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Hygro-Thermal Transient Analysis for Highly Stable Structures

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Abstract

This paper presents the results obtained with the simulations of a sandwich rectangular plate made of carbon/epoxy composite when subjected to temperature and humidity cycles. Fickian diffusion process, moisture transport along the interfaces and damage caused by slipping and debonding between the components of the microscopic structure are considered. The application of the design methodology to a real structure is shown.

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1 Introduction

Our understanding of nature's fundamental particles and the forces which act between them resulted in a theory, known as Standard Model, considered one of the greatest intellectual achievements of physics. At present, we know that this theory can only be part of a more complete one because it leaves too many questions unanswered. How do particles get their masses, for example? And why does nature triplicate the family of basic particles which make up all matter as we know it? At CERN we plan to address these and other fundamental open questions of physics with the two general purpose experiments, ATLAS and CMS, that will operate at the Large Hadron Collider, LHC. Both these experiments have the typical onion-like layout of a High Energy Physics collider detector with sub-detectors disposed symmetrically around the interaction point. Each of these sub-detectors is able to measure one or more of the parameters that are needed for the full identification of each particle.

Typically with several tens of meter long and weighting between 9000 and 14000 tons, these experiments are both huge in size and complexity and cannot be compared with any other particle physics experiment done so far.

The inner sub-detectors of these experiments require the use of light and stable structures capable of supporting delicate and precise radiation detection elements [1]. These structures need to be highly stable under environmental conditions where external vibrations [2], high radiation levels, temperature and humidity gradients should be taken into account. Their main design drivers are high dimension and dynamic stability, high stiffness to mass ratio and large radiation length. For some applications, these constraints lead us to choose Carbon Fiber Reinforced Plastics (CFRP) as structural element. The construction of light and stable structures for these applications can be achieved by careful design engineering and further confirmation at the prototyping phase. The experimental environment can influence their characteristics and behavior and good simulation tools are needed for evaluate the impact of these effects on the performance of the structures [3,4].

In this work we study the influence of moisture and temperature variations on a CFRP/aluminum honeycomb sandwich plate. Factors such as debonding, properties degradation and hygro-thermal coupling were taken into account. We first present the predictive model used in the simulations and compare it with experimental data and other existing models. This model is then applied to a real detector structure under realistic environmental conditions.

2 Model for Prediction of Dimensional Stability of Composites

A predictive model of the hygro-thermal behavior of composite materials was preliminary used to estimate the composite properties.

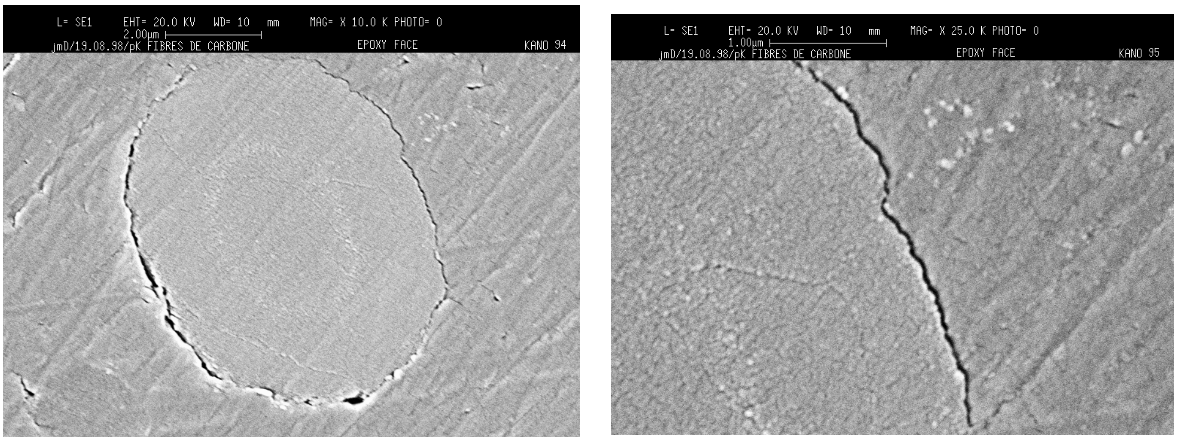
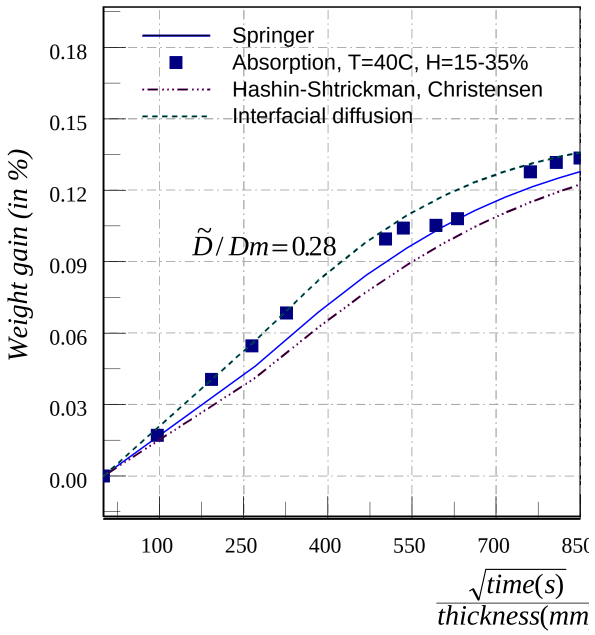


