MONITORING THE RESIDUAL STRAIN FORMATION IN CFRP/PMI FOAM CORE SANDWICH STRUCTURES

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Abstract

Using CFRP/PMI foam core sandwich structures for primary structures in commercial aviation a lot of advantages could provide. With the cost effective manufacturing process of vacuum infusion several integral structures with high light weight potential can be built. A disadvantage is the residual strain that is mainly caused by the different coefficients of thermal expansion and stiffness's of the sandwich components. It already occurs at the manufacturing process during cool down from curing to room temperature. In this study the formation of these residual strains was observed experimentally during the manufacturing process. Outgoing from these results concepts of reduced residual strains of the cured sandwich structure were derived and tested. To determine the foam core strains left after manufacturing a curvature measurement of the halved sandwich specimen was done to validate the measured in-situ strain data.

1. Introduction

The sandwich structure consists out of a Polymethacrylimide (PMI) closed cell foam core from ROHACELL®, two symmetric face sheets of Non Crimp Fabrics (NCF) and a matrix of epoxy resin HexFlow®RTM6. The manufacturing process of the sandwich structure is a vacuum assisted resin infusion process (VARI) which is represented in the category of the liquid composite molding techniques. The triaxial lay-up of non crimped fabrics carbon fiber and the core of PMI foam are stacked dry to a symmetrical sandwich and sealed by a vacuum bag. Fig. 1 is shown the lay-up of the sandwich structure for the VARI manufacturing process schematically. After evacuating the resin RTM6 and the sandwich lay-up the infusion process starts at 120 °C. The following curing is carried out at 180 °C. The Coefficient of Thermal Expansion (CTE) of the PMI foam core is specified as isotropic and in a range of 3.3 to 3.5 10^{-5} 1/K by the manufacturer [1]. The CTE of the laminate face sheets can be assumed to be zero in lengthwise direction. Not only the different thermal dimensional variations are important factors of residual strain formation. There is a volumetric shrinkage of the resin, which induces inner stresses in the layers and the face/core interface area, too [2].

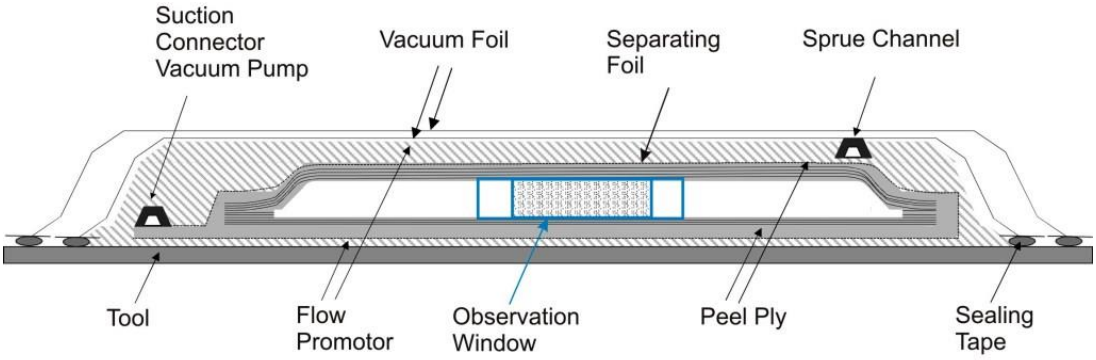

Figure 1. Vacuum assisted resin infusion: sandwich lay-up for infusion process with observation window for strain measurement

