On Composite Model Calibration for Extreme Impact Loading Exemplified on Aerospace Structures

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Abstract

This contribution will present some simulation related work carried out within a public funded Horizon2020 project of the European Community. Focus is set on composite damage and fracture modelling available in the finite element solver LS-DYNA® and the constitutive models developed within the project. Based on use-cases identified within the project EXTREME, experimental testing and numerical modeling techniques for continuous fiber reinforced aircraft structures such as turbine blades and wing sections are shown. The contribution will showcase results of work packages of the project, such as physical tests conducted to determine the various model parameters which are needed to accurately describe the anisotropic material behavior on a macroscopic length scale that is considered being state-of-the-art in numerical simulations.

Introduction

Composite materials play a fundamental role for future aircraft structures to improve fuel efficiency, reduce CO_2 emissions and certification costs. However, the vulnerability of composite structures to dynamic and unexpected loads such as blade off events or foreign object impact may result in unpredictable, complex, localized damage and a loss of residual strength that is difficult to predict and model in the design phase. This leads to overdesigned aerostructures with consequent weight penalties. It was therefore a viable path to apply for public funding within the Horizon 2020 framework of the European Community to address this issue and provide guidance for the A&D industry when tackling the above-mentioned engineering challenges. EXTREME (see [1, 2]), which is the acronym of the then successful proposal and of the now finished project, was a research and innovation action (RIA) bringing together international partners and leading researchers from seven European countries (see Figure 1).
The main objectives of the project within the framework of the overall aim were to develop:

- Improved material characterization techniques allowing for development of new and improved material models, and for damage assessment during and after extreme events. This will lead to a better understanding of materials' behavior under shock and shock-less loading.
- Advanced integrated experimental and numerical procedures and guidelines in support of design and certification of aeronautical structures.
- Smart impact sensing concepts under extreme dynamic loading
- To reconstruct and warning of occurrence of extreme dynamic events and associated effects.
- To measure failures parameters as occurs to feed new material models.
- Novel and more accurate multiscale and multilevel simulation tools, leading to improved environmental and structural performance of future structures with no decrease in safety standards.

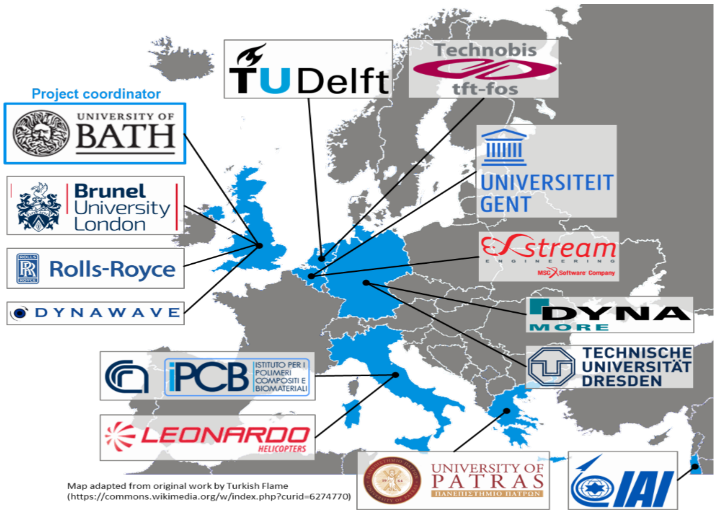


Figure 1: Partners of the Horizon 2020 European research project EXTREME

EXTREME has pioneered experimental and numerical tools for the accurate and reliable design and manufacturing of aircraft composite structures under dynamic loadings. Novel material characterization and in-situ measurement techniques, advanced multiscale simulation methods were developed to achieve a significant reduction of weight, design and certification cost, and environmental signature. The developed simulation tools lead to reduced physical testing by improving the accuracy of the predictions by 20% and contributing to the reduction of the development costs by 10%. Advanced modelling algorithms were included in industrial software codes and novel optoelectronic devices were successfully commercialized up to TRL9. EXTREME's findings will allow lighter design of aeronautical structures in line with EU environmental goals set in FlighPath2050 and leading to a new "right at first time" design philosophy.