Figure 1: *Observation of interfacial debonding for a T300/Epoxy 1808N unidirectional composite.*

The influence of environmental effects on composite structures has received a great deal of attention in the literature. Classic theories, which assume perfect contact between the fibers and the matrix, as the *Springer* [5] and *Hashin-Shtrickman/Christensen* [6] models for diffusion, are very often insufficient to describe accurately the behavior of the composites [7 to 10]. Experimental results have effectively shown that apart from a simple diffusion of water in the matrix, we have also to consider a diffusion along the interfaces between the fibres and the matrix



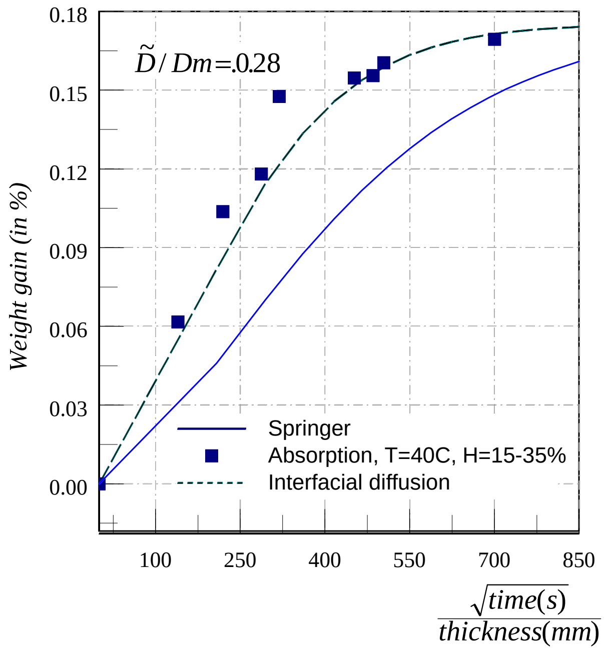
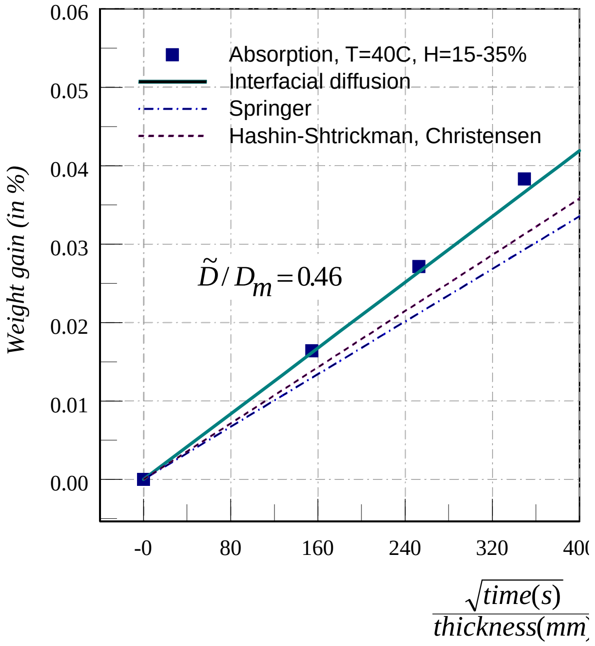