2. Experiments

2.1. Dielectric Analysis (DEA)

The DEA detects changes in ionic and dipolar mobilities of a given material while exposed to an alternating electric field [3]. The conductivity and capacitance are measured as a function of time, temperature and frequency. Interdigitated Electrode Sensors (IDEX) with comb structure and a filter cloth have been used to avoid a circuit because of the electrical conductivity of CFRP and to ensure that the matrix flow disruption through the build-up is minimal with having a sensor penetration depth of 115 µm. The frequency used providing the best response was about 10 Hz. There is a linear correlation between the slope of the degree of polymerization α and the slope of the logarithmic ion conductivity η during isothermal regime so that this data can be used to analyze the progress in cure [3].
A DEA of the matrix system HexFlow®RTM6 was carried out to determine the moment when the bonding between foam and matrix material of the face sheets is achieved. As is known the gelation describes the change of the polymer from liquid to solid state during thermoset cure. Two DEA sensors were placed at the interface between the foam core and the CFRP-layers, one at each side to continuously monitor the progression of cure in terms of change in logarithmic ion conductivity and permittivity. The temperature gradient was also measured using OMEGA PT100 fine wire thermoelements distributed all over the sandwich cross section.

2.2. Monitoring the Residual Strain Formation

In order to get a closer look at the foam core to matrix interaction during sandwich manufacturing, a float glass panel was integrated sideways the VARI setup for in-situ observation of the foam by the optical 3D full field measurement system ARAMIS, see Fig. 2. An advantage of the usage of float glass plates is the relative low CTE and their good thermal and mechanical stability which make them suitable for that application where a bending free surface is needed to avoid a lens effect. The prepared sandwich build-up was positioned in the oven by that way to be able to observe the process in-situ with the high resolution 3D optical strain measurement system ARAMIS through a two layered glass window in the oven door. The lengthwise and the thickness direction were analyzed to get a deeper understanding of the foam interaction during curing process in terms of determining the foam strain when gelation of the resin takes place. Fig. 3 is shown the strain in lengthwise direction.

