NUMERICAL PREDICTION OF THE RESIDUAL STRESSES CONSECUTIVE TO THE INTEGRATION OF SENSING DEVICES IN COMPOSITE STRUCTURES AND OF THEIR IMPACT ON THE IN-SERVICE RESPONSE

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Abstract
Sensing devices to monitor the condition and health of structures need to gather information as close as possible to critical locations. In composite structures, they need to be integrated in or on composite structures and must withstand the same conditions as the structure and may locally modify the behavior of the part. This paper will present the simulations made in order to study the integration of credit-card sized monitoring systems in the frame of the FP7 project TRIADE.

Curing simulations of the adhesive were performed based on the physical properties of the resin or the adhesive as well as the curing cycle of the material to predict the residual stress field. Results show relatively low stress build up after the integration of the component, but that could change the structural behavior and impact the integrity and thus premature failure of the structure.

1 Introduction
1.1 The "Smart Tag" concept
Remote sensing is critical to be able to assess the structural health aircraft or helicopter parts in flight and be able to monitor any operation outside of the designed flight envelope and record external parameters (temperature, pressure,…) or structural behavior (strain, acoustic emission,…)

In the TRIADE European FP7 project, "Smart Tags" are developed to be able to monitor composite structures using ultra low power components running off a rechargeable battery, all fitting inside an area smaller than a credit card and no thicker than 4 millimeters. Integration of such tags is of prime importance to be able to limit their impact on the structural behavior while allowing monitoring critical structural areas. This is why part of the effort put in to developing and building these innovative "tags" was dedicated to finite element analysis and experimental validation of the integration process.

1.2 The TRIADE project

The TRIADE project involves 13 different partners from across Europe active in fields such as small high performance batteries, electronics and SOI technologies, neural network processing but also partners such as EADS, Eurocopter and Dassault that will be "end users", interested in using the developed technology.

The 45-month project will result in the manufacturing and testing of 10 "Smart Tags" on different target applications. A TRL level of 4 or 5 should be reached within the timeframe of the project, but work remains to miniaturize, improve processing and further test according to standards the sensor and the full assembled tag.

1.3 Integration of "Smart Tags"

The "Smart Tags" can be integrated on structures in different configurations including simply fastening the PCB board to a structure, but also of greater interest is the bonding of the Smartag to the composite structure or even placing the Smartag between composite plies.

Figure 1. Possible configurations for the integration of Smart tags on the composite structure

In Figure 1, the two studied configurations are pictured showing what interfaces are used. In the first configuration where the tag is placed on the structure, a two part epoxy adhesive is used to form a low temperature curing bond. When the tag is placed in the structure, for feasibility reasons, we currently study the case where the part is first cured without the tag and the tag is later added, gaps are filled with resin and layers of glass fibers are placed over the tag to allow RFID transmissions (current technology does not allow transmission through the carbon fibers).

Hysol EA9323 adhesive resin is used in the case of bonding, while RTM6 resin is added to fill gaps in the case where the tag is integrated.

2 Curing simulations

2.1 Hypotheses and principles

The curing simulations performed aim at predicting any distortions of the assembly and, more important, the stress build up they may lead to. There are several factors leading to distortion, the most important of which are the chemical shrinkage, the mismatch of coefficients of thermal expansion (CTE) and the partly irreversible thermal expansion of the resin due to the significant CTE variations during the cure.

To simplify the number of material parameters in the model and still be able to take into account the different properties of the resin as it cures, an approach using three material states is used: a liquid state where stiffness is set to a very low value, a rubbery state when the resin is near the transition temperature (Tg) and internal stresses can be relaxed and finally a glassy state.