Figure 2: *Comparison between the experimental data and the interfacial diffusion model when the diffusion direction is perpendicular to the fibers for a T300/Epoxy 1808N unidirectional composite.*

Figure 3: *Comparison between the experimental data and the interfacial diffusion model when the diffusion direction is parallel to the fibers for a T300/Epoxy 1808N unidirectional composite.*



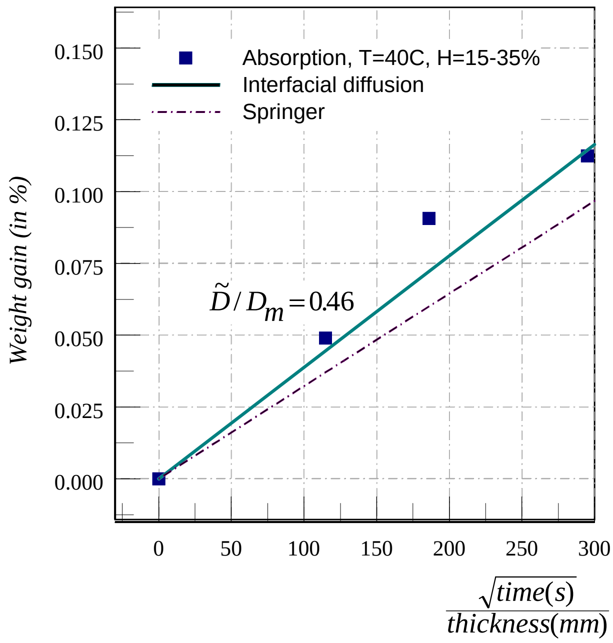


Figure 4: *Comparison between the experimental data and the interfacial diffusion model when the diffusion direction is perpendicular to the fibers for a T300/Rosalie cyanate ester unidirectional composite.*

Figure 5: *Comparison between the experimental data and the interfacial diffusion model when the diffusion direction is parallel to the fibers for a T300/Rosalie cyanate ester unidirectional composite.*

[10]. Interfacial debonding, which may occur like it is shown in Figure 1, could also have an important influence on the properties of swelling of the composites. Improved models of the hygromechanical behavior of composites based on the homogenization theory of periodic media were then developed in order to include the contribution

of the interfacial regions. To describe moisture transport along the interfaces, an interfacial law, asymptotically equivalent to a thin diffusive layer, was introduced at the microscopic level. Degradation at the interfaces by differential swelling and dilatation were also considered. Slipping and debonding effects at the interfaces were defined in terms of the relation between interface traction and displacement jumps [11]. In the proposed model the influence of diffusive interfaces is taken into account by the parameter $\widetilde{D}$. Its introduction in the model leads to a good correlation between experimental values for different composites [10]. For a T300/Epoxy 1808N unidirectional composite the experimental characterization of this parameter gives $\widetilde{D} = 0.28\ D_m$, where D_m is the moisture diffusion coefficient of the matrix. In the same way the experimental measurements on the swelling in composites have shown that by taking into account debonding of the interfaces one obtains a very good estimation of the hygro-mechanical properties of the composite.

The good agreement obtained between the experimental data and the interfacial models [10] show that they can be used to predict the dimensional stability of composite structures (see Figure 2 to Figure 5).

3 Specific case of the Alignment Wheel of CMS

The two large LHC experiments, ATLAS and CMS are foreseen to start to operate in the year 2005. The structures for their inner sub-detectors are presently under engineering design and prototyping. Some of these structures are designed to support the detection elements [1] whereas others will be used to monitor the position of the different inner sub-detectors. It is foreseen to install a position monitoring system able to measure the relative deviations of the these sub-detectors from their nominal positions.

A fundamental piece of the system are two disk-like structures, known as alignment wheels, housing precise detection elements. The requirements of high dimensional stability, high stiffness to mass ratio and maximum displacements at the micron level, oriented the design towards the use of sandwich technology in the case of this particular application.

