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Virtual allowables approach for the design phase of a composite fuselage



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The development of new composite materials in the aerospace field has been limited due to high cost and time impacts against their promise of lightweighting advantages and optimization of tailored design space. Advancements in non-linear finite element analysis methods with a multiscale approach let virtual testing approach a new challenging scenario that can enhance physical testing.

As in other industrial sectors, evolution in the aerospace field is driven by economics, logistics and market expectations. With build rates rising to satisfy the demand, OEMs are looking for a way to increase production rates and avoid autoclave manufacturing without compromising quality.
This trend is even more relevant for very large-scale structures such as new-generation aircraft composite fuselages and wings that require in-depth knowledge of composite materials, processing and tooling.

Design and industrialization

As part of the Clean Sky 1 Joint Undertaking Initiative, the Italian aerospace tier-1 DEMA SpA, as a member of the Green Regional Aircraft platform, consolidated a strong background in the design and industrialization of integrated composite fuselages produced with a one-shot curing process. To take this expertise one step further, the company's engineering department is now designing a new contoured fuselage entirely produced by automatic fibre placement lamination (see Figure 1). This new concept will reduce assembly and inspection times while improving the quality of the manufactured product, speeding up the process and limiting the weight of the complex-shape structure.

Fig. 1: Contoured fuselage barrel

Fig. 2: Project phases

To design the fuselage in accordance with the new process and material, the engineers decided to use a virtual allowables numerical methodology supporting Phase 2 with Digimat, the material modelling software developed by e-Xstream engineering (see Figure 2).

Given the recent introduction of automatic fibre placement technology in the aerospace industry, the availability of materials in the form of tows (1/8'' to 1/4'' width) is limited in terms of resin, fibre and fibre areal weight. Once the material system for the specific application is established, an intermediate-modulus fibre is required to achieve the desired stiffness, stressing the need to have the corresponding design allowables.

Validated procedure

During the preliminary stage of the project, a Hexcel 8552 AS4 material in slit tape form with a 194g fibre areal weight (FAW) was selected as it was available in the European plant of the material vendor. The allowable data for the specific material system configuration were not available but a different combination of fibre and areal weight was found in the Advanced General Aviation Transport Experiment (AGATE) database. The chosen strategy was to validate the software predictions by comparing the available AGATE data against virtually obtained data. The validated procedure, up to minor numerical differences, was scaled-up to the desired material system, generating the required design allowables.

The Digimat platform provides various tools to manage the material architecture, from the description of micromechanical phases to the definition of macroscopic composite properties. The material data can be stored in an internal database, Digimat-MX, and exported to the main FE solvers to improve the structural predictions.

The VA (Virtual Allowables) module of Digimat was used, selecting the AS4 fibre and 8552 epoxy resin. A fibre areal

Fig. 3: Digimat-VA shell

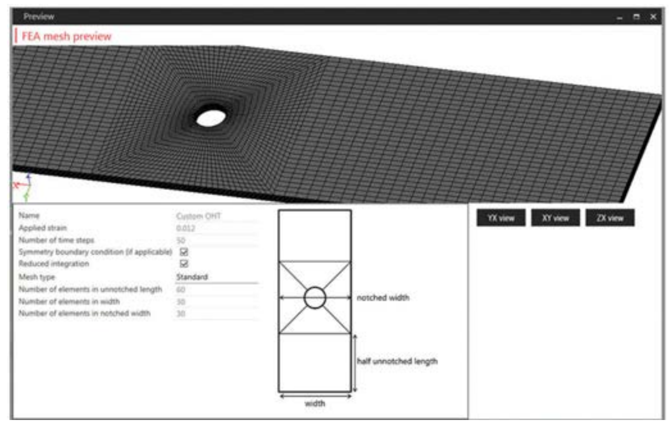

Fig. 4: Virtual specimen

weight and resin content (RC) from the AGATE available material database were used (190gsm and 35% RC).

Typical tests to determine the material behaviour, such as unnotched and open-hole tension/compression tests, were simulated based on specific test specifications (ASTM D3039, D6641, D5766 and D6484). Three typical lay-ups (quasi-isotropic, hard and soft) and three environmental conditions (cold dry, room dry and elevated wet) allowed to create an allowables database to characterize the material and size the structure (see Figure 3).

Strength and stiffness

Digimat-VA can manage a high number of "virtual" tests represented through finite element models in conjunction with Digimat calibrated material models (see Figure 4). A non-linear static analysis was carried out to determine the failure load of each specimen under different types of loads, environmental conditions and lay-ups sequences. The results were examined and post-processed to obtain the strength and stiffness values to be validated against the AGATE material database.