The curing properties of the EA9323 epoxy adhesive are described through the two following equations that define respectively the relationship between the transition temperature and the degree of cure (1), and the differential equation of the curing kinetic model (2):

$$T_g(°C) = \ 113\,X - 23 \tag{1}$$

$$\frac{dX}{dt}\,(s^{-1}) = 4.61\;10^4\;e^{-\frac{4.66\;10^4}{8.3145\,T}}\,X^{0.5}\,(X_{max} - X)^{1.12} \tag{2}$$

These parameters were taken from an experimental campaign including DSC analysis at fixed temperature and fixed heat ramp, chemical shrinkage measurements, thermal expansion and specific heat measurements. The values used for the mechanical and thermal properties of the Hysol EA9323 adhesive are the following:

Property	**Glassy state**	**Rubbery state**
ρ [kg/m³]	1090	-
E [MPa]	2380	750
υ [-]	0.36	-
G [MPa]	875	120
ε_{ch}	0.018	0.018
α	$5.0\;10^{-5}$	-
k [W/m.K]	0.22	-
c_p (25°C)	1.47	-
c_p (90°C)	1.9	-

For the RTM6 resin, values found in literature [2], [3], were used as first input to calculate the cure kinetics and thus evaluate the stress field near the Smart tag.

2.2 Finite element model

The model built for the finite element simulations was built based on the dimensions of the Smart tag tested in the frame of the project. It has an added thickness (4.4mm total) to the dimensions originally planned due to time and design constraints, but is representative in area to the final design. The adhesive layer thickness used was of 0.2mm for the first configuration shown in Figure 2 and for the embedded configuration, a top layer of 0.6mm of glass fiber was used as well as a gap of 1mm filled with resin around the tag.

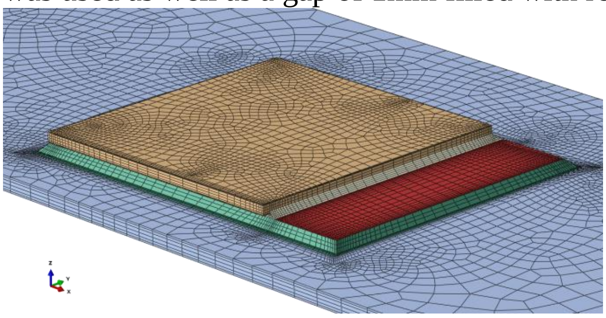

Figure 2. Smart tag model bonded on the surface indicating the different materials making up the assembly

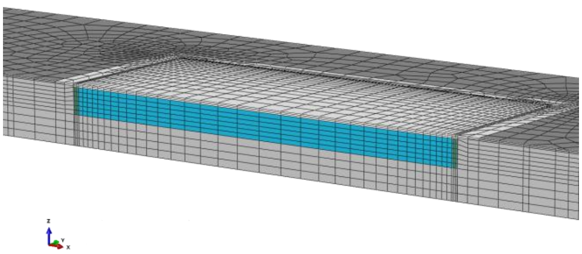

Figure 3. Embedded Smartag model showing the added GFRP plies added on top of the component

User subroutines (UMATs) are introduced in the Abaqus model to include the different materials behavior equations related to the curing process. Temperature is considered constant through the thickness, which can be seen as valid comparing the thickness of the part to the length of the panel (400mm).

In the current simulations, curing of the GFRP plies was not included in the model, but could be using two different cure kinetics equations and adding a state variable to elements that would allow differentiating the two materials.

2.3 Curing simulation results

The specified cure cycle for the Hysol EA9323 is of one hour at 82°C. A standard heating rate of 1°C per minute was used and the cooling stage lasts 25 minutes. A time step of 60 seconds is used, giving to a total of 147 time steps. The temperature, cure rate and cure percentage history of the adhesive layer is plotted in Figure 4.