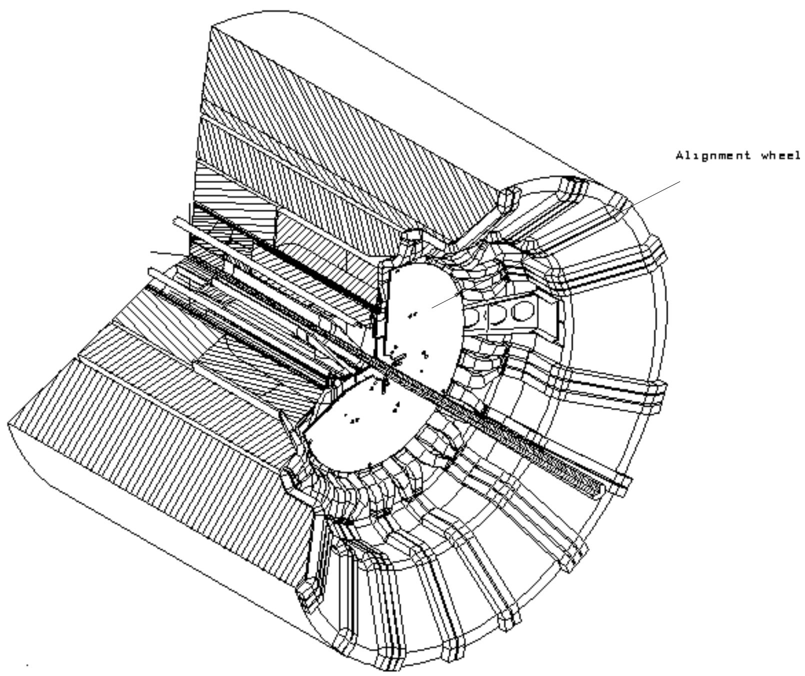


Figure 6: *Partial view of CMS inner detectors showing the location of the 2.4m diameter alignment wheel.*

The alignment wheels, with an outer radius of 1.22 m and an inner radius of 0.15 m, are vertically placed and isostatically supported in three points at an intermediate radius. The first point at 90 degrees is supported in the $z-direction$ (out-of-plane), the second point at 210 degrees is supported in all directions and the third one, at 330 degrees, is supported in the $z-direction$ and in the $y-direction$ (vertical). The use of aluminum honeycomb and carbon fiber skins in the disks reflects the need of an almost insensitive structure to moisture and temperature variations. A static analysis was performed using a finite element code with 3-D elements. If we consider the gravity force as the only load, we obtain a maximum displacement of $1.0\mu m$. A simple static analysis may not be sufficient to fully characterize the performance of the structure in terms of dimensional stability and the influence of environmental conditions should be taken into account.

4 Environmental Conditions

The experimental halls of the future LHC collider at CERN will have a temperature and dew point controlled with an accuracy of $\pm 2C^{\circ}$. From previous experiments in similar conditions, we extracted an average humidity variation during the year. Figure 7 represents the humidity conditions in the experimental halls and will be used in all simulations as an approximation of the moisture content at the level of the detector's internal structures. In the future particle detectors, some of their sub-structures will be in an environment with dry nitrogen during periods of 6 months. In this case the humidity cycle will not be the one presented before and the variations in the humidity will be more important and should be taken into account during the analysis.