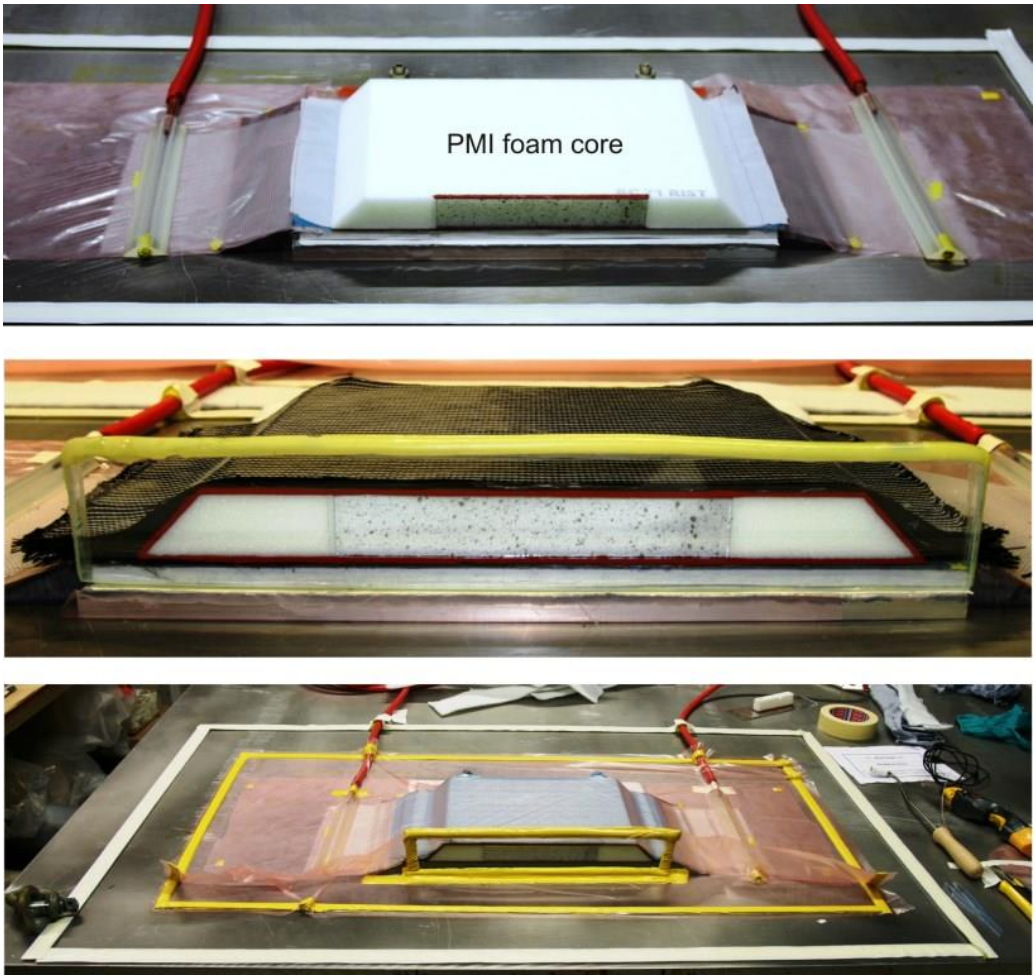

Figure 2. Experimental infusion lay up with observation window to the foam

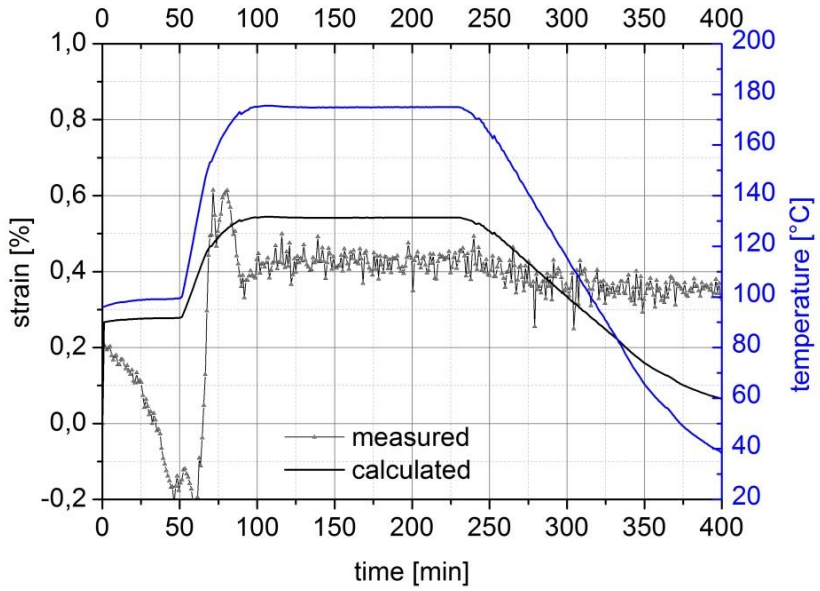

Figure 3. In-situ strain measurement of the foam core in lenghtwise-direction

The results from the temperature measurement over the cross section of the sandwich specimen are shown in Fig. 4. For the standard VARI manufacturing local heat- and cooling-rates are following with 4.8 K/min at the upper site of the sandwich structure and 3 K/min in the inner foam core and 2 K/min at the outer side.