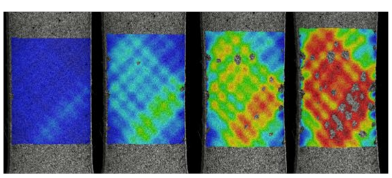


Figure 2: Material Characterization

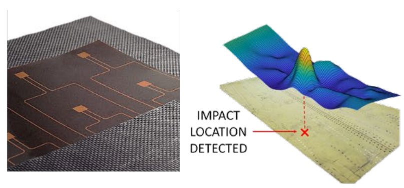


Figure 2: In-Situ Smart Sensing

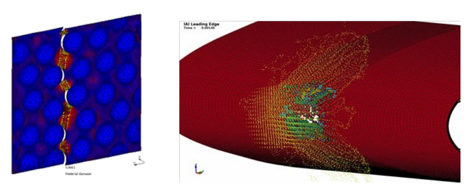


Figure 3: Multiscale Modelling

The EXREME project targeted the whole range of manufacturing, non-destructive testing (NDT), classical destructive testing on coupon and on component level [8] as well as all ranges of simulation as depicted in Figures 2-4 (see also [9]). In the following, however, only a subpart of the various simulation aspects in the project are covered and briefly presented. Other interesting aspects of the project on NDT, strain softening in composites and chemistry of matrix material are published in [3, 4, 5] respectively.

Experimental investigations: Coupons and validation structures

In the framework of EXTREME, high performance Cytec's CYCOM 977-2-34-24KIMS-194 material was examined and tested by researcher partners of the University of Patras (GRE). The matrix constituent is a 177ºC curing toughened epoxy resin for autoclave or compression molding process, whilst the reinforcement is made by carbon fibers named IMS60 of TohoTenax Company. To determine the mechanical properties of CYCOM 977-2 composite and to obtain the experimental force-strain or force-displacement curves, basic material characterization tests were performed. The tests were executed using the servo-hydraulic testing machines INSTRON 8872 and 8802 of the Applied Mechanics Laboratory at the University of Patras, Greece, whose load capacity is ±25 kN and ±250 kN respectively.

All tests were carried out according to the suitable standards (ASTM, AITM, and EN) for polymer matrix composite materials. Some of the executed tests and the broken coupons are depicted in Figure 5 and the extracted results are given in Figure 6. Further reading of the test campaign may be found in [6] and [7].