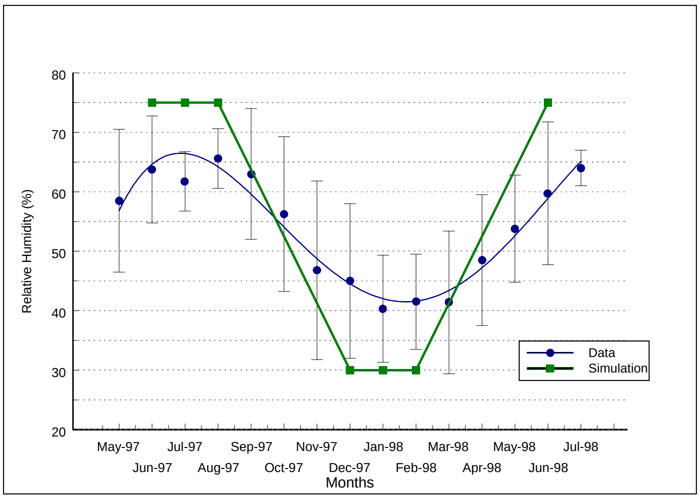


Figure 7: *Humidity cycle used for the numerical simulations.*

5 Results and Discussion

5.1 Hygromechanical analysis of a CFRP sandwich plate

The dimensional stability analysis of a cell element (sandwich plate with 500 mm length and 250 mm width) of the global alignment wheel structure was performed using ANSYS 5.4 . The skins, with 2 mm thick, have a quasi-isotrope lay-up - $[0, 90, \pm 45]_s$ - and are made of carbon/epoxy (T300/3501-5). The plate was supported as indicated in Figure 8. The hygro-mechanical properties of the sandwich skins were obtained by using the interfacial diffusion model presented before. The honeycomb (HEXCEL 1/8-5056), with a thickness of 16 mm, is made of aluminum and the used properties were the ones given by the manufacturer (see Table 1).

Table 1: Hygro-mechanical properties for the skin carbon/epoxy composite (quasi-isotrope lay-up) and for the aluminum honeycomb.

	T300/3501-5	Aluminum honeycomb
$E_{xx} = E_{yy}/E_{zz}$ $[GPa]$	42.9 / 10.9	0.001 / 1.28
$G_{xy}/G_{xz}/G_{yz}$ $[GPa]$	16.3 / 3.2 / 3.2	0.00037 / 0.483 / 0.193
$D_x = D_y/D_z$ $[m^2/s]$	2.5x10^{-14} / 2.0x10^{-14}	0.0 / 0.0
ν_{xy} / $\nu_{xz} = \nu_{yz}$	0.32 / 0.3	0.35 / 0.0
$\beta_x = \beta_y$ / β_z	1.9x10^{-4}/2.4x10^{-3}	0.0 / 0.0

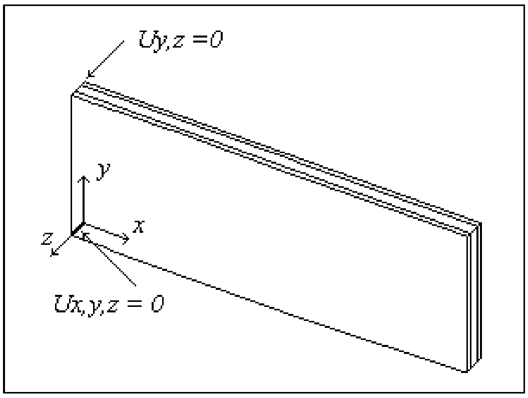


Figure 8: *Sandwich plate used in the numerical simulations.*

The first simulation of the influence of the humidity cycle (Figure 7) on the sandwich plate was performed at different time instants assuming the existence of non-diffusive interfaces (Figure 9 and Figure 10). Due to a null moisture diffusivity coefficient of the aluminum honeycomb we observe a zero moisture content inside the honeycomb. We can also verify that the saturation level is not attained after 5 cycles, the period of time considered in this analysis. This fact is in agreement with what is reported in the literature about saturation under cyclic loads. For a 0.5 mm thick composite plate with reinforced fibers, *G.S.Springer* reached the saturation plateau after 10 years and showed that the saturation is attained after a certain number of cycles depending more on the temperature than on the characteristics of the humidity cycle itself. In terms of dimensional variations we observe that the displacements are not negligible - the internal stresses in the skins, due to the humidity variations, produce displacements also at the level of the honeycomb. The non-symmetric profile is due to the assimetrical fixation of the plate.