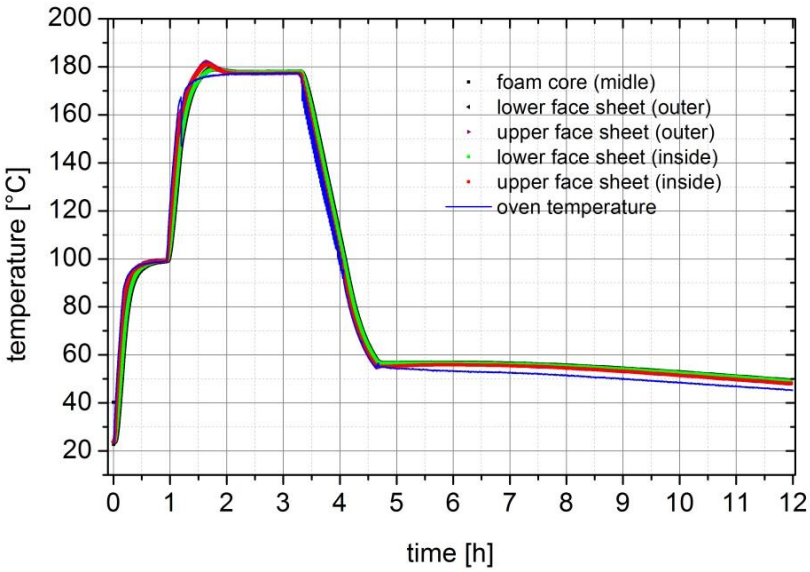

Figure 4. Temperature measurement over sandwich cross section at standard VARI

2.3. Curvature Measurement

To determine the foam core stresses left after manufacturing a curvature measurement of the halved sandwich specimen was done. The different pretreated sandwich structures were cut in the middle of the foam core lengthwise. The fixed strains results in a curvature of the halved sandwich specimen. The curvature of the sandwich was measured optically via a gray scale pattern on the specimen surface. They were heated up to 180 °C again and cooled down to room temperature to determine the stress free state comparing it to the results from the in-situ strain measurement during the manufacturing process. The calculation of the residual strains can be done by a relation of Timoshenko [4, 5]. σ_{max} is calculated like it is shown in Eq. (1) using the curvature k, the elastic modulus of the components and the specimen dimensions h and d, thereby the specimen width is normalized by 1. Figure 5 is shown the principle of experimental procedure.

$$\sigma_{max} = k\left(\frac{2}{h\,d_F}(E_{CFRP}I_{CFRP} + E_F\,I_F) + \frac{d_F\,E_F}{2}\right) \tag{1}$$

$$k = \frac{(\alpha_F - \alpha_{CFRP})(T_0 - T)}{\frac{h}{2} + \frac{2(E_{CFRP}\,I_{CFRP} + E_F\,I_F)}{h}\left(\frac{1}{E_{CFRP}\,d_{CFRP}} + \frac{1}{E_F\,d_F}\right)} \tag{2}$$

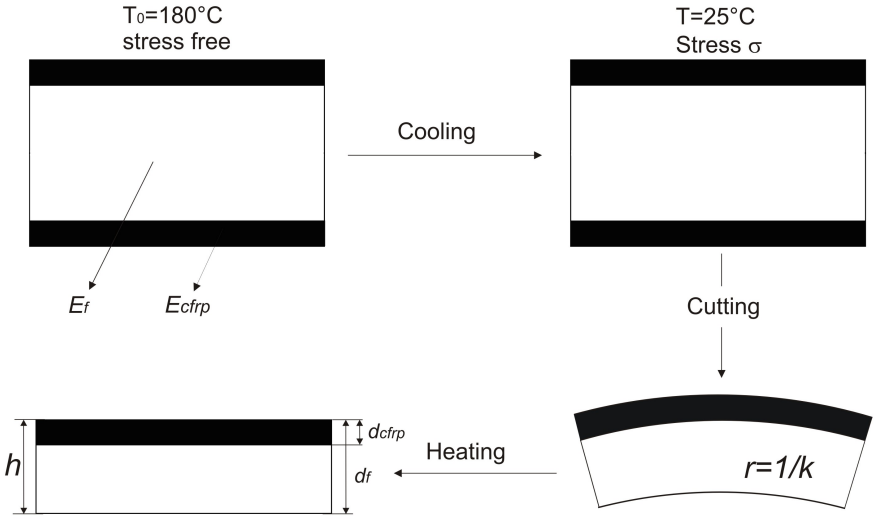

Figure 5. Curvature due to residual strains - experimental procedure

3. Results and Conclusion

For a lower stress free temperature a modified curing regime at 130 °C with a post-curing ramp at 180 °C was used. It can bee seen in Fig. 6 that there is a lower stress free state of these sandwich specimen compared to the conventional VARI. When the halved sandwich specimens were heated up to 180 °C for the first time the stored water diffuses out. The moment when the curvature reaches the zero baseline again, determines the point where the strains are frozen

