Experimental and Theoretical Investigation of Thermal Stress in CFRP Foam-core Sandwich Structures

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ABSTRACT

This paper focuses on the determination of thermal stress in advanced CFRP foam-core sandwich structures. The sandwich was manufactured by open mould vacuum infusion process with polymethacrylimide- (PMI-) foam core and NCF carbon fibres. The thermal residual stress was determined by Timoshenko's theory based on the measured curvature of bisected sandwich specimen. The theory firstly was proved for applicability by means of numerical calculations, because it was original derived from bi-metals. The sandwich specimen were cut into two half specimens at room temperature. The separated halved specimens were heated up to 180°C and cooled down to 30°C for several times with defined temperature ramps and the curvature was imaged with contactless optical measuring system. Based on the measured curvature the residual stress was calculated and compared to theoretical results. It was found out that the specific relaxation behaviour of the foam has an important influence of the residual stress in the investigated sandwich. To verify these results separated foam specimens were heated and cooled with the same proceedings and the thermal expansion behaviour of the foam was measured.

1. INTRODUCTION

Sandwich structures possess a good ratio of bending stiffness and strength to weight. The application of a carbon fibre reinforced polymer for the face sheets in combination with lightweight core material offers potential for optimization. Using closed cell foams complex core preforms can be manufactured; therefore it is possible to produce high integral and cost-efficient sandwich components. These benefits can especially be used in structures which have a high ratio of strength and stiffness to weight and are at risk to fail by buckling. Hence, sandwich structures qualify for application in shells of commercial aircrafts [1].

Compared to monolithic structures the mechanical behaviour of a sandwich is more complex due to the mechanical interaction of the different materials. It demands on investigations both of the components and of the whole composite. It has to be proved whether the use of failure criteria for the separate components is sufficient and what additional effects of interaction have to be considered furthermore.

In the observed sandwich residual stress significantly influences the deformation and failure behaviour. The residual stresses induced by chemical, hygroscopic and thermal effects. Chemical stress arises from the chemical shrinkage of the epoxy resin while curing process, which amounts about 5% [2]. This affects the laminated CFRP skin but not for the foam core, because its polymerisation is completed before the infusion process. Both, the PMI foam and the CFRP skin can absorb water. This results in moisture expansion of the epoxy - which is constricted by the stiff carbon fibres - and a foam expansion, and therefore leads to small permanent stresses too. However, the primary cause of the residual stress in composite structures are thermal stresses [3], especially for the CFRP foam-core sandwich, whose constituents have a very different thermal expansion coefficients.

2. FORMATION OF THERMAL STRESSES

The source of thermal stress is the different thermal expansion behaviour of the sandwich components and their mutual obstruction of contraction in the sandwich. The thermal expansion coefficient of the carbon fibre is negative along the longitudinal axis and positive transverse to the fibre axis [4]. The epoxy resin has a positive isotropic thermal expansion coefficient. This results in microscopic residual stresses between fibre and resin [5]. The combination of fibres and resin in an unidirectional layer yields transversal-isotropic thermal properties (see Table 1). In fibre direction, the stiffness is high and the thermal expansion is negative. In transverse direction, the thermal expansion is positive (dominated by the resin) and the stiffness is lower. The laminate of the skin investigated in this work is composed of six layers with different orientations: $[45/0/-45]_S$. The thermal expansion of each layer is impeded by each other, which results in mesoscopic residual stresses between the single CFRP layers [6, 7]. Considering the Classical Laminate Theory (CLT), the mixture of all layers in the laminate yields an orthotropic material behaviour of the sandwich skin. In the special case, the thermal expansion coefficient of the 0-degree laminate axis is nearly zero.

E_{11} $[GPa]$	E_{22} $[GPa]$	E_{33} $[GPa]$	G_{12} $[GPa]$	G_{13} $[GPa]$	G_{23} $[GPa]$
135	9.75	9.75	6.0	6.0	2.99
υ_{12}	υ_{13}	υ_{23}	α_{11} $[10^{-6} * 1/K]$	α_{22} $[10^{-6} * 1/K]$	α_{33} $[10^{-6} * 1/K]$
0.28	0.28	0.64	-0.1	31.0	31.0

Table 1: Material properties of the single unidirectional CFRP layer.

