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VIRTUAL TESTING OF THERMOPLASTIC COMPOSITES: TOWARDS A HYBRID SIMULATION-PHYSICAL TESTING PYRAMID

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Abstract
This paper summarizes the implementation of a Virtual Testing methodology in an industrial environment to predict the mechanical behaviour of composite material through the different scales of the conventional physical testing pyramid. A robust Virtual Test Lab allows for the generation of virtual allowables, while advanced interface models ensure accurate simulation of critical interfaces up to structural level. Hybrid simulation-physical testing approaches, that can support both conventional rapid sizing and high-fidelity analysis methods, have been applied during the development of a thermoplastic orthogrid fuselage shell and will be coupled with the manufacturing process though a virtual process chain for the development of a thermoplastic fuselage for the next generation aircraft.

1. Introduction

With the recent growth in available computational power and advanced modelling techniques, the use of efficient simulation tools has the potential to enable economic advantages for the aerospace industry [1]. However, the increased application of fibre reinforced composite materials in aircraft design has presented new challenges to aeronautical engineers due to the highly complex failure mechanisms and uncertainties introduced by the manufacturing process. This in combination with certification requirements to justify the influence of damage, temperature and other environmental conditions makes full reliance on large scale numerical models unmanageable [2]. In order to mitigate this challenge it is decided to develop a hybrid simulation-physical testing strategy that can support both conventional rapid sizing and high-fidelity analysis methods.

Traditionally, at the lower end of the conventional testing pyramid, material behaviour is tested by means of coupons. These coupons form the basic building-blocks during the conventional design and certification approach of aircraft structures. However, availability of design allowables is generally limited early on in the design and the reliance on physical testing makes it difficult to achieve confidence in new structural concepts. This can be addressed by hybrid experimental and numerical approaches [3] that rely on a bottom-up approach in order to accurately predict the corresponding failure modes through the higher levels of the testing pyramid. Deployment of this strategy has already been proven successful for material selection of aircraft structures under extreme loading situations where understanding of the complex failure modes of composite materials are of high importance [4].

Higher up the testing pyramid, at structural detail and panel level, it is not computationally efficient to model the composite structure in full detail. At this scale the emphasis is at global structural behaviour, for example during (post)buckling and the performance of critical interfaces such as skin-stiffener connections are of high importance. Interface failure and delaminations are particularly important when dealing with composite structures or fastener-free designs, however commercial software codes have not been properly assessed under mixed-mode loading conditions [5] and are rather limited in providing sufficient insight in the fracture process.

This has led to the development of a Virtual Testing framework that is able to accurately predict the mechanical behaviour through the conventional testing pyramid while staying close to the aerospace test standards. For the development of this framework digital twins of the physical coupon test standards are developed. Following this approach allows for ease of validation and verification of the modelling strategy and provides insight in the difference between the different test standards and their (dis)advantages, including predicting difference in loading, gripping, machine misalignment and size effects caused by difference in specimen dimensions. This, combined with variation in material properties from the manufacturing process needs to be addressed as fundamental steps towards increased use of simulation in the design and certification of aircraft structures.

An additional benefit of this strategy is the ability to create a hybrid database of virtual and physical test allowables that enables input for conventional rapid sizing methods that can be applied at large structural scale and are traditionally based on empirical data. The predictive capability of legacy analytical methods can be challenged and improved and design charts supported by simulation can provide new insight in optimum designs while high-fidelity methods allow for evaluation of structural details that cannot be analysed with conventional methods and would normally require physical testing.

2. Modelling and simulation methodology

The Virtual Testing methodology applies a systematic strategy [3] to determine the mechanical behaviour of composite materials up to failure using numerical and experimental approaches in parallel. This approach takes into account the physical mechanisms of damage at the different length scales, so the influence of each contributing failure modes on the performance of the part can be taken into account rigorously. One additional advantage of this bottom-up approach is that changes in the properties at the lower scale can be easily incorporated to provide new predictions of the macroscopic behaviour at structural level.

2.1. Virtual Test Lab for coupon testing

The Virtual Test Lab [6], developed as part of the VIRTEST project, which is implemented in the finite element package Abaqus takes into account the physical mechanisms of damage at lamina level. The toolset relies on a ply-by-ply modelling approach based on mesh structuring, a cohesive-frictional penalty-based contact surface and advanced crack-band erosion techniques coupled with a sophisticated three-dimensional continuum damage model to accurately capture the appropriate failure modes.

Implementation at the industrial environment is achieved by modelling the coupons in an automated fashion by means of Python scripting. This ensures the use of correct modelling techniques by non-expert users and enables rapid generation of virtual allowables.

