Virtual testing activities for the development of a hybrid thermoplastic composite material for the NHYTE project

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Abstract. Designing composite structures with a good level of confidence and accuracy requires access to allowables values. The allowables generation is extremely time and cost consuming. In fact, various layups, experimental tests and environmental conditions have to be taken into account for each material to be characterized. Moreover, each test configuration needs many repetitions to obtain a statistical evaluation of the mechanical property. A robust alternative to reduce the experimental time and costs is the use of virtual allowables calculated and predicted thanks to advanced multiscale simulations. This paper deals with the activities of virtual testing carried out in the European NHYTE Project for the development and characterization of a hybrid thermoplastic composite material for the aerospace sector. The main aim has been to reduce tests and risk associated with the use of the hybrid composite in aerospace structures. This can be achieved by lowering the probability of failure of primary structures through the use of A-basis or B-basis strength allowables as design values. For this purpose, coupons of the hybrid thermoplastic composite have been accurately analysed using virtual tests. Starting from a micromechanics approach and taking into account the different constituents (PEEK matrix, PEI films and fibre reinforcement), a material model has been implemented; then it has been propagated to different scales until the element level. For virtual testing to be useful in the certification process, this numerical model has been validated by a synergic approach, correlating the simulation results with the experimental data carried out by Applus+ Laboratory. At the end, it has been possible to demonstrate that the resulting models are an excellent tool to speed up the certification process for complex structures, as required in the Aeronautical industry.

1. Introduction
This paper deals with the activities of virtual testing carried out in the European project NHYTE (New Hybrid Thermoplastic Composite Aerostructures manufactured by Out of Autoclave Continuous Automated Technologies) for the development of a hybrid thermoplastic composite material in the aerospace sector. As partners of the project, CETMA and the University of Patras have carried out numerical simulations and the comparative testing phase by means of CAE software, supporting the experimental material characterization carried out by the partner Applus. The aim of the numerical activities has been to reduce the number of real tests and the risks associated with the use of the hybrid
composite in aerospace structures. Virtual Testing activity completes the material characterization based on the experimental results and allows to investigate quickly different configurations of laminate. The material analysed in the project is based on a commercial PEEK-Carbon Fibre Prepreg with the addition of amorphous Polyetherimide (PEI) films, in order to reduce the weight and, consequently, the fuel consumptions of an aircraft, as well as manufacturing and operational costs.

2. Description of hybrid composite materials
The configuration of the representative hybrid single ply, as reference for all the laminates, is reported in Figure 1. The thicknesses of materials have been defined for a technological reason as their weldability; in detail, the unidirectional Carbon Peek ply is 0.14mm thick, instead of the two external layers of PEI that are 0.0508mm thick each one. The main mechanical characteristics of materials are summarized in Table 1.

![Figure 1. Detailed view of the hybrid single ply](image)

### Table 1. Mechanical characteristics of the constituent ply materials

| Constituent Material | E<sub>Young</sub>[MPa] | Density [t/mm³] | Poisson | Strength [MPa] | Tensile failure strain |
|----------------------|------------------------|----------------|---------|----------------|-----------------------|
| APC-2 PEEK matrix    | 3600                   | 1.32e-09       | 0.2     | 100            | 0.5                   |
| Unidir. prepreg      | 228000                 | 1.7e-09        | 0.28    | 3447           | 0.015                 |
| PEI Ultem resin 1000 Matrix | 3200-3500 | 1.27e-09       | 0.3-0.36 | 85-110         | 0.6                   |

3. Description of the numerical approach
Allowables are the fundamental material properties used for composite structural design. They consist in statistically derived values representative of the behaviour of a composite material system in a given structural context. In particular, they quantify the strength of the material as characterized by various coupon tests according to dedicated standard methods.

For the prediction of the virtual allowables of the hybrid laminate configurations, the software Digimat-VA (Virtual Allowables) has been used, an integrative solution that combines multiscale modelling, failure modelling, non-linear finite element analysis, stochastic methods and post-processing of the simulations of composite coupons [1]. Starting from a micromechanics approach and taking into account the mechanical characteristics of the single constituents (PEEK matrix, PEI films and carbon fibres), a material model has been implemented; then it has been propagated to different scales until the element level.

In particular, in the first step, the ply properties have been calculated with the numerical code Digimat MF (Mean-Field homogenization) collecting and calibrating the mechanical properties of the fibres and the two thermoplastic matrices (PEEK and PEI) [1], [2], [3]. Within Digimat MF the failure criteria have been also defined for the carbon prepreg and the PEI layer together with their stress-strain curves [4],[5]. These numerical models have been defined in order to be imported in Digimat VA.