The ROHACELL foam core shows isotropic thermal behaviour with positive coefficient of thermal expansion (see Table 2). The difference of thermal expansion behaviour compared to the CFRP results in macroscopic residual stresses, especially when the foam in the assembly is completely sheathed by the CFRP skin. Because of the low strength of the foam compared to the CFRP, these stresses are most critical for the foam core.

T $[°C]$	G_F $[MPa]$	T $[°C]$	E_F $[MPa]$	T $[°C]$	α_F $[10^{-6} * 1/K]$
0	30	20	70	-150	24
50	28	40	65	-100	24
100	22	60	60	-50	27
150	18	80	58	0	30
200	4	100	52	20	33
		120	45		
		140	38		
		160	32		

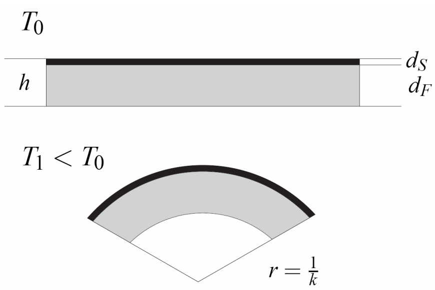
Table 2: Temperature dependent material properties of PMI foam ROHACELL 51WF.

The sandwich curing temperature normally ranges between 160°C and 180°C [8]. With cooling down to service temperature, the foam tends to contract while the CFRP face sheets show no thermal expansion. Because of the very high stiffness of the face sheets compared to the stiffness of the foam, the core cannot contract and retains residual stresses. Assuming here that the relative offset of skin and core is frozen at maximum curing temperature of 180°C and the behaviour of the foam is linear elastic, residual stresses in the foam core rise up to 0.5 MPa by cooling down to room temperature (25°C). Considering foam strength of 1.8 MPa the thermal stress amounts nearly 30% of it [9].

The material behaviour of investigated PMI foam core is ascertained as semi-thermoplastic. That means, the foam creeps under constant load or relaxes under constant strain. In practice the residual stresses in the sandwich core can be smaller than predicted with the usual assumption of linear elastic material behaviour. Thus, for optimal weight and cost design of complex sandwich structures it is essential to describe the residual stresses as a function of time and temperature. With the following investigations, the real residual stresses will be determined.

3. MEASUREMENT OF CURVATURE

Removing one face sheet from the sandwich or cutting it into two parts results in an asymmetric bi-material specimen. The residual stresses in the sandwich causes a curvature of the specimen (see Figure 1). At room temperature the foam core is loaded by tensile stresses. Cutting the sandwich into two parts, it bends to foam side. The curvature (k) is a measure of the residual stress: The curvature develops with increasing stress. After splitting a specimen at room temperature, a very small curvature was measured and the residual stress was calculated. The specimens used have a length of 100mm and a width of 10mm. Timoshenko [2] submitted an equation to calculate residual stresses (σ_F) in bi-metals. In equation (1) and (2) this theory is applied to the investigated sandwich, where E_F and E_S are the Young's moduli of foam and skin, I_F and I_S their moments of inertia of area, α_F and α_S the thermal expansion coefficients, d_F and d_S the thicknesses, h the thickness of the bisected sandwich, T_0 the strainless reference (curing) temperature and T_1 the load (room) temperature. Following the residual stress in the investigated sandwich is calculated with this assumption. Firstly their applicability for the sandwich has to be proved by theoretical investigations, see next chapter.



$$\sigma_F = k\left(\frac{2}{hd_F}\left(E_F I_F + E_S I_S\right) + \frac{d_F E_F}{2}\right) \quad (1)$$

$$k = \frac{(\alpha_F - \alpha_S)(T_0 - T_1)}{\frac{h}{2} + \frac{2(E_F I_F + E_S I_S)}{h}\left(\frac{1}{E_F d_f} + \frac{1}{E_S d_S}\right)} \quad (2)$$

Figure 1: Curvature of sandwich specimen after cutting it into two parts.

3.1 Numerical calculations

To verify the method of residual stress determination based on experimental measured curvature, numerical calculations were carried out. Equation (1) was formed by Timoshenko [2] for bi-metals. The material behaviour of the investigated sandwich differs from the behaviour of metals in many points. The orthotropic CFRP skins are composed of unidirectional layers. Both, stiffness and thermal expansion behaviour differ in their principal axes. By contrast the foam core can be assumed as isotropic, but the stiffness and the thermal expansion coefficient depend on the temperature (see Table 1). The curvature measured by Timoshenko was compared to FEA calculations with several material models, because the theory of Timoshenko does not account the non-linear material behaviour of the foam and also not the orthotropic behaviour of the skin.