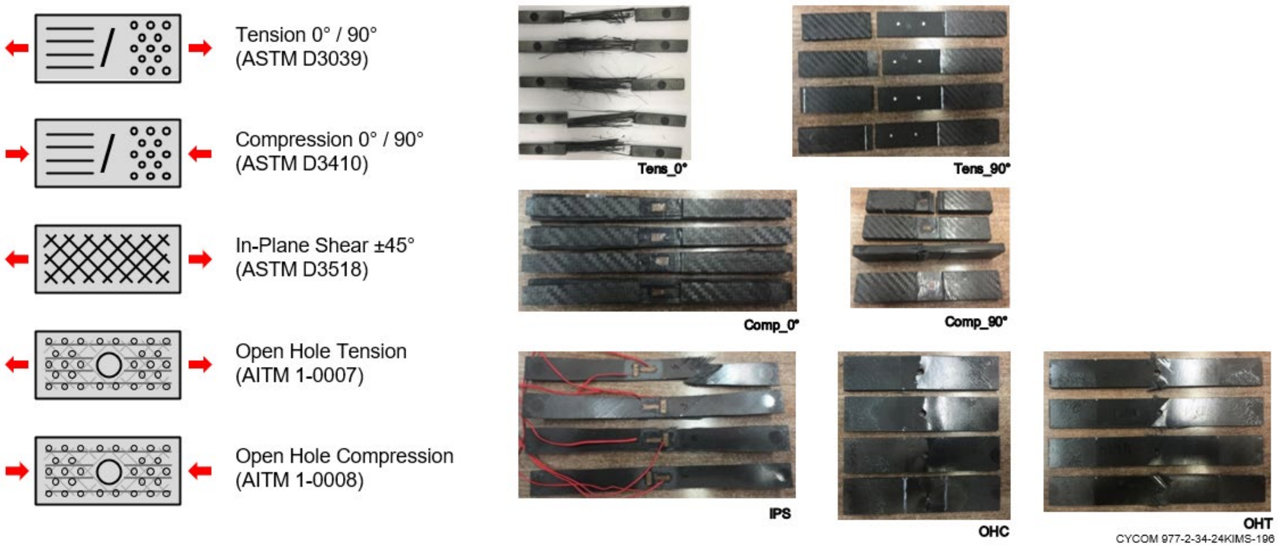


Figure 5: Basic quasi-static characterization tests

Mechanical Property	Mean value	Units	Standard test
Tensile Modulus 0°	180.72	GPa	ASTM D3039
Tensile Strength 0°	3172.10	MPa	ASTM D3039
Ultimate strain 0°	1.72	%	ASTM D3039
Tensile Modulus 90°	8.68	GPa	ASTM D3039
Tensile Strength 90°	66.47	MPa	ASTM D3039
Ultimate strain 90°	0.78	%	ASTM D3039
Compressive Modulus 0°	124.5	GPa	ASTM D3410
Compressive Strength 0°	911.15	MPa	ASTM D3410
Comp. Ultimate strain 0°	0.74	%	ASTM D3410
Compressive Modulus 90°	8.73	GPa	ASTM D3410
Compressive Strength 90°	170.27	MPa	ASTM D3410
Ultimate strain 90°	2.26	%	ASTM D3410
Shear Modulus	4.385	GPa	ASTM D3518
Shear Strength	78.55	MPa	ASTM D3518
Fracture toughness G_{IC}	352.5	J/m²	AITM 1.0005
Fracture toughness G_{IIC}	586.7	J/m²	AITM 1.0006

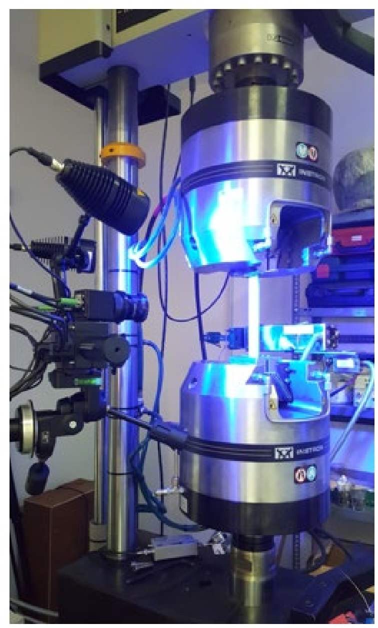


Figure 6: Selected results of static characterization tests of CYCOM 977-2 and testing equipment at University of Patras

Further testing within the EXTREME project was done at the University of Gent (BEL) and the Brunel University (UK) to also capture the dynamic effects and to allow parameter identification for loading at higher speed.

Modelling of coupons

The numerical analysis of quasi-static tests was performed by research partners from the University of Patras utilizing LS-DYNA with an implicit time integration scheme (Figure 7) [6]. In essence, a ply-based discretization with stacked 3D solid elements was adopted for the simulation of laminated specimens where *MAT_54 was applied. This technique allows shear deformations of the laminated structure across the thickness direction since each lamina is explicitly modelled. Moreover, by using solid elements instead thin or (layered) thick shells, no geometric and no loading assumptions are required. Whereas the boundary conditions are treated more realistic. The 3D solid elements allow the 3D stress state of the simulated component to be fully captured. Also, a fully integrated first-order element formulation was adopted and hence no hourglass stabilization is needed. Furthermore, in order to capture delamination initiation and propagation of plies a cohesive zone model (CZM, namely *MAT_186) was applied at each ply-to-ply interface. Clearly, the main advantage of the CZM method is that the location of delamination onset is captured automatically within the discretization. All numerical models were created following the corresponding specimen dimensions, the experimental cured ply thickness (CPT), the span length and the adopted stacking sequence.

