle of MTM-46 resin consists of curing phase in 80^{o}C and post-cure in 120^{o}C. After the cure phase, composite material is in state, which prevents permanent change of shape. A conclusion can be drawn from previous considerations, that occurring of process-induced distortions takes place mainly in cooling from 80^{o}C to ambient temperature, and so, such thermal load was applied to numerical model.

6 Results. Plies orientation influence on spring-in

Spring-in values for different lay-ups are presented below *(tab.2)*. Only 0º and 90º fibre direction were taken into consideration in order to avoid shear-extension and bend-twist couplings. In the first table column various lay-ups are shown, in next two – laminate CTE calculated from *eq. (3)*, in fourth and fifth spring-in value calculated from *eq. (1)* and FEM analysis.

Lay-up	$\alpha_{L\,X}$ [με/ºC]	$\alpha_{L\,Y}$ [με/ºC]	"Spring-in" [º] - equation (1)	"Spring-in" [º] - FEM calculations
[90º$_{12}$]T	40.000	0.800	-0.211	-0.214
[0º/90º$_5$]S	11.260	1.845	-0.206	-0.258
[0º/90º$_4$/0º]S	6.090	2.689	-0.201	-0.261
[(90º/0º)$_3$]S	3.913	3.913	-0.194	-0.256
[90º/0º$_4$/90º]S	2.689	6.090	-0.183	-0.242
[90º/0º$_5$]S	1.845	11.260	-0.155	-0.206
[0º$_{12}$]T	0.800	40.000	0.000	0.000

*T*ab. 2 Spring-in values for various lay-ups

As it was expected, spring-in values varies for different lay-ups as a result of differences in CTE for each laminate. There also exist difference between spring-in calculated from *eq. (1)* and from FEM analysis. The difference has value of about tens of percents. In the former way of spring-in determination, the value of it equals to zero for unidirectional lay-up consisting of 0º plies and increases with growth of 90º plies number. In the latter – the highest value occurs in case of [0º/90º$_4$/0º]S lay-up. For unidirectional lay-up of 0º plies, like in *eq. (1)* results, the effect does not occur, because in-plane and through-thickness CTE are identical. The difference between both methods results arises from factors other than different in-plane and through-thickness CTE, that are not taken into consideration in *eq. (1)*. In numerical model, quasi-isotropic lay-ups cause occurring of larger spring-in effect, than 90º unidirectional lay-up, which should result in the highest effect according to *eq. (1)*. It is in agreement with results obtained by the other authors [3,11]. The physical reason of such laminate behavior is fact, that contraction in through-thickness direction is higher for quasi-isotropic lay-ups than for unidirectional, due to the Poisson ratio effects [10]. FEM analysis proved also, that ply sequence in lay-up does not influence the result, as long as laminate is symmetric and balanced.

In virtue of previous considerations, it can be assumed, that regarding simplicity of *eq. (1)*, it can be used only for preliminary calculations of spring-in effect. However, in calculations, in which precise quantitative results are needed, such as tool correction method, FEM analysis is a better solution.

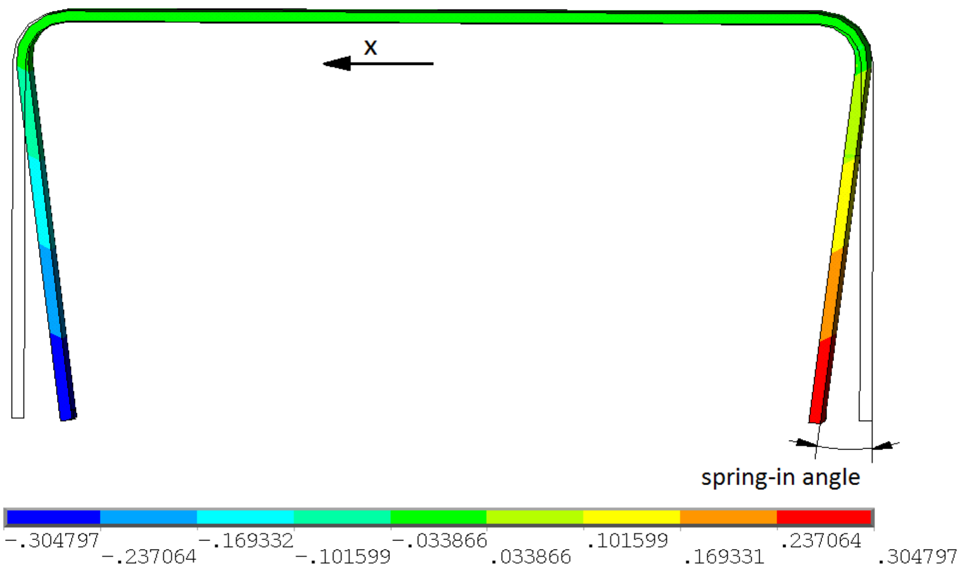

Fig.7 Displacement of cured part with [0°/90°$_4$/0°]S lay-up in x direction, calculated in ANSYS [mm]

7 Experimental verification

In order to verify FEM results, on aluminium tool, with the same dimensions as in numerical model, a C-sectioned specimen with [0°/90°$_4$/0°]S lay-up was cured *(fig.8)*. The cure cycle had two phases: first dwell in 80°C temperature and post-cure in 120°C. The cure was performed in vacuum bag.