For the finite element analysis a 3D model was used, with one element layer for each CFRP unidirectional layer. The NASTRAN solver was used for the calculation, PATRAN for the pre- and postprocessing. To reduce the number of equations, only a quarter of the specimen was modelled using symmetry conditions. Three calculation methods were compared: i) linear-elastic, ii) linear-elastic with temperature dependent foam behaviour (physical non-linear) and iii) great displacements and temperature dependent behaviour of the foam (geometrical and physical non-linear). The material datasets were filled with the mechanical properties listed in table 1. For temperatures with unknown properties, the solver calculates it by linear inter- and extrapolation. Temperature and time dependent material behaviour is not modelled, creep and relaxation are not considered at this point.

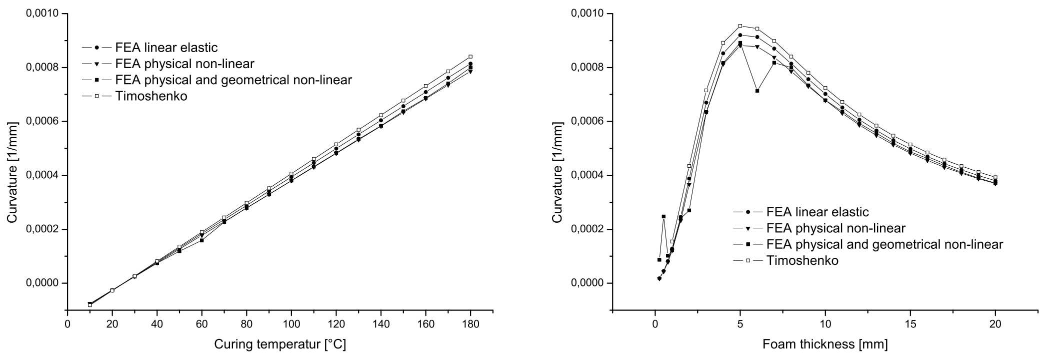


Figure 2: Calculated curvature as a function of curing temperature and foam thickness.

Figure 2 (left) shows the calculated curvature at room temperature (this curvature should be measured after cutting the sandwich into two parts) as a function of the assumed strainless reference (curing) temperature T_0. It is apparent, that all calculations (the non-linear finite element analysis too) result in a nearly linear increase of curvature with rising curing temperatures. The theory of Timoshenko determines the greatest curvature, and therefore the highest residual stress at the same temperature load. That means the use of the Timoshenko equation is conservative compared to all investigated FEA models. It is also apparent, that the decrease of the foam stiffness with rising temperature does not have an visible impact on the calculated curvature. The difference between the linear elastic and the physical non-linear solution is negligible. The calculated displacements are small, so the difference between geometrical linear and non-linear curvature are not significant. Both variants yield nearly the same curvatures.

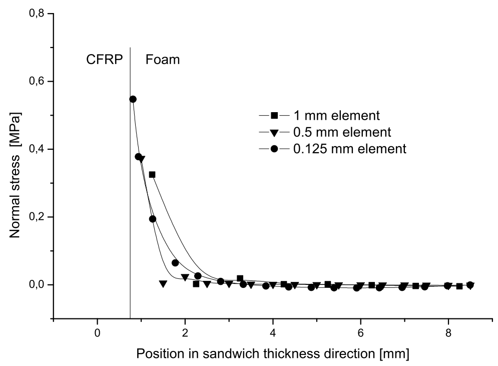
The accuracy of the measured bending radius becomes more exact with increasing curvature, which is inherent to the optical measuring method used here. The thickness ratio of skin vs. core significantly influences the amplitude of the curvature. To optimize the specimen dimensions for the test assembly, the quantitative impact of the thickness ratio was determined by numerical studies. The skin thickness was assumed to be constant, because variation of the skin would increase the costs and effort for specimen manufacturing immensely. The foam thickness however can easily be adjusted with the cut, so in the numerical studies only the foam thickness was varied. Figure 2 (right) shows the curvature vs. the foam thickness with a temperature ramp of -155 K. The numerical results correspond well with the theory of Timoshenko. For the constant skin thickness, a foam thickness of 0.25mm results in a very small curvature. With increasing foam thickness up to 5mm the curvature arises. Within the range of 5 to 20mm the curvature decreases. This trend results from the path of the neutral axis of the sandwich half. With small foam thickness, the neutral axis is near the CFRP skin and so the bending moment is small. The distance between the neutral axis and the skin increases with rising foam thickness and so the bending moment arises. But the section modulus increases too, because of the higher moment of inertia of area. This results in a maximum curvature with a foam thickness in the range from 5 up to 10mm. This thickness should be chosen for the experiments to get the maximum curvature for optimal measurement. In the following experimental investigation a foam thickness of 8mm was defined.