An extensive and rigorous validation of the overall approach is performed through testing the implemented methods such as the failure criteria and cohesive laws at the single element level for any given 3D stress, through benchmarking the approach against experimental data for several material

systems at the coupon level, demonstrating that the virtual testing laboratory is robust and can be reliably used in for composite materials screening, design and assist in certification activities.
Both the progressive failure mechanisms and the failure load have been predicted with high accuracy with respect to the results obtained experimentally for plain, open-hole, low-velocity impact and compression-after-impact tests. Figure 1 demonstrates the excellent prediction of failure modes for different coupons.

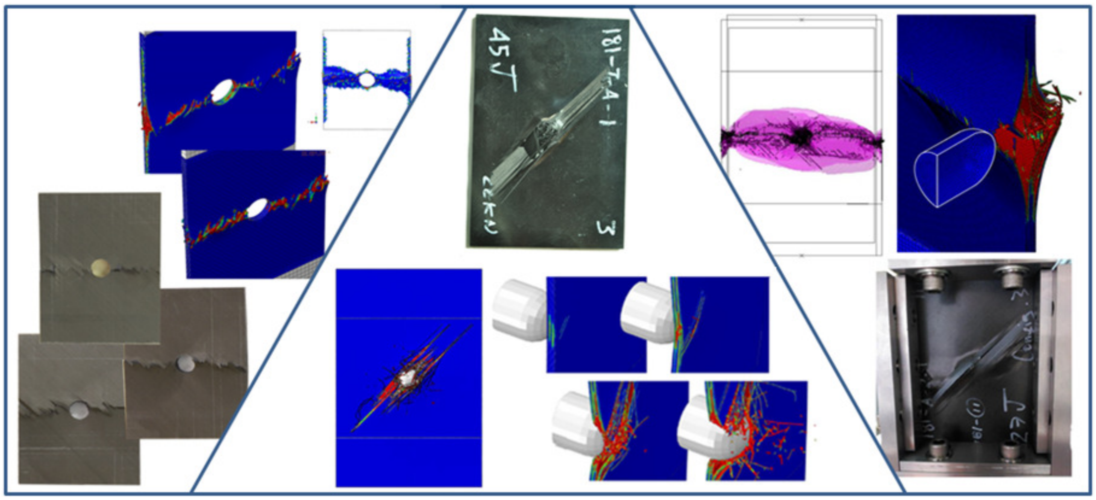

Figure 1. Virtual Coupon Testing, simulation versus test result.

The next step in the development of the Virtual Testing framework is taking into account the influence of the manufacturing process, this is especially important for thermoplastic materials as their processing conditions are of great importance for the ductility of the material. Besides that, out-of-autoclave manufacturing operations such as hot- or pressing forming can influence fibre directions and may also induce undesired wrinkles and waviness in the laminate. Furthermore, taking into account other effects of defects from the manufacturing process, damages, thermal history and stresses, the influence of temperature and environmental conditions all need to be addressed as fundamental steps towards increased use of simulation in the design and certification of aircraft structures.

2.2. Accurate simulation of interface failure up to structural level

A common analysis technique that is used to evaluate interfaces is the cohesive zone model. One of the drawbacks of these models is that very fine meshes are required to assure a reasonable number of elements in the cohesive zone. This makes the use of these models difficult, especially in large composite structures where the requirements of extremely fine meshes cannot be met. This has led to the development of engineering solutions such as [7] that solve the mesh size effects by reducing the interface strength while assuring the correct dissipation of fracture energy.

However, most of the existing formulations, even those implemented in commercial finite element codes, have not been properly assessed under mixed-mode loading conditions. Application of these models can lead to unconservative numerical results, especially in combination with inaccurate selection of model input parameters or engineering approaches that require modification of the interface strength. A comparison of the existing and new formulation [5], which guarantees correct dissipation of fracture energy under mix-mode loading by applying a mode-dependent penalty stiffness is shown in Figure 2.

The new formulation, extended to account for the effect of interface thickness [8], has been implemented to accurately simulate interface failure up to structural level. The method is implemented in the finite element software Abaqus for both standard and explicit by means of user-subroutines. Customized state variables, such as the ratio of dissipated energy, instantaneous and historical mixed-mode ratios, are used to provide more insight in the fracture process, which is generally not provided by commercial software.