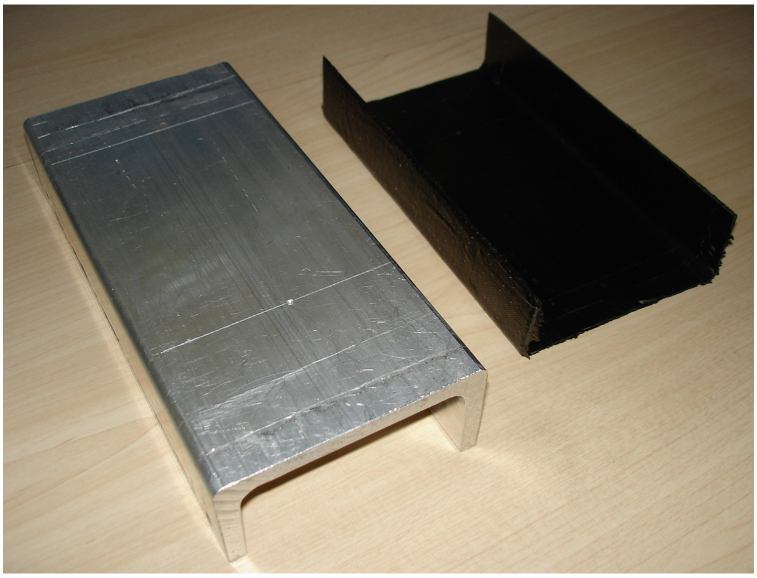

Fig.8 Tool and cured part

Outer surface of the tool and inner of the part was measured with use of Coordinate Measuring Machine in two arbitrarily selected sections in both ends of the tool and specimen. Relative positions of adequate points on tool and part surface are shown below *(fig.9&10)*.