The Engineering constants, preliminary calculated and calibrated with Digimat MF for a laminate with 60% fibre volume fraction, are compared with Laminate data sheet with 60% fibre from Solvay [2], [6],[7]. The difference between calculation and experimental data is less than 3%.
3.1. Input Data for the virtual test in Digimat

The workflow in Digimat VA consists of three key steps as shown in Figure 2.

- Test Matrix (including material, layup, testing and boundary condition definition);
- Simulation;
- Allowables.

![Image](image.png)

**Figure 2.** Digimat Virtual testing - Steps for Allowables calculation

In the materials definitions, all the material models defined in Digimat MF are imported and completed with additional information as, for example, the shear stress and the strain at break.

For the layup definition, the four hybrid composite configurations analysed are listed below with the number of plies and the total thickness:

- **Laminate 3** [90,45,0,-45]s consisting of **24 plies**: 8 plies of Carbon PEEK, 16 plies of PEI; total thickness = **1.93mm**;
- **Laminate 4** [45,-45,0,90,45,-45]s consisting of **36 plies**: 12 plies of Carbon PEEK, 24 plies of PEI; total thickness = **2.89mm**;
- **Laminate 3s (IsoUPat)** [90,45,0,-45]2s consisting of **48 plies**: 16 plies of Carbon PEEK, 32 plies of PEI; total thickness = **3.86mm**;
- **Laminate Unidirectional** [0°]15s consisting of **30 plies**: 10 plies of Carbon PEEK, 20 plies of PEI; total thickness = **2.41mm**.

Tensile and compression tests have been selected for the configurations according to the ASTM standards D3039 and D6641 as indicates in Figure 3 with the corresponding finite element models used for the virtual testing. The conditions of temperature and humidity have been: 20°C and 0% of relative humidity.

![Image](image.png)

**Figure 3.** Summary of material layup and tests carried out for the virtual activity
The test matrix is completed with the variability of the inputs, as the mechanical properties of constituents, the manufacturing process of the composite material and the experimental testing. The input values are summarized in Figure 4, Figure 5 and Figure 6.

![Figure 4. Variability of constituents, process and experimental testing](image)

The values of material variability adopted are listed in Figure 5.

| ACTIVE | PARAMETER                                      | VALUE | UNITS |
|--------|-----------------------------------------------|-------|-------|
|        | Constituent variability (coefficients of variation) |       |       |
| ☑      | Matrix tensile young’s modulus                | 8     | %     |
| ☑      | Matrix compressive young’s modulus            | 8     | %     |
| ☑      | Matrix tensile strength                       | 8     | %     |
| ☑      | Matrix compressive strength                   | 8     | %     |
| ☑      | Matrix shear strength                         | 8     | %     |
| ☑      | Fiber tensile axial Young’s modulus           | 5     | %     |
| ☑      | Fiber compressive axial Young’s modulus       | 5     | %     |
| ☑      | Fiber tensile strength                        | 3     | %     |
| ☑      | Fiber compressive strength                    | 3     | %     |

![Figure 5. Material variability](image)

The values of process and testing variability are listed in Figure 6.

- Process variability
  - Fiber volume fraction coefficient of variation: 3 %
  - Ply misalignment (aligned plies) standard deviation: 4 °
  - Ply misalignment (off-axis plies) standard deviation: 4 °

- Testing variability
  - Coupon misalignment standard deviation: 4 °

![Figure 6. Process and testing variability](image)
The definition of the Standard scenario of variability, according to the military handbook workflow [1] (MIL-HDBK), allows the calculation of the A-basis and B-basis values for strength, as defined below:

- A-Basis (T99) -> At least 99% of the population of material values is expected to or equal or exceed this tolerance (with 95% confidence).
- B-Basis (T90) -> At least 90% of the population of material values is expected to or equal or exceed this tolerance (with 95% confidence).

As reported in Figure 4, taking into account the batches of material, the panels and tests, the number of specimens to be tested for each layup is 18. Finally, the total number of tests generated for the 4 layups has been equal to 144; the finite element models of the tensile test and compression test have been created by Digimat VA with all the boundary conditions, ready to be submitted as 144 jobs.

3.2. Results of the virtual testing

At the end of the 144 simulations, global results such as stress-strain curves, stiffness and strength have been extracted and post-processed within Digimat VA. In particular, the diagram in Figure 7 summarizes the behaviour of composite with different layups in terms of strength after tensile (column on the right) and compression (column on the left) tests.