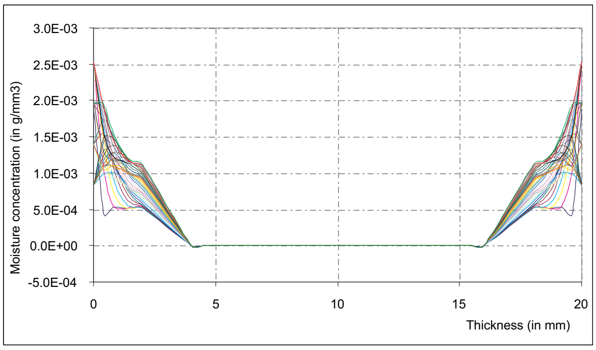


Figure 9: *Moisture content in thickness for non-diffusive interfaces and for different time instants in a point with coordinates x/length=1.0 and y/width=1.0. The different curves show the time evolution over 5 cycles (lower curve t=0).*

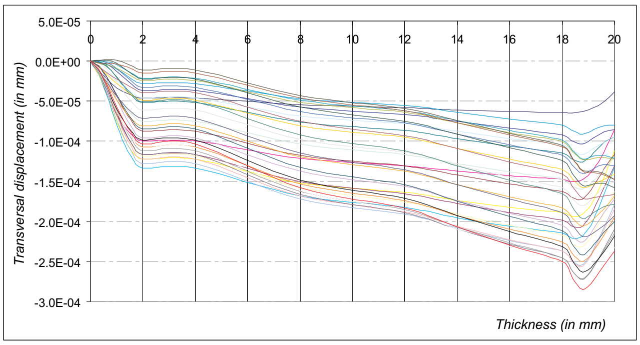


Figure 10: *Relative transversal displacement ($y-axis$) in thickness for non-diffusive interfaces and for different time instants in a point with coordinates x/length=1.0, y/width=1.0. The different curves show the time evolution over 5 cycles (upper curve t=0).*

5.2 Influence of interfacial diffusion

The influence of interfacial diffusion in the dimensional stability of the sandwich plate was studied. An initial moisture content of 20% was considered and the new values for the diffusivity coefficients were determined taking into account the interfacial diffusion model presented before ($D_{xx} = D_{yy}$ =8.59x10^{-14} m^2/s and D_{zz} =3.36x10^{-14} m^2/s). As expected, the interfacial diffusion leads to an acceleration of the diffusion process and consequently to an increase of the moisture absorption and of the dimensional variations between the absorption and desorption phases (Figure 11) [7]. The longitudinal displacement amplitude over one cycle increases approximately 30% with respect to the previous case, when interfacial diffusion is considered (Figure 12).

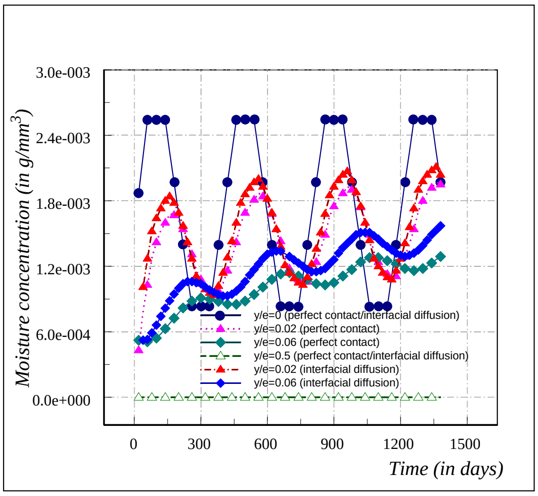


Figure 11: *Comparison of the moisture concentration for non-diffusive and diffusive interfaces for a point with coordinates x/length=1.0, y/width=1.0 and z/thickness=0.0.*

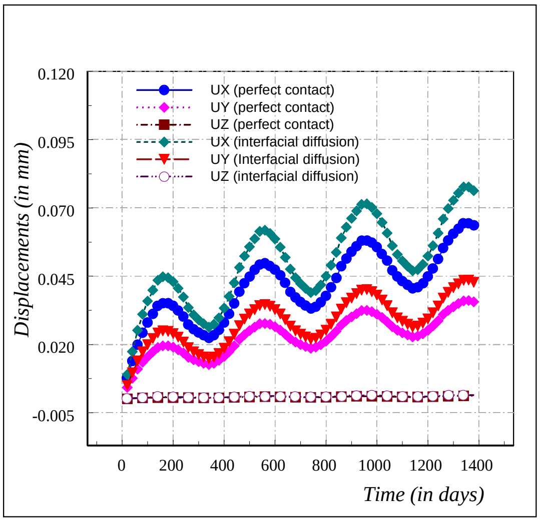


Figure 12: *Comparison of the displacements for non-diffusive and diffusive interfaces for a point with coordinates x/length=1.0, y/width=1.0 and z/thickness=0.0.*

5.3 Influence of interfacial degradation

The influence of the properties degradation at the level of the fiber-matrix interface leads to a significant increase in the displacements. In fact, we can observe at the end of the cycle (Figure 13) an increase from 60μm to 900μm when a severe interfacial degradation (fully damaged interfaces) is considered.