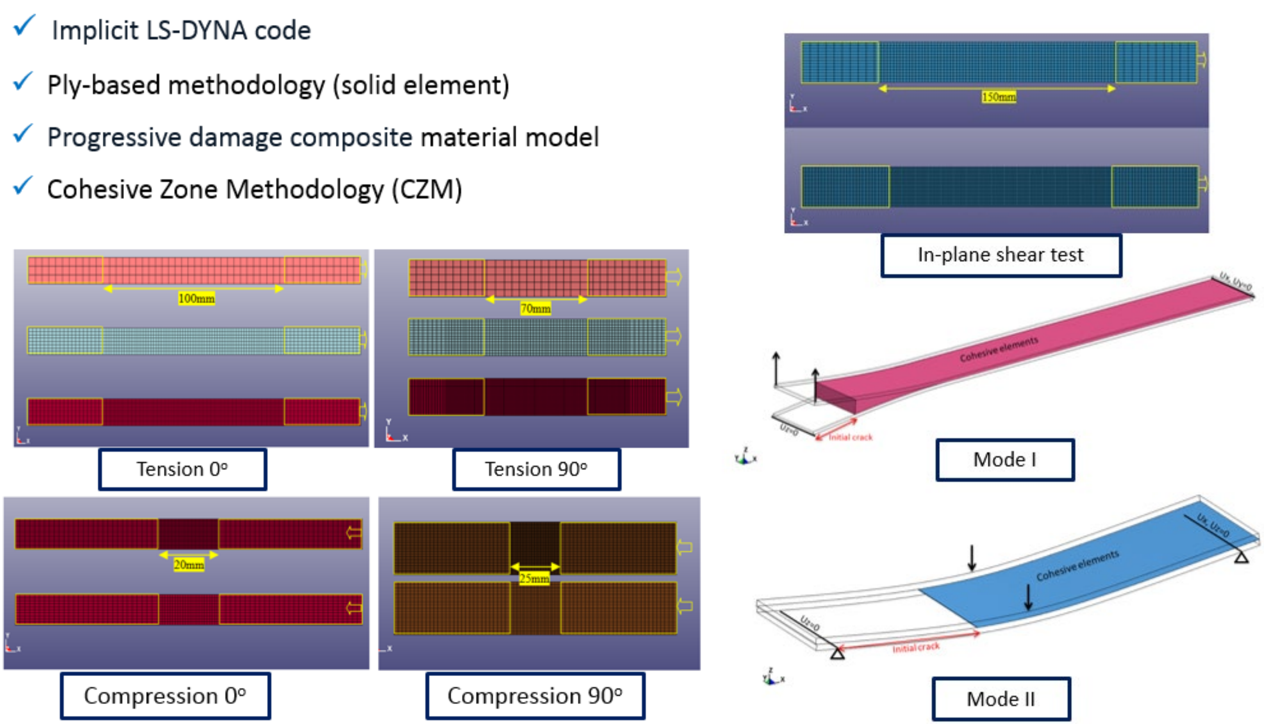


Figure 7: Finite element models of quasi-static tests

An automatic calibration process (see [7]) based on the comparison of the numerical results with the corresponding mean experimental ones using MATLAB was applied to facilitate parameters identification. To reduce the problem complexity, the calibration process was divided into two parts with a number of sub-stages. The first part includes six stages, namely the in-plane loading tests in tension and compression respectively in 0° & 90°, in-plane shear and the open hole tension (OHT) test for calibration of the orthotropic model parameters of *MAT_54. The second part consists of the parameter identification for the cohesive model *MAT_186, where the interlaminar fracture tests in mode I and mode II were used to identify the respective parameters. The calibration logic for one stage (test) is shown in Figure 8.

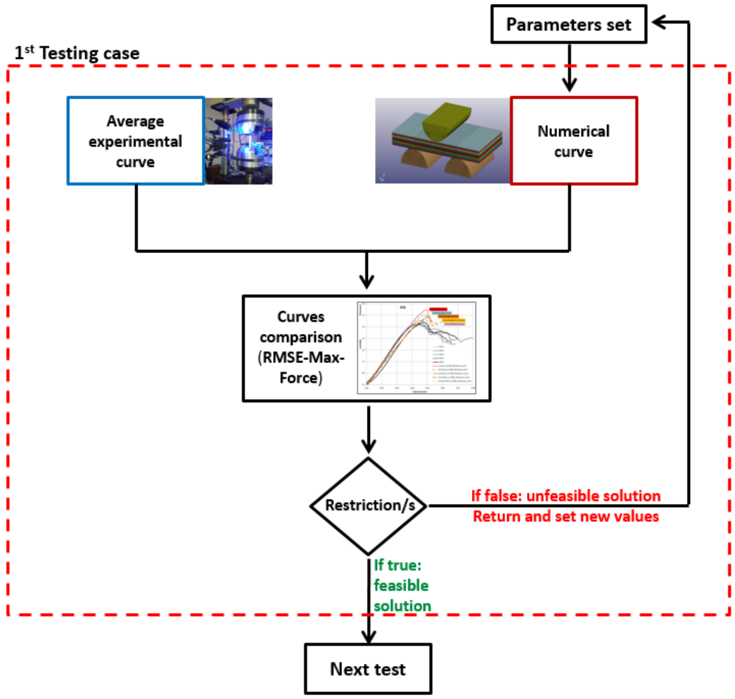


Figure 8: Flow chart of algorithmic concept (one stage)

Independent variables	Objectives for minimization
For orthotropic material model (MAT_54): • Elastic moduli (E_a, E_b) for tension • Elastic moduli (E_a, E_b) for compression • Poisson's ratio ν_{ab} • In-plane shear modulus G_{ab} • Out of plane shear modulus G_{ac} • Tensile strength in fiber axis (X_T) • Compressive strength in fiber axis (X_C) • Tensile strength in matrix axis (Y_T) • Compressive strength in matrix axis (Y_C) • Shear strength in ab plane (S_{ab}) • Nonlinear shear stress parameter (ALPH) **For cohesive material model (MAT_186)** • Fracture toughness energy to mode I (G_{IC}) • Fracture toughness energy to mode II (G_{IIC}) • Peak traction in normal direction (T) • Peak traction in tangential direction (S) • Normalized separation at peak traction (λ_o) • Exponent of power law mixed-mode criterion (xmu)	**1st stage (7 objectives)** • RMSE for tension 0º test • RMSE for tension 90º test • RMSE for compression 0º test • RMSE for compression 90º test • RMSE for in-plane shear test • MaxForceError for in-plane shear test • RMSE and MaxForceError for OHT **2nd stage (5 objectives)** • RMSE for fracture mode I • Max Force Error for mode I • RMSE for fracture mode II • Max Force Error for mode II • RMSE for ILSS test

Table 1: Independent variables and objectives of calibration algorithm.