It was observed up to now, wether the displacements calculated by Timoshenko and several FEA models correspond. Also an optimal foam thickness was defined for the experiments. The main task is not the measurement of the curvature, but the residual stress in the foam. Following the method is proved for determining the residual stress based on the measured curvature. The residual thermal stress in the foam ($\sigma_{F,\max}$) can be determined by:

$$\sigma_{F,\max} = \frac{(\alpha_S - \alpha_F)(T_1 - T_0)E_F}{1 - \upsilon_F} \qquad (3)$$

where α_S and α_F are the thermal expansion coefficients of the CFRP skin and the foam core, E_F and υ_F the Young's modulus and Poisson's ratio of the foam, T_0 the reference (curing) temperature and T_1 the load (room) temperature. The stress calculated with Eq. (3) is a maximum value, which only occurs when the contraction of the foam is completely constricted. This case is nearly achieved, when the foam in the assembly is completely sheathed by the CFRP skin, but not for the investigated specimen. On the one side the foam is free and can contract. At this face the stress becomes zero, on the CFRP side it reaches its maximum value. Figure 3 shows the residual normal stress in the foam against the sandwich thickness for the investigated sandwich half calculated by FEA. The maximum normal stress determined by Timoshenko (0.54MPa) is nearly achieved by the numerical calculations, but only for the area near the CFRP skin. The tensile stress decreases significantly with the distance to the skin. To calculate the real stresses near the interface, it is necessary to use small element sizes. In this study the stresses are averaged over the element; modelling with to coarse mesh (1 and 0.5mm element edge length) underestimates the stresses near the interface. With 0.25mm edge length the calculated stress amounts 0.51MPa, an adequate result to legitimate the use of the Timoshenko theory for the stress calculation.

The numerical calculations have shown that the application of Timoshenko's theory for the investigated sandwich is justified.



element size	$\sigma_{F,\max}\,[MPa]$
1,0 mm	0,33
0,5 mm	0,37
0,125 mm	0,51
Timoshenko	0,54

Figure 3: Residual stress in the bisected sandwich specimen vs. sandwich thickness.

3.2 Measurement setup and test execution

The curvature is quantified with a contactless optical measuring system. This needs a speckle pattern to be applied onto the specimen's surface by using black and white colour components (see Figure 4 right). Individual images or synchronised stereo images of the pattern are recorded at different load stages using CCD cameras. After the first image record, the sandwich specimens are cut through using a diamond saw and put to their basic position. The 3D coordinates and 3D displacements of the first and the following stages are calculated automatically using photogrammetric evaluation procedures. For this investigation the measuring system ARAMIS developed by GOM mbH is used.

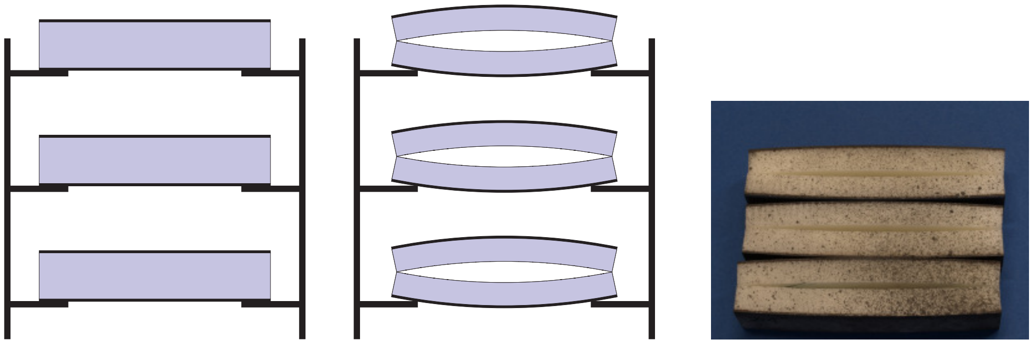


Figure 4: Measurement setup and separated sandwich specimen.