The analysis showed a good comparison in terms of strength and stiffness (error within 10% for almost every value, a few of them within 20%) for lay-ups at room temperature in the

TEST	Properties	UNIT	Quasi Isotropic 25/50/25			"Soft" 10/80/10			"Hard" 50/40/10		
@RTD			NCAMP	DIGIMAT	Error	NCAMP	DIGIMAT	Error	NCAMP	DIGIMAT	Error
OHT	Strength	MPa	328	360	9.6%	270	249	-7.8%	473	558	18.1%
OHC	Strength	MPa	326	328	0.6%	280	319	13.7%	433	425	-1.8%
UNT	Strength	MPa	611	631	3.3%	439	408	-7.1%	1050	1069	1.7%
	Modulus	MPa	47988	47549	-0.9%	31233	31075	-0.5%	72740	72510	-0.3%
UNC	Strength	MPa	561	519	-7.4%	430	356	-17.2%	904	777	-14.0%
	Modulus	MPa	44333	41192	-7.1%	29647	27751	-6.4%	66397	61938	-6.7%

Fig. 5: Virtual allowable comparison

dry condition (see Figure 5). The effect of environmental conditions (ETW and CTD) in the numerical simulation increased discrepancies with the AGATE database (up to 30% for some values), requiring further investigation to detect the root cause. First, a sensitivity analysis of the mesh sizing and integration time step was carried out and the results showed that the latter improved the correlation. The greatest effect found was related to the formulation in the AGATE specification about the tensile and compression test of the laminate, called UNT0. The strength showed an increasing value when passing from RTD to ETW, while the properties obtained in Digimat showed the opposite behaviour (as LT test formulation), with strength values reducing with increasing temperature and moisture.

Material and process

With the Digimat-VA module, the variability of the material and the composite manufacturing process according to the CMH17 recommendations can be introduced. For each of the material characteristics (fibre tensile axial Young's modulus, fibre tensile strength, matrix tensile Young's modulus, fibre volume fraction, fibre alignment, etc.), a covariance value was introduced and the effect of such variabilities on the composite strength could be analyzed, paving the way for the generation of b-basis values.

Once the numerical difference between the Digimat analysis and experimental literature values was established, the prediction for the material selected for the AFT fuselage contoured barrel was carried out. The new fibre areal weight (194gsm) and resin content (34%) values were reflected in a different fibre volume fraction (0.58 vs. 0.57). This resulted in an increased strength and stiffness (about 2%) for all conditions and lay-ups due to the laminate's higher fibre content with better performance than the resin.

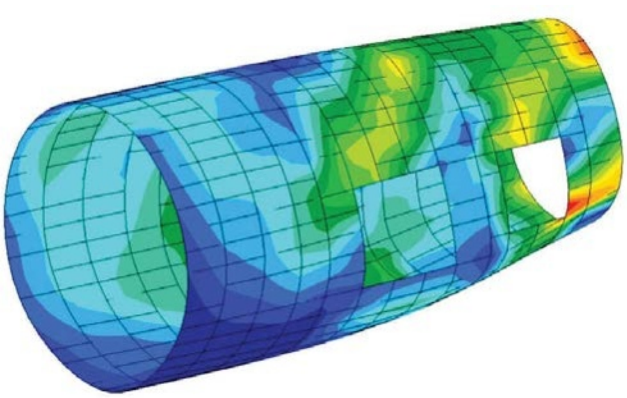

Fig. 6: Failure index map

The Digimat-VA module encouraged engineers to make a simulation for the low fibre areal weight material that can be adopted in regions/areas where reduced thickness is allowed, while keeping the minimum number of plies required for a symmetric and balanced lay-up. The material available from the composite manufacturer has a 130gsm FAW and 35% RC with a 0.126mm resulting thickness (vs. 0.185mm). The strength and stiffness evaluation showed little variation (within 1%) with respect to the reference material (190gsm FAW and 35% RC) as expected since the material properties were expressed in force per area (MPa).
The developed allowable database was used for the preliminary sizing of the aft fuselage contoured barrel to establish the thickness (number of plies) and shapes of the stringers and skin (see Figure 6).

The failure index map highlighted the opportunity to redesign the crown stringers with a 130gsm AS4/8552 material (instead of 194gsm), saving up to 3% weight.
In conclusion, Digimat-VA proved to be a powerful tool that avoided an expensive test campaign to obtain allowables for a project requiring a short time and limited budget to identify the material suitable for the structure. Moreover, a potential weight saving was clearly established with the design provided, supporting a fundamental decision for the continuation of the programme.

The Digimat-VA results validation will be finalized by means of a compression test on sub-component items.ch field, Dr Hamid Saeedipour is currently leading three research projects on in-situ healing of internal and external damages in composite aerostructures, biocomposite green structures, and nanomagnetic particles for composite repair. He produced 12 publications and presentations on the outcomes of his composite repair research. □

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