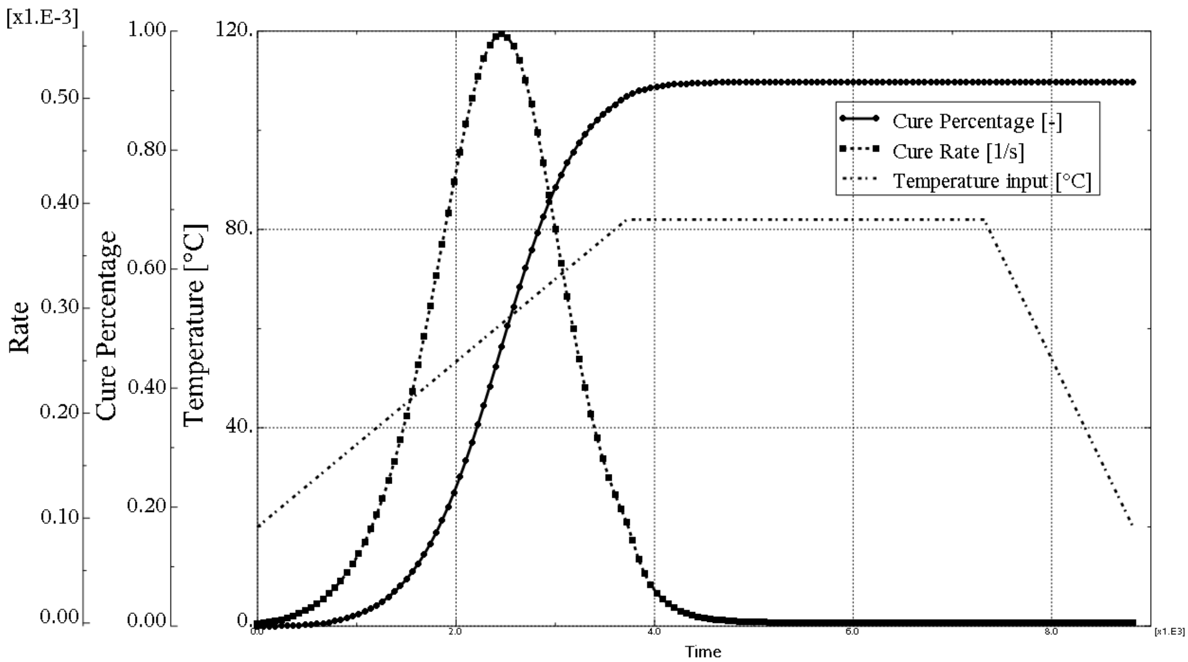

Figure 4. Temperature, cure rate and cure percentage history in the Hysol EA9323 adhesive

The polymerization reaction of the resin starts quite rapidly as a cure rate of 50% is reached when the temperature is still only at 60°C. The reaction continues for about 15 minutes once the maximum temperature of 82°C is reached, but due to the relatively small size of the specimen and surface covered by the Smart tag, most of the second half of the curing cycle does not increase the cure percentage of in the adhesive.

At the end of the cure cycle, the resin has reached a polymerization ratio of 91%. This is in relation with the experimental data that was measured on resin test samples where the DSC measurements made on the adhesive indicated that the enthalpy of reaction of an isothermal test at 120°C was higher than that of a test done at 80°C. This should be confirmed in a more complete and extended experimental campaign.

In both configurations, the curing process induces distortions in the structure near the Smart tag. Deviations in terms of displacements perpendicular to the surface of the panel are of very small magnitude in the order of hundredths of millimeters. As the resin has a low modulus, it will create a “soft” interface limiting the impact on the global static behavior of the structure. Below, we illustrate the displacement field in both configurations. In the first, the plate was clamped on both edges, leading to bending at the center of the tag, while in the second configuration; the plate was clamped at one end. In this case, integrating the tag creates a bending moment that leads to a maximum deflection at the opposite tip of the panel.