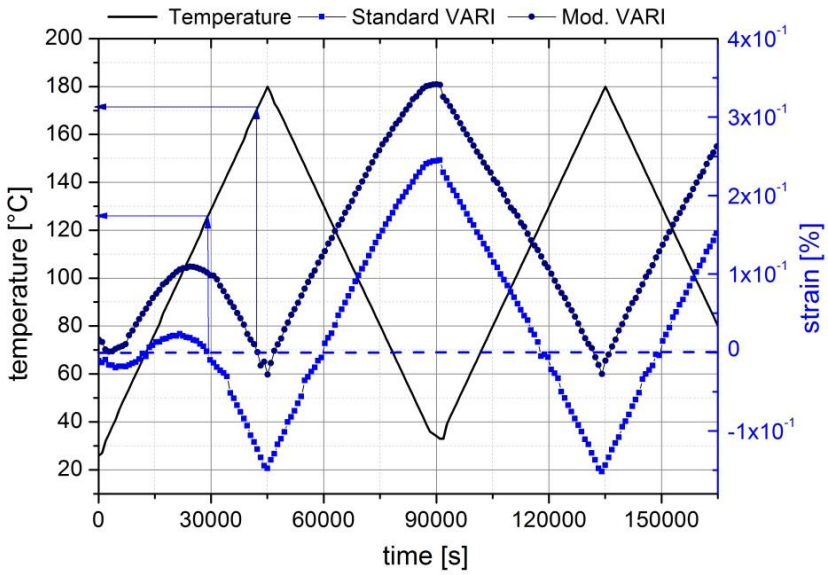

Figure 6. Strain results from curvature measurement of the halved sandwich specimen in the range from 180 °C to 23 °C

during manufacturing process. By comparing those two points it can be demonstrated that the modified process leads to lower strain fixation during the curing stage. The curvature left at room temperature is also lower than that of the standard manufacturing process. The residual strain formation in the foam core of a CFRP sandwich structure can be measured simultaneously during manufacturing process. For a standard VARI process the residual strains in lengthwise direction were determined to 0.4 %. This is a more qualitative method to determine and evaluate the effectiveness of new concepts of reduced inner stresses - for example modified curing ramps or thermal conditioning concepts. In addition with a curvature measurement of halved sandwich specimen the residual strains can be determined more quantitatively. For the standard VARI there was determined a residual strain of 0.35 % left in the foam core at room temperature. A reason for the lower determined strain compared to the in-situ measurement is the relaxation potential of the PMI foam core. When the curvature measurement was done there was a view time left after the manufacturing, thats why the foam could reduce inner stresses by relaxation. After the modified VARI process there are left residual strains of 0.25 % in the foam core. The simultaneous measured ion-viscosity with dielectric sensors has shown that the cross-linking of RTM6 is also finished after the modified curing. The stress free state for conventional manufactured sandwich structures was determined at 174 °C. For the modified process it can be found at 122 °C.

References

[1] Evonik. Properties of rohacell®rist. Produktdatenblatt, Evonik Performance Polymers Darmstadt Germany, 2008.

[2] K. Magniez, A. Vijayan, and N. Finn. Apparent volumetric shrinkage study of rtm6 resin during the curing process and its effect on the residual stresses in a composite. *Polym Eng Sci*, 52(2):346–351, 2012.

[3] H. F. Seibert. Applications for pmi foams in aerospace sandwich structures. *Reinforced Plastics*, 50(1):44–48, 2006.

[4] S. Timoshenko. Analysis of bi-metal thermostats. *J. Opt. Soc. Am.*, 11(3):233–233, 1925.

[5] M. Rinker, M. Gutwinski, and R. Schaeuble. Experimental and theoretical investigation of thermal stress in cfrp foam-core sandwich structures. In *13th International Conference on Composite Materials European Society for Composite Materials*, 2008.