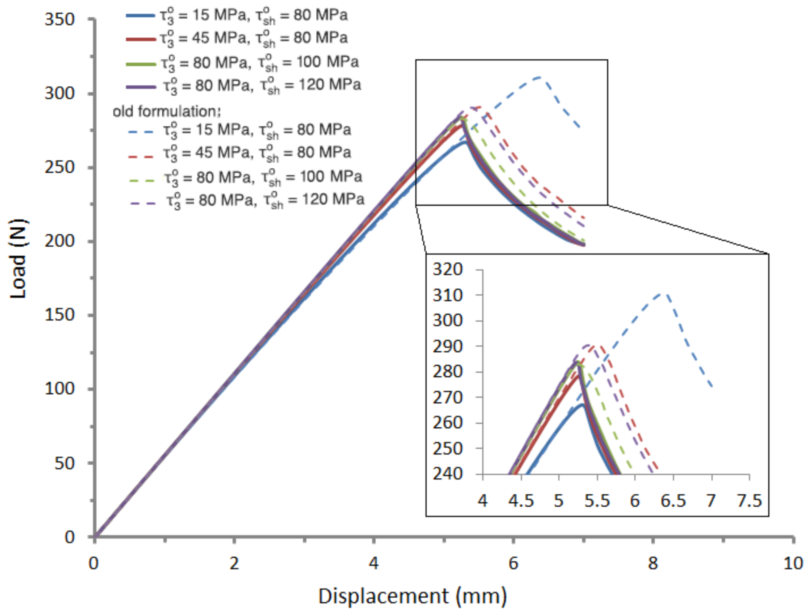

Figure 2. Effect or reducing interface strength under Mixed mode (50%) loading, comparison between old [9] versus new [5] formulation.

3. Application to new structural concepts for aircraft fuselages

3.1. Thermoplastic orthogrid fuselage shell

During the development of the TAPAS thermoplastic orthogrid fuselage shell [10] which features new thermoplastic materials and a fastener-free design, a hybrid simulation-physical testing approach was chosen to allow for an increased understanding of failure mechanisms and structural response through the different scales of the testing pyramid.

The orthogrid is manufactured of flat laminates which are placed in a mould and are co-consolidated to create a single part. This process is shown in Figure 3a. At the joints, special injection moulded Short-Fibre Reinforced Plastic (SFRP) fillers join the stiffener cap to the web and the web to the skin.
This new structural concept features advantages such as a minimum of stress concentrations at the stringer-frame intersection and omission of flanges at the joints of stringers and frames to the skin. On the other hand integrity at large delaminations in the faster free joint between skin and sub-structure requires special attention, although the fracture toughness of thermoplastic material is higher compared to thermoset composites.

Several finite element models were developed at different scales of the pyramid and correlated to physical tests. At the lowest scale, the SFRP material was characterized by means of dog bone specimen while taking into account different fibre orientations and the actual processing conditions.

Cyclic testing was performed to distinguish between softening of the material due to plasticity and damage. The Mori-Tanaka mean-field homogenization technique (M-T), which provides convenient and direct numerical equations for the micro-macro relation of ellipsoidal included matrix materials, in combination with resin plasticity and damage was implemented in an Abaqus subroutine. The prediction of the elastic properties as well as the failure behaviour, were compared with test data and showed good correlation. The M-T method also provided the tools to effectively study the influence of different constituents, fibre orientation, fibre aspect ratio and volume fractions to come up with the optimum compound design. A parametric non-linear finite element model was developed to create design charts that capture the effect of different filler geometry, skin layup and loading allowing for rapid sizing based on coarse shell-based finite element models, demonstrating the effectiveness of a hybrid simulation strategy.

At the structural element level, see Figure 3b, a short-column test specimen was designed by means of Virtual Testing to evaluate the strength of the interface under compression loading and buckling of the skin, while preventing global buckling of the specimen. Interface damages, similar to those observed after impact were applied in order to demonstrate ultimate load capability and fatigue tests were performed to show no detrimental growth of the interface damage during the aircraft life. The aim of this strategy is to verify and validate the analysis methods at the lower scale and predict the effect of damage at the larger scale under various loading conditions, as physical testing every possible configuration is too expensive.