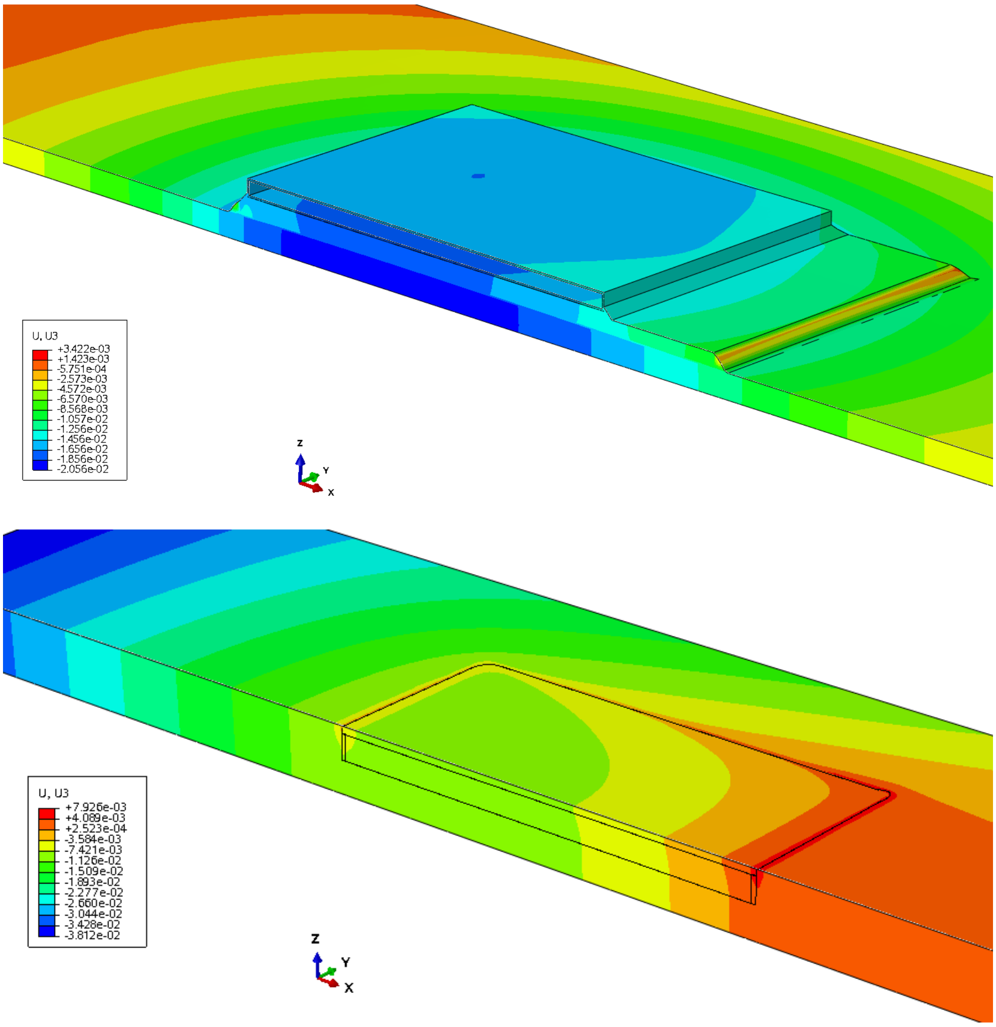

Figure 5. Displacement field in the Z direction after the cooling phase of the curing cycle

2.3 Post-cure stresses

After the cooling down phase, residual stress will be mostly localized near different interfaces between the different parts of the assembly. As the resin has a tendency to expand during the heating up phase (in a liquid state), will contract over the whole curing phase, and finally will shrink some more as the temperature decreases (partly in a glassy state), stresses will accumulated due to this non reversible process. In Figure 6, we can observe that higher stress levels are reached at the corners of the different components of the Smart tag and in particular at the interface between the battery (located on the top) and the PCB board (just below the battery). The antenna, at the right side of the tag does not show high levels of stress as it is embedded in a soft material.

The stress on the perimeter of the adhesive interface is quite homogeneous. A smooth drop off was chosen to improve the transfer of loads on the edges where it is more critical. According to simulations the stress in the adhesive reaches around 10 MPa after curing.