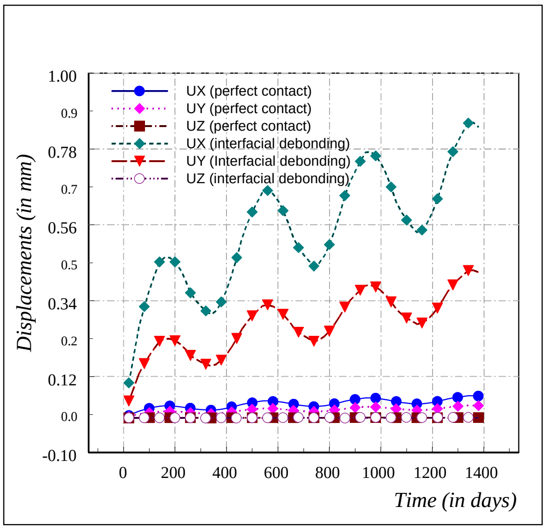


Figure 13: *Comparison of the displacements with and without interfacial debonding for a point with coordinates x/length=1.0, y/width=1.0 and z/thickness=0.0.*

5.4 Influence of temperature

We consider now the case when the humidity cycle is coupled with a temperature variation of 5^0C. Figure 15 shows an increase of almost 25%, over one cycle, in the longitudinal displacement when both effects are considered. The time offset between the maximum values of the moisture concentration observed in Figure 14 (between 2-3 months) is due to a slower diffusity in the desorption phase caused by the decrease of the temperature.

5.5 Dimensional stability of the alignment wheel structure

A finite element model (3-D elements) was used to calculate the displacements due to the hygrometric variations when an initial moisture content of 20% and 50% is considered. In these calculations we did not consider interface

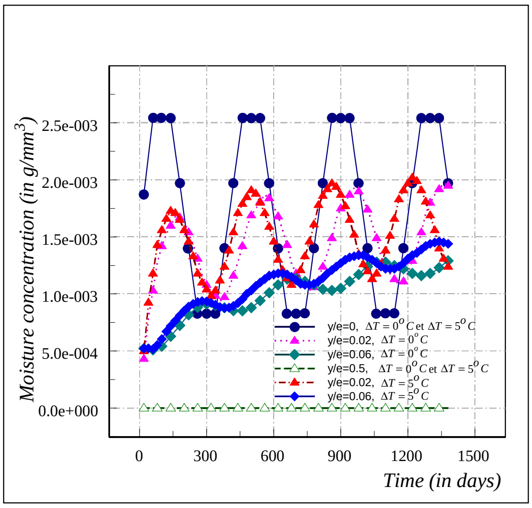


Figure 14: *Comparison of the moisture concentration for $\Delta T = 0^0C$ and $\Delta T = 5^0C$ for a point with coordinates x/length=1.0, y/width=1.0. An initial moisture content 0f 20% was considered.*

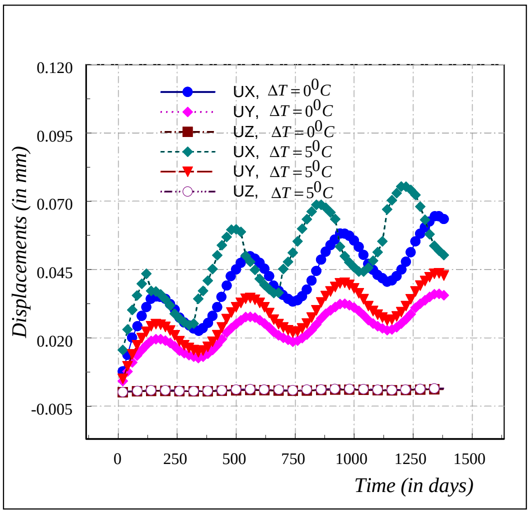


Figure 15: *Comparison of the displacements for $\Delta T = 0^0C$ and $\Delta T = 5^0C$ for a point with coordinates x/length=1.0, y/width=1.0 and z/thickness=0.0.*

diffusivity and interfacial debonding. The materials used in the simulations are the same ones used before (Table 1).