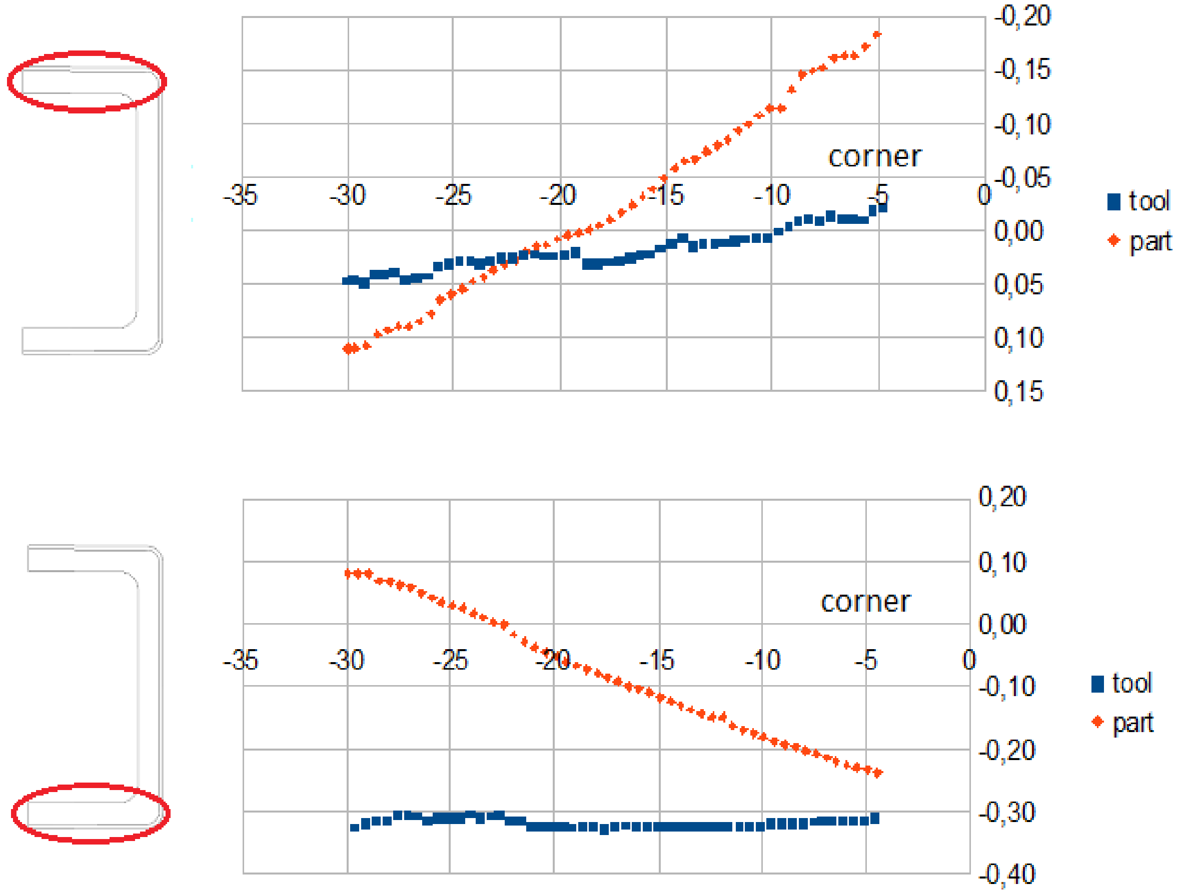

Fig.9 Positions of adequate points on surface of tool and part in section 1 [mm]

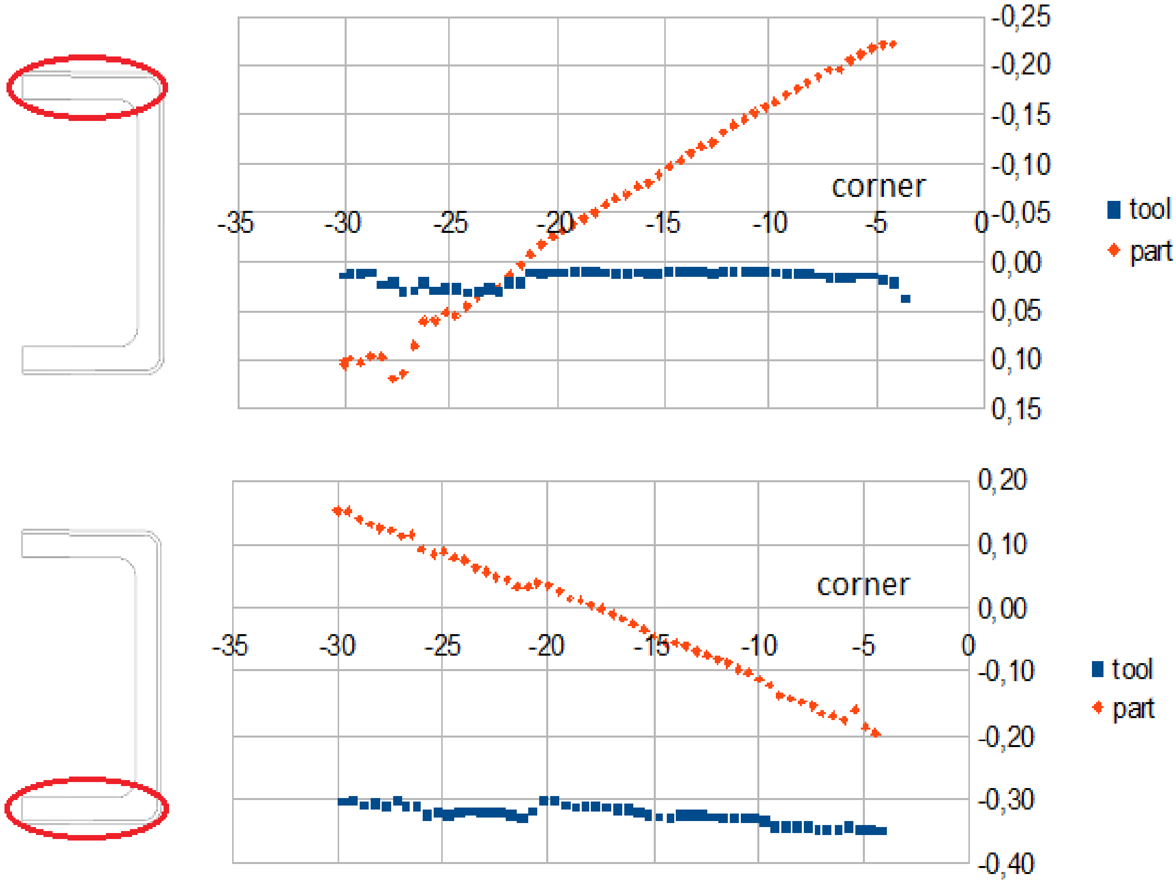

Fig.10 Positions of adequate points on surface of tool and part in section 2 [mm]

It was observed, in virtue of the numerical results, that the highest distortions are on horizontal parts of C-sectioned specimen, so only these parts were measured. The resulting from FEM analysis value of spring-in for considered lay-up was 0,261°. The results of experiment are in one side 0,504° and in other 0,710° of spring-in angle in section 1, 0,733° and 0,802° respectively in section 2.