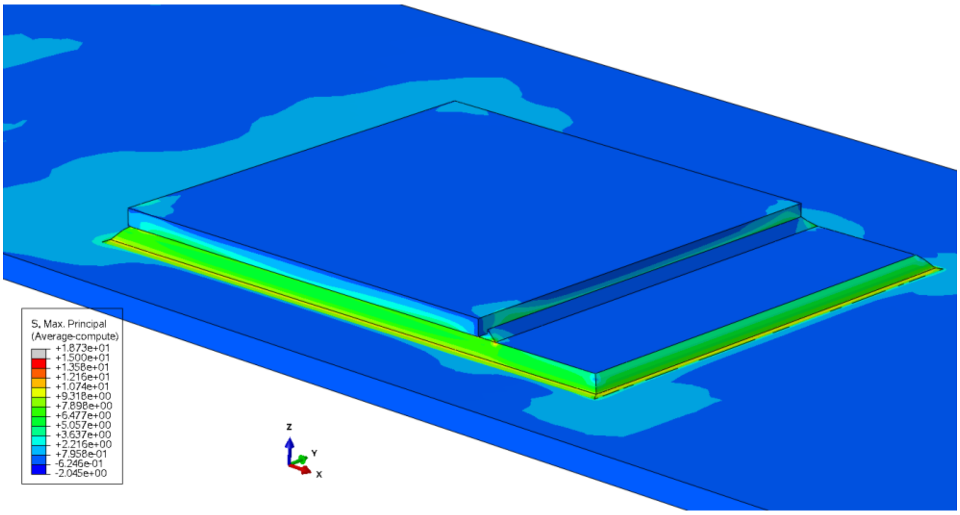

Figure 6. Maximum principal stress in the adhesive interface, smart tag and composite panel after cool-down

Figure 7 illustrates the stress on the surface of the CFRP panel. The stress levels found here are nowhere near critical values. This shows that the CFRP part will probably not be affected directly in terms of its structural integrity, but what may become a problem is the added mass of the sensor. Simulations and experimental modal identifications showed that the added mass of 20 grams from the Smart tag will create a shift of 6Hz on the first bending mode and 10Hz on the second bending mode and increases the amplitude of vibrations under the tag by a factor of 2 for a given base vibration input on the third mode of vibration.

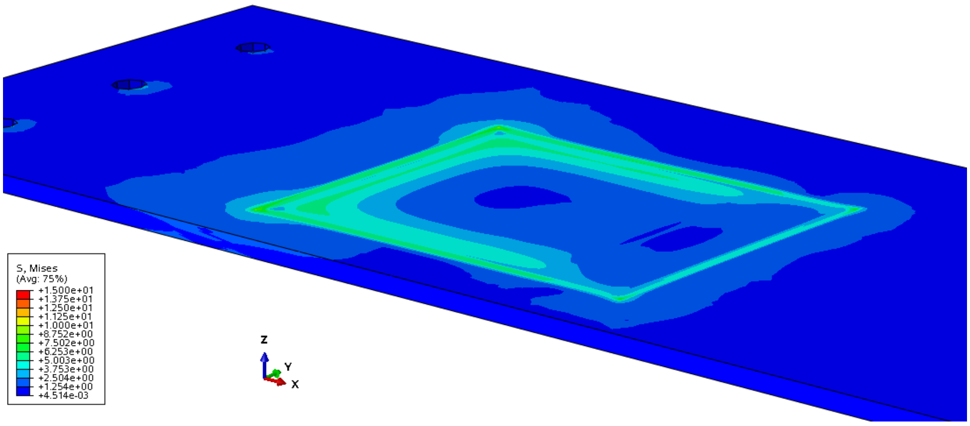

Figure 7. Maximum principal stress on the CFRP panel near the location of the Smart tag

In the embedded configuration, the added mass is a more complex problem. In the Smart tag can be integrated in a non-critical area, the added mass could be minimized by replacing part of the composite structure with the Smart tag, but usually, the Smart tag will monitor critical areas, and it will be important to eventually reinforce the structure leading to additional mass. The effect of this still has to be quantified.

In terms of stresses, the principal stresses will act mostly in compression as the resin will be "trapped" between the Smart tag and the rest of the composite structure as depicted in Figure 8. Although not currently included in the model, the structural integrity of the interface between the glass fiber window and the carbon fiber structure will also have to be verified as tested to make sure it will withstand the bending forces that can be applied on the composite part.