Further calibration of constitutive models based on the quasi static and dynamic test data provided by the university partners was done at DYNAmore (GER) particularly for *MAT_261 (*MAT_DAIMLER_PINHO) and *Mat_262 (*MAT_DAIMLER_CAMANHO). Results of the calibration in tension and compression in transverse and longitudinal direction are depicted in Figure 9. It can clearly be seen that the calibration suffers to some extend of the tension-compression asymmetry in fiber direction. This should be addressed in future work. However, the remaining calibration is seen as sufficient for the targeted applications.

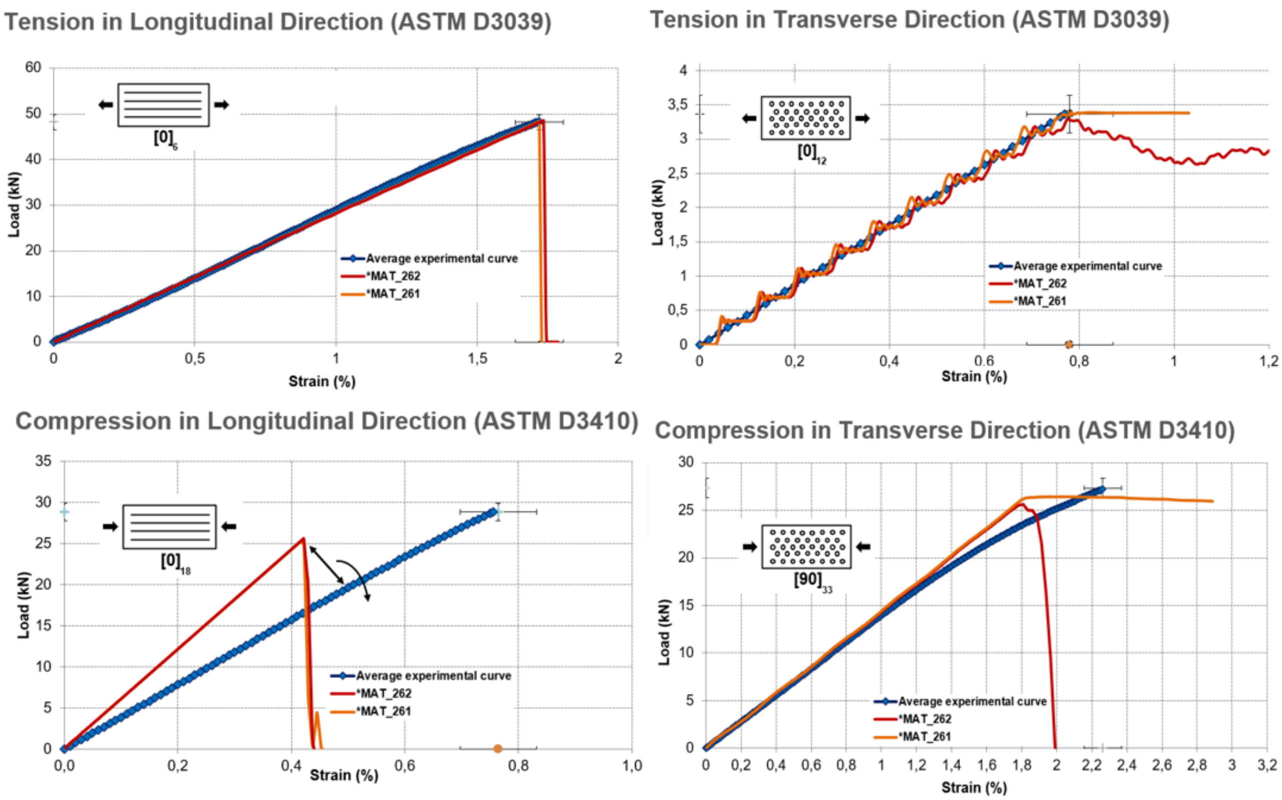


Figure 9: Standard tests in tension and compression