Measured differences between the tool and part width are 0,14 mm in first section and 0,09 mm in second. The reason of the different width values of tool outer shape and part inner shape are different CTE of aluminium and laminate. Composite properties change into elastic on extended tool. Then after cooling, aluminium tool contracts more than cured part and so, the part is wider. This consideration appears to be in agreement with experiment. The value of difference calculated from CTE (23 με/°C of tool material and 2,689 με/°C of laminate in y axis direction - see *tab.2*) for 60°C temperature difference equals to 0,12 mm.

Numerical results appeared to be inconsistent with experiment. However, although values of experimentally measured spring-in are two or three times higher than the calculated one, the numerical approach seems to give qualitatively correct results. There are several possible reasons, why the numerical results are not in agreement with experiment:

1. The material model may be too simple. Taking into account change of resin state from viscoelastic to elastic may be needed to cover all factors, that contribute significantly to spring-in effect, such as viscoelastic properties in rubbery state,

2. Cured part may achieve elastic properties in temperature higher than assumed 80°C,

3. Some factors, that may contribute significantly to spring-in effect, such as chemical shrinkage, and tool-part interaction, were not taken into account,

4. CTE of fibers and resin taken from literature may have inaccurate values.

However, only too simple material model and chemical shrinkage seem to be reasonable causes. There was no bend in flat parts, characteristic for tool-part interaction, observed and the CTE for tool and part materials, as well as temperature, in which material achieves elasticity, seem to be assumed correctly in virtue on agreement between calculated and experimental difference in tool and cured part widths.

8 Tool correction

Since the results of spring-in value, obtained from numerical analysis, are qualitatively incorrect, it is not possible to carry out effective correction of the tool shape. The FEM analysis however, seems to be a promising method. It needs to be developed in order to fit real results in both qualitative and quantitative way.

Correction of the tool, in case of C-sectioned spar, will consist of two parts: width correction and change of angle between spar walls. In virtue of numerical results, verified by experiment, it is possible to make correction of tool width by decreasing it by 0,12 mm. The angle correction will be carried out after obtaining reliable results, by changing the angle between walls by spring-in angle *(fig.11)*.

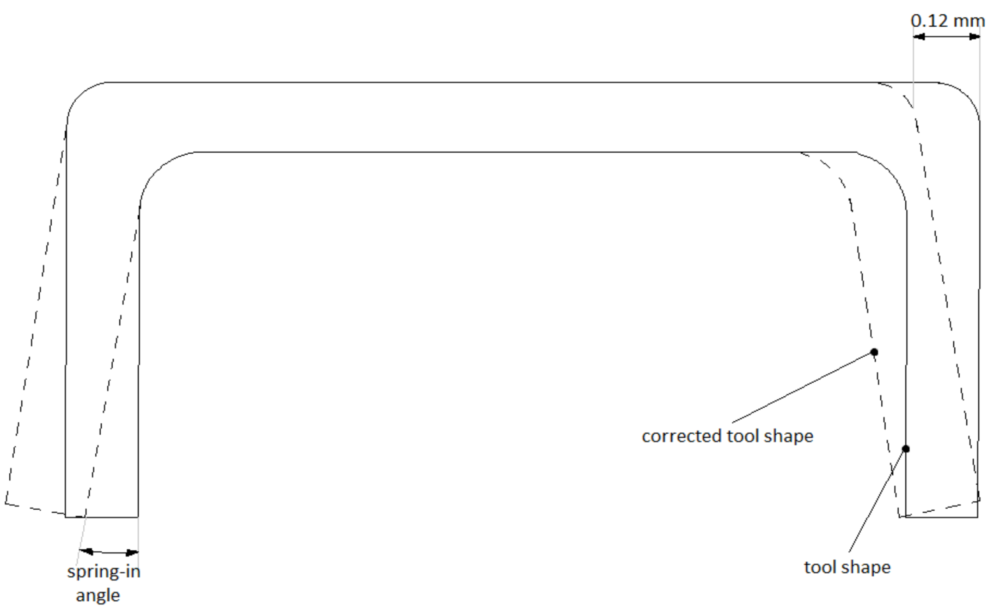

Fig.11 Tool correction method

The method shown above appears to be effective for correction of C-sectioned spar tool. It will be developed in further works.

9 Conclusions

1. Use of OoA prepregs technology can speed up development of aerospace engineering. However, the problem of manufacturing distortions needs to be solved to enable efficient use of it.

2. Magnitude of process-induced distortions may cause problems in assembling parts together even in case of low-temperature prepregs.

3. FEM analysis seems to be an efficient way of predicting manufacturing distortions and correcting tool geometry, but numerical model used in present work is too simple to obtain quantitatively correct results and so, needs development.

Acknowledgment

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