![Figure 7. Strength of all Laminate configurations](image)

Even if the unidirectional configuration has the higher values of strength, the investigation is focussed on the others layups designed to ensure a structural response in all the directions of loading. For this consideration, the Laminate 3 with 24 plies and a thickness of 1.93mm shows a promising behaviour in comparison with the Laminate 4 and Laminate 3s (IsoUPat) that have, on the contrary, higher thickness; as a matter of fact, Laminate 4 is realized with 36 plies, the total thickness is 2.89mm. Laminate 3s is realized with 48 plies having a total thickness of 3.86mm.

4. Comparison with experimental results

To evaluate the accuracy of the simulation results, a comparison with the experimental tests, provided by the project partner Applus, has been carried out.

In particular, tensile test values of Laminate 3 and Unidirectional, and compression test values of Laminate 3s have been used for the comparison as summarized in Table 2. As reported, the differences for strength are in the range of 2.8±3.4% and the differences for stiffness are in the range of 0.87±4.3%. In both cases, the differences are representative for this material and within the range of appropriateness.
The stress-strain comparison for Laminate 3 is reported in Figure 8. The experimental curves of the tensile tests (black solid lines) are laid on the 18 curves of the simulation results generated by the variability. The tested coupons show a linear stress–strain curve behaviour with slight non-linearity due to the matrix cracking and PEI layers failure during the tests. In addition, the stress-strain curves highlight the effect of the variability of all parameters on the material characterization. For Laminate 3, the mean strength is 410.81 [MPa] with a strain at failure of 0.0145.

![Figure 8. Laminate 3 – Numerical-experimental Stress-Strain curves comparison](image)
5. Calculation of Allowables
After the numerical-experimental comparison of the finite element model results for evaluating their accuracy, the allowables calculation assumes importance also because it takes into account all the variabilities. In particular, allowables quantify the strength of the material as characterized by coupons tests statistically representative of the real behaviour. Laminate 3 with 24 plies confirms its promising behaviour with the highest allowable: the B-basis value is 400 [MPa], as shown in Figure 9 with the red line. Excluding the unidirectional one, Laminate 4 and Laminate 3s (IsoUPat) have lower B-Basis allowables values, respectively 331[MPa] and 364[MPa]. In addition, these two configurations have higher thickness than Laminate 3.
Moreover, the evaluation of the coefficient of variability (CoV) evidences low level for Laminate 3 respect to all the other configurations with higher coefficients. In particular, Laminate 3 has a CoV of 3.4% while the values for all the other layups are in the range of 7.3÷15.3%.

6. Conclusions
Simulations and comparative activities have been carried out aimed at reducing the number of mechanical tests and verifying the capabilities of the numerical tools to match the real properties of material. In particular:

- 144 virtual tests carried out have allowed to analyse 4 different configurations of hybrid laminates, reducing the number of physical tests;
- 48h has been the calculation time for all these virtual tests, including pre-processing and post-processing. On the contrary, at least 1 week would have been necessary to analyse the same quantity of specimens with an experimental characterization;
- Excluding the unidirectional laminate, Laminate 3 has the maximum tensile allowable and strength values;
- The experimental results have permitted to evaluate the error in predicting the Allowables. The difference between numerical and experimental values in terms of strength and stiffness has been lower than 4%.

On the basis of this agreement, the developed numerical model is robust to support the mechanical properties investigation of additional configurations.

7. References
[1] Digimat User’s Manual 2019
[2] https://www.solvayultrapolymers.com/en/index.html
[3] https://www.sabic.com/en
[4] B. Zuanetti, N. Mutter and Ali P. Multi-rate and Multi-modal Characterization of an Advanced Polyetherimide: Ultem 1000, Materials Performance and Characterization ASTM V.3 1 2014.
[5] Polymer matrix composites materials properties vol. 2, Composite materials handbook, USA Department of defense handbook.

[6] Tserpes KI, Papanikos P, Kermanidis Th. A three-dimensional progressive damage model for bolted joints in composite laminates subjected to tensile loading. Fatigue & Fract Eng Mater Struct 2001;24:663e75.

[7] Wang D, Wen W. Three-dimensional progressive damage analysis of composite laminates containing a central hole subjected to compressive loading. In: Proceedings of 2012 International Conference on Mechanical Engineering and Material Science (MEMS 2012); 2012 [December, China].

Acknowledgements
Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723309.
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