While recording the first and the second image, it is important to put the specimens to their basic position accurately, otherwise the measuring system has difficulties to recognise the pattern. Preliminary tests have shown that a horizontal position is better than vertical, because the specimens tend to overbalance at high curvatures. For this reason a frame was built, which enables to measure three sandwich specimens (6 half specimens) at the same time (see Figure 4 left).

The sandwich specimens are cut through at room temperature (25°C). Not only the stress at this temperature should be determined, but also the stress development due to a defined temperature ramp. Therefore the measurement was set up in a heating cabinet with a window glass, to record the images from the outside. The threefold temperature ramp was defined by heating up to 180°C and cooling down to 30°C with a rate of 0,2 K/min. Every 15 minutes an image was recorded. The curvature is determined by calculation based on the measured displacements. They are fitted to the circle equation and the radius and curvature are calculated. Therefore a routine was programmed, which calls for each image the fitting software Gnuplot.

4. EXPERIMENTAL RESULTS

4.1 Curvature of asymmetric sandwich specimens

Figure 5 (left) shows the determined residual stress based on the measured curvature against the temperature ramp. Two foam types were investigated: Rohacell 51WF (also used for the numerical calculations) and Rohacell 71Rist. Rohacell 51WF has a density of 52 kg/m³ and 71Rist has 85 kg/m³. The number in the name of the foam type stands for the target density; the real density can vary in a certain range. The middle cell diameter of the Rist foam is nearly five times smaller than in the WF type, because the Rist was optimized for minimized resin absorption during the infusion process. The face sheets are equal for both sandwiches: The CFRP described in the last chapters with six single layers $[45/0/-45]_S$ was used.

After cutting through the sandwiches at room temperature, a small curvature was determined. The stresses based on this curvature are compared to the numerical and theoretical calculations too small. With heating up, the curvature and the stress firstly arise, contrary to the assumption of linear elastic material behaviour. After exceeding 60°C (71Rist) and 90°C (51WF), respectively the stress decreases with rising temperature like assumed. After passing the first maximum (180°) both sandwich types now show a linear bending behaviour at all temperature ramps, where the maximum stress arises at the minimum temperatures (30°C). For the 51WF foam 0,5 MPa could be determined, which compares well with the theoretical values calculated in the chapter before. The maximum stress in the 71Rist foam is greater (0,85 MPa) because of the higher stiffness. Considering the foam tensile strength (1,8 MPa for 51WF and 2,8 MPa for 71Rist), the residual stresses amount to 30% of it.

The thermal expansion at the first temperature ramp seems very strange, but can be explained by considering semi-thermoplastic behaviour of the foam. Under constant loads the foam creeps and its stress decreases under constant strain. The sandwich plates were made in February (71 Rist) and April (51WF Plate) 2006 and cutted through in January 2008. During the two years, the plates were stored at room temperature. The residual stresses in the foam relaxed, so the curvature after sawing was smaller than assumed. The polymers are stretched. But the stresses are only relaxed at this temperature. With heating up, the polymers want back to their initial position and the stresses increases again. After the first temperature maximum, this effect is gone, because of the free foam side. The foam now can expand and contract and the half sandwich specimens show a linear bending behaviour. For dimensioning foam sandwich components this behaviour is fundamental. It means, that the residual stresses can partly relax, but only in a defined temperature range. The minimum weight design can be optimized by knowing the service temperature of the component.

4.2 Thermal expansion of PMI foam core

To verify the last results, the thermal expansion of the separated foam was investigated. Therefore the CFRP skins were detached from the foam. Foam specimens with 100mm length and 10mm width were heated and cooled down with the same proceeding like the sandwich before.