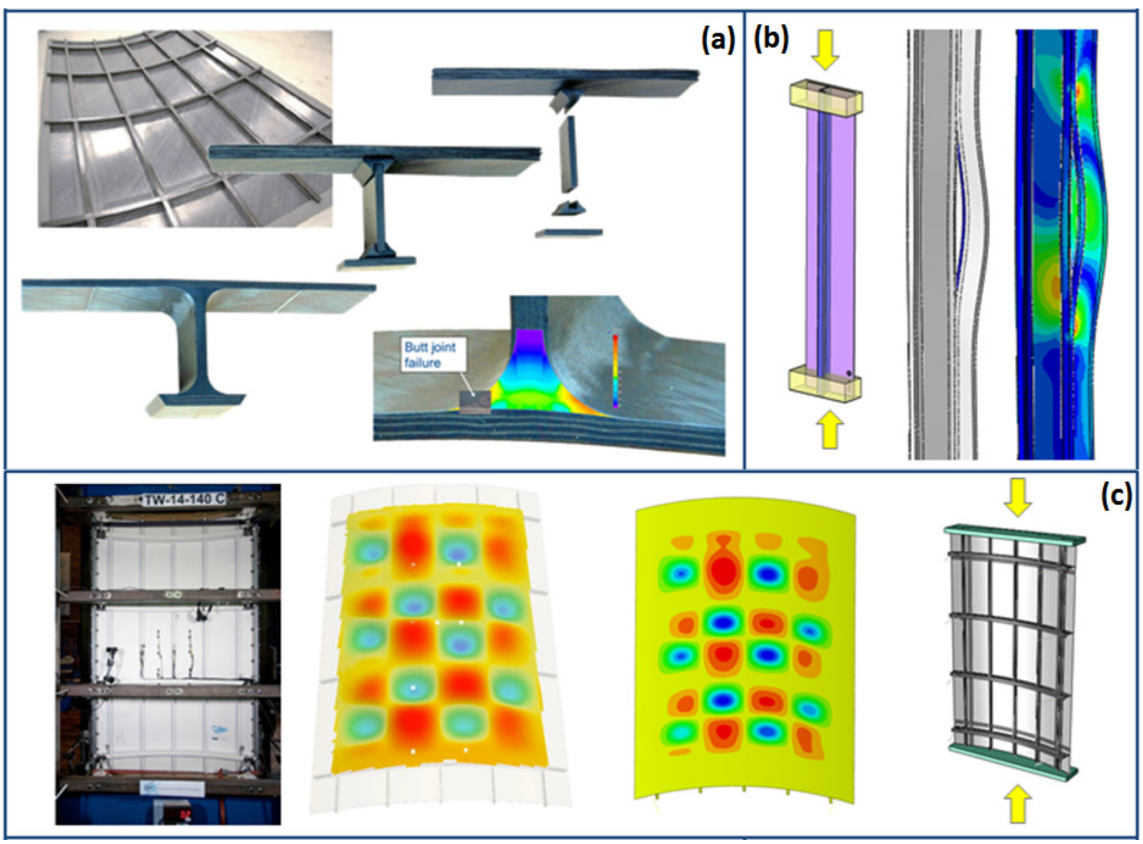

Figure 3. (a) Manufacturing of orthogrid and stress concentration at SFRP filler. (b) Simulation of Short-column test specimen with delamination. (c) Post-buckling compression panel test.

Fine-grid finite element modelling was correlated, as shown in Figure 3c, to pristine compression and shear panel tests and aligned with the modelling approach for the fuselage. Sizing criteria such as post-buckled skin laminate strength, buckling level, and strength of the joint between the skin and sub-structure could thus be analysed. While unnotched and notched laminate strength are covered by traditional analysis methods for conventional ply angles, the Virtual Testing coupon Lab may be used to estimate knockdown factors for skins with non-standard angles, for example manufactured by automatic fibre placement for the application of double curved fuselage skins. The developed methods provide confidence in the design and allow for prediction of configurations which have not yet been validated by means of physical testing. Analysis of large delaminations at visible impact damage, its validation by test, and substantiation of the no-growth approach are planned as following steps.

3.2. Thermoplastic fuselage for next generation aircraft

In current aircraft design, fuselages are designed and optimized mainly within single disciplines (stress, design, cost, weight, manufacturing) and cross functional requirements between structure, systems and interior are hard to take into account. Furthermore, the strong reliance on the conventional physical testing pyramid makes it difficult to achieve confidence in the structure at an early stage of the design process. Potential defects and damages that were not taken into account may lead to extensive rework, with significant impact on lead time, potentially disturbing the whole high-volume manufacturing process and over-stringent manufacturing quality requirements associated with 'Zero-defect' part production policies, can result in high production costs, scrap and long lead times.

For the development of a thermoplastic fuselage for the next generation aircraft, as part of the STUNNING project, advanced multi-disciplinary design, manufacturing, and simulation methods may be applied to improve cost, quality, robustness and performance of thermoplastic components. This can be achieved through development of a virtual process chain [11] coupled with advanced Virtual Testing and optimization techniques. This process controls the flow of information from product design through the manufacturing process and testing pyramid, allowing for optimization of the process as a whole. An example of this virtual process based on typical manufacturing processes for a thermoplastic fuselage is shown in Figure 4.