Figure 16 and Figure 17 present the total displacement in the wheel obtained after 1200 days of exposure to the imposed humidity cycle. A maximum displacement of 273μm and 359μm was found at point MX for an initial moisture content of 20% and 50% respectively. However these results must be carefully analyzed in time. The 20% initial moisture concentration corresponds to a case where the structure has an initial concentration lower than the minimum value of the imposed cycle. In this case, we observe a monotonic increase of the average displacement value towards saturation (simulated in a point close to MX, $r = r_{max}$ $\theta = 90^o$). A rate of a few $\mu m/year$ was found for the first four years studied and $\sim$ 76 μm pic to pic fluctuations around the mean value reflect the periodicity and the sinusoidal-like shape of the imposed humidity cycle. In the case of 50% initial moisture content, the structure already attained the saturation plateau for the average displacement under this humidity cycle. Only the periodic fluctuations are present with a pic to pic amplitude of $\sim$ 67 μm. The average saturation value for the displacement of the point we studied, is $\sim$ 315 μm, already attained in the 50% initial moisture content case while for the 20% case this average is still at $\sim$ 230 μm after 4 years.

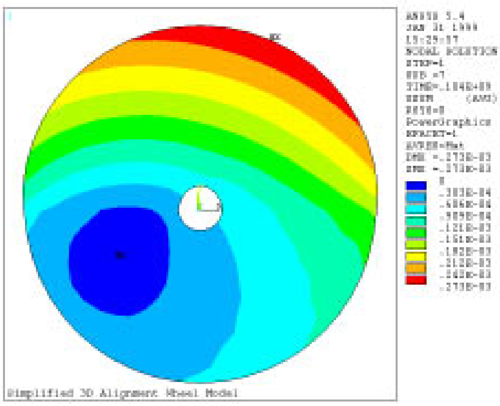


Figure 16: *Total displacement [m] for an initial moisture content of 20% after 1200 days.*

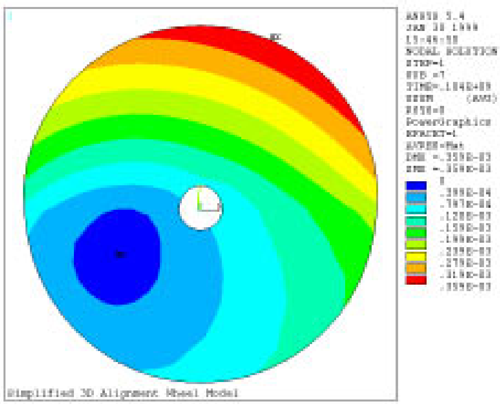


Figure 17: *Total displacement [m] for an initial moisture content of 50% after 1200 days.*

6 Conclusions

By focusing our attention into the dimensional variations we can confirm the deleterious effect that the environmental conditions may have on the long time scale behavior of CFRP structures. Factors such as debonding, property degradation and hygro-thermal coupling were included in the *Interfacial Diffusion* model and were able to validate the use of commercial finite element code in performing dimensional analysis under the influence of humidity variations. The results obtained for this model and for the simulations are in good agreement with experimental data.

One of the major problems of high stable structures is not the static deflections in itself but the dynamic ones. We showed how temperature and humidity cycles can influence the dimensional properties and moisture content of a CFRP plate and a real structure of CFRP/aluminum honeycomb sandwich. Two orders of magnitude between the values of the static and of the hygrometric analysis were observed in our case. Humidity cycles alone can have a dramatic influence on the dimension stability of the structures. In our case, the average displacement is attained after many one year cycles, then only the cyclic variations remain. However, when coupled to temperature variations, this time scale can be substancialy reduced. In the case studied the requirements concerning the displacements were not fullfiled in the long time range, however a better performance is expected after optimizing the choice of the fiber, the resin and the lay-up.

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