Figure 5 (right) shows the strain of the foam against temperature and time. After passing the first temperature maximum, both foam types show linear expansion behaviour. The thermal expansion coefficients can be determined from these curves to $37*10^{-6}$ 1/K and agree well with the value provided by the manufacturer ($35*10^{-6}$ 1/K) for both foams. At the first heating ramp, non linear expansion behaviour can be seen. Both foams firstly expand in longitudinal and transverse direction. With exceeding 50°C (71Rist) and 70°C (51WF) the foam contracts while heating. Whereas the 71Rist contracts until reaching the first temperature maximum, the 51WF foam expands again after exceeding 120°C. This different behaviour results in two offsets for the next temperature ramps and shows, that the 71Rist foam was more relaxed than the 51WF. After the experiments, the 71Rist specimens were 0,8% shorter, the 51WF only 0,4%. When no relaxation in the sandwich occurs, the strain at the end of the experiments has to be the same like beginning (0%).

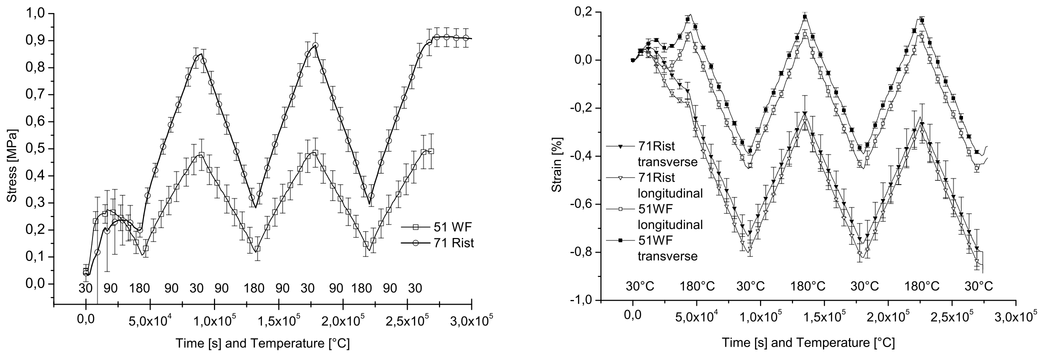


Figure 5: Determined residual foam stress based on measured curvature of halved sandwich specimens (left) and thermal expansion of the separated foam (right) against temperature ramp.

The different relaxation of the foam types can mainly result from three effects: Rist and WF consist of some different chemical mixture. Different polymers can offer a different creep and relaxation behaviour. The second different is the density: The Rist specimens have 1.6 times more solid material, which dominates the relaxation process. This increases the effect compared to lower density foams. The third cause can be the relaxation time: The Rist specimens were stored longer for two month. However this fact can have an effect, but it should be small in face of the whole storing time (2 years).

Another effect can be seen in Figure 5 (right): For both foams, the difference of strain between begin end of the tests is greater in longitudinal direction compared to transverse direction. This effect results from the laminate orientation. The difference of the thermal expansion coefficients of foam and CFRP skin is in longitudinal direction greater, because more carbon fibres are oriented in this direction.

The experiments with the separated foam approve the results from the measurement of curvature: The PMI foam tends to relax in the investigated sandwich, but new temperature loads can reverse this. It seems that there are differences in the relaxation behaviour of Rist and WF, which should be investigated systematically. Higher density foams tend to relax more than foams with lower percentage of solid material.

5. BEHAVIOUR OF WATER INGRESS UNDER TEMPERATURE CHANGE

Next to the mentioned temperature changes occurring while curing during the manufacturing process and leading to residual stresses, sandwich structures undergo a range of temperature changes according to their application. Depending on the environmental conditions the structures may come in contact with water, which may intrude. One scenario to be considered is a temperature drop below 0°C of the structure with water inclusions.

For honeycomb sandwich structures this case is known. Once the face sheet is fractured, water can enter the cells of the honeycomb core through cracks in the face sheet. If the temperature of the sandwich structure in service drops due to environmental conditions below 0°C, the presence of standing water in the honeycomb core can destroy the honeycomb core through a freeze-thaw mechanism. The volume of the freezing water expands due to its density anomalies by about 9% under atmospheric pressure and hence stresses the honeycomb cell walls. At temperature increase the water melts and the honeycomb wall relaxes. After a number of these freeze-thaw cycles the cell walls will catastrophically fail and destroy the structure of the honeycomb. If a honeycomb cell contains a substantial amount of water, the freezing water can also expand against the face sheet and delaminate or disbond the honeycomb core and the face sheet [11].

For closed-cell foam core sandwich structures water ingression is not as likely as for honeycomb core sandwich structures since foam core structures do not possess analogically large cavities. Still, in case of impact damage that may lead to core and/or face-sheet damage as well as debonding of the face sheet from the core a cavity can occur.