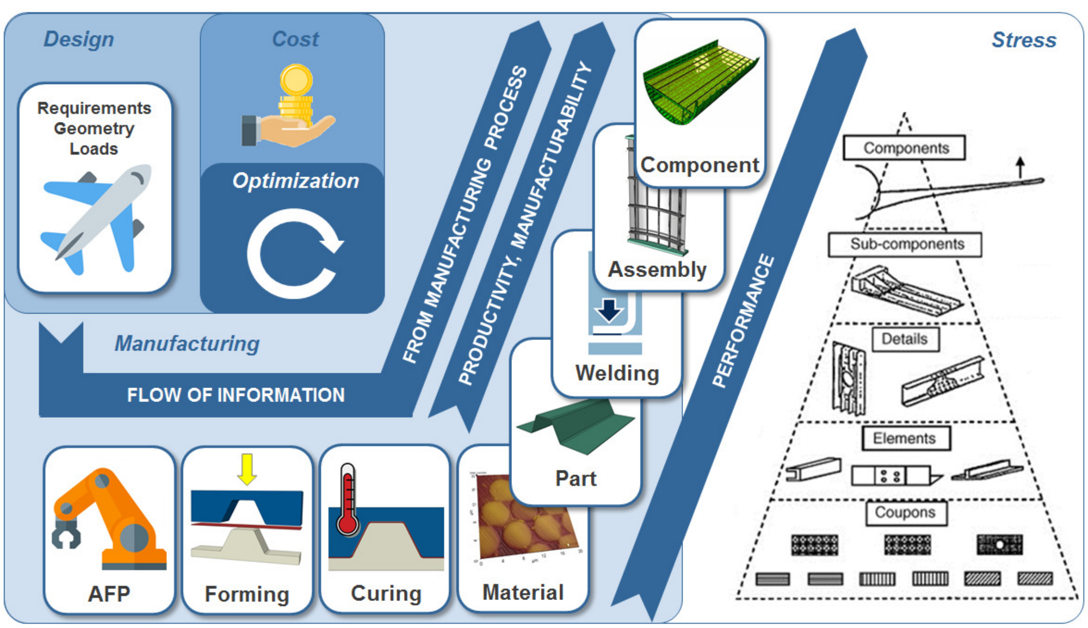

Figure 4. Multi-Disciplinary Optimization of Virtual Process Chain for aircraft structures.

Skins may be manufactured by means of Automatic Fibre Placement (AFP), while frames or stiffeners can be manufactured with out-of-autoclave processes such as press-forming or Continuous Compression Moulding (CCM). Both processes will influence the fibre directions and volume fractions of the composite and can also create undesired wrinkles, waviness, gaps and overlaps that need to be taken into account for the performance of the part. Curing and the rate of cooling influences the ductility and mechanical properties of the thermoplastic material at the bottom of the testing pyramid where design allowables are determined.

One of the advantages of thermoplastic material is that advanced joining techniques such as thermoplastic welding can be applied to manufacture aircraft structures and reduce both weight and costs by reducing the amount of mechanical fasteners required. Advance simulation techniques may be applied to study the effect of defects in the laminate and interface models can provide insight in the fracture process and crack arresting characteristics of welded joints, this to ensure a robust and damage tolerant fuselage design.

Understanding the flow of information and influence of the different material, manufacturing process and design choices in combination with the influence of the manufacturing process on the performance of the structure will allow for optimization of the cost, quality and weight and is an enabler for high-volume manufacturing in the aerospace sector.

4. Conclusions

It has been demonstrated that with the recent growth in available computational power and advanced modelling techniques, the use of efficient simulation tools have already added significant value for the aerospace industry. Successful industrial implementation of a Virtual Test Lab combined with advanced interface models ensures accurate simulations through the different scales of the Virtual Testing Pyramid.

During the development of the thermoplastic orthogrid fuselage shell it has been demonstrated that a hybrid simulation-physical testing approach provided means of analysing the structure by rapid conventional methods supported by simulation and high-fidelity methods allowed for evaluation of new structural details that would normally require physical testing.

The next step in the simulation strategy is to develop a virtual process chain that controls the flow of information from product design, through the different manufacturing process steps along the testing pyramid in order to optimize for costs, quality and weight and enable high-volume manufacturing in the aerospace sector.

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