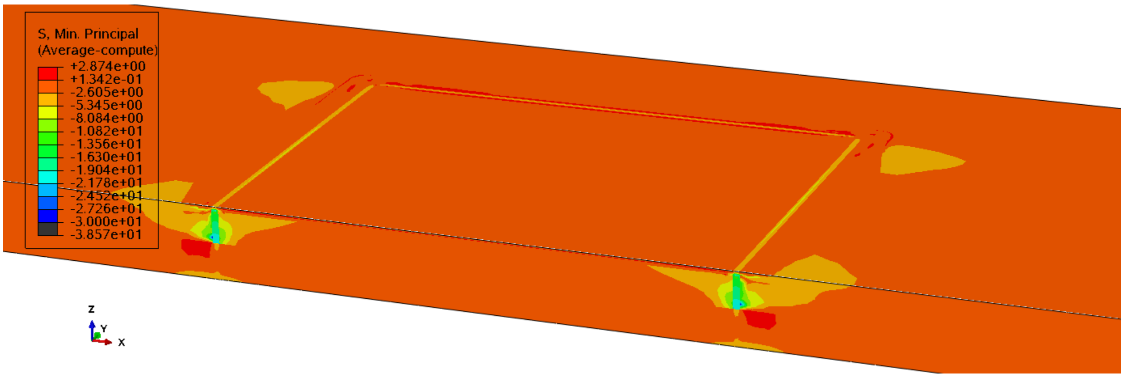

Figure 8. Principal stresses in compression with the Smart tag embedded in the structure

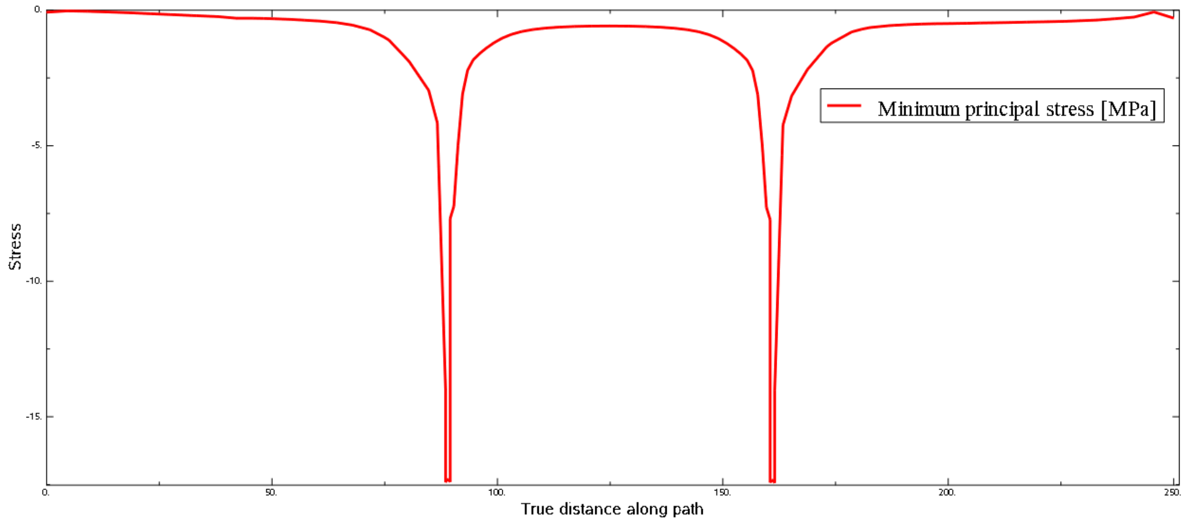

Figure 9. Principal stresses along the x-direction path at mid-thickness

Figure 9 shows the evolution of the stress level along the X-axis cutting through the resin and Smart tag. Stress in the tag is relatively low as well as in the carbon fiber plies, but further investigation and testing must be done on this configuration to better understand the critical aspects of integrating large sensors in structures.

3 Conclusions

This paper presented part of the work done in the frame of the TRIADE project to study the impact the integration process may have on the structure and sensors. Limiting the risks of integrating new components in structures will help implementing new remote sensors in critical structural parts such as aircraft fuselage and wings or helicopter blades and tail beam. The curing simulations performed allowed to show how the structure but also other interfaces might be affected and lead to potential structural problems. Further work experimental validation and higher fidelity simulation work will still have to be performed to fully predict the impact these integration processes will have.

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References
[1] Karkanas, P. I. Partridge, I. K. Cure Modeling and Monitoring of Epoxy/Amine Resin Systems. Part I: Cure Kinetics Modeling. *Journal of Applied Polymer Science*, 77, pp. 1419-1431 (2000).
[2] Skordos, A. A. Partridge, I. K. Cure Kinetics Modeling of Epoxy Resins Using a Non-Parametric Numerical Procedure. *Polymer Engineering and Science,* **41**, pp. 793-805 (2001)