5.1 Finite Element Analysis

To monitor the behaviour of water ingress in impacted areas of foam core sandwich structures under repetitive cyclic loading a finite element analysis was carried out. For the model a 5mm deep slice of a 50mm-diameter spherical shape was cut-out of the 25mm thick PMI ROHACELL RIST 71 foam core of a sandwich panel with 2,5mm CFRP face-sheets. The face-sheets were considered to be not damaged, hence having their non-reduced properties. The cut-out cavity in the core was considered to be completely filled with water. Two cases where simulated: the expansion due to freeze of the water-filled cavity as well as the shrinkage due to a temperature drop of the frozen cavity down to -55°C with an expansion coefficient of ice of $51*10^{-6}$[1/K]. The shrinkage showed no effect to the structure, since the volume reduction is compensated by the foam core's ductility. However the expansion of the water ingression showed an effect. Because of the high stiffness of the face-sheets compared to the core, the face-sheets perceive no influence and the expansion is absorbed by the core. Part of the volume-increase is compensated by the ductility of the foam core, while part of it leads to stresses in the range of the foam's strength.

5.2 Experimental investigation

Subsequent to the numerical FE-Analysis experimental investigations considering cyclic temperature changes of a water intruded sandwich panel were carried out. A sandwich-panel with the same dimensions of the FE-model was manufactured and impacted by 7 different energy-levels from 4 to 28 Joule and the impacted areas were afterwards filled with water. Water was inserted into the impacted areas through two 0,75mm-diameter fine drilled holes using an injection with a needle of 0,5mm. The water-filled sandwich panel was exposed to freeze-thaw cycles from +23°C to -18°C, every cycle consisting of 18h freezing and 6h thawing. In between each cycle the impacted areas were refilled with water such that the cavities were completely filled during each cycle to represent a worst case scenario. 30 cycles were carried out up to now while another 30 cycles are running at present. To assess the behaviour the panel was NDT inspected prior and after impacting as well as after 6 and 30 cycles using air-coupled ultrasonic inspection.

5.3 Results

No significant change was detected in the US-scan of the impacted areas of the foam core sandwich panel before and after freeze-thaw-cycling. The differences detected were in the range of the resolution of the US-inspection device and correlated with changes in the measurement of the attached reference indication. Hence no major growth of the impacted areas could be established.

This result conforms to the conclusion of previous investigations of the freeze/thaw behaviour of water ingress of honeycomb core sandwich panels that stated foam filling the honeycomb core to be significant in minimizing damage propagation. It first decreased the initial damage size of an impact minimizing the amount of microcracking and delamination at the point of ingression. The foam also filled the empty cells of the honeycomb and prevented water from filling those cells. Through both of these mechanisms, the foam minimized the propagation of damage normally observed in the standard honeycomb core [12]. Since water ingress occurs due to the cavities of the empty cells of honeycomb cores, foam core sandwich panels are less susceptible to water ingress in general and hence less susceptible to freeze-thaw cycling of water ingress. The investigation showed that if water intrudes into impacted areas of a foam core sandwich the effect on the structure is remote.

6. CONCLUSIONS

Thermal stresses in CFRP foam-core sandwich structures are caused by the different thermal expansion behaviour of the sandwich components. Whereas the CFRP skins show nearly no thermal expansion, the foam wants to contract while cooling down after curing process. The contraction is prevented because of the bonding of skin and core. This results in residual stress, which is most critical for the foam, because of its small strength compared to the strength of the CFRP. To determine the thermal stress is fundamental for an optimal light weight design and so for the use in commercial aircrafts.

One method to measure the residual stress is the measurement of curvature of asymmetric sandwich specimens. This method was developed for bi-metals by Timoshenko and was now applied to the investigated sandwich. With numerical calculations the validity of the Timoshenko theory was proved.

The experimental results have shown that the residual stresses are smaller than assumed. The foam core was stretched in the sandwich and the stresses relaxed. With heating up to new temperature condition, the foam wants to deform to its initial shape and the stresses arise again. After the first heating cycle, the determined maximum stress agrees well with the theoretical value. The minimum weight design can be optimized by knowing the service temperature of the component.

This relaxation behaviour depends on the foam type, foam density and relaxation time. More extensive investigations are necessary to determine the stresses in various foam types, foam densities and at various relaxation times and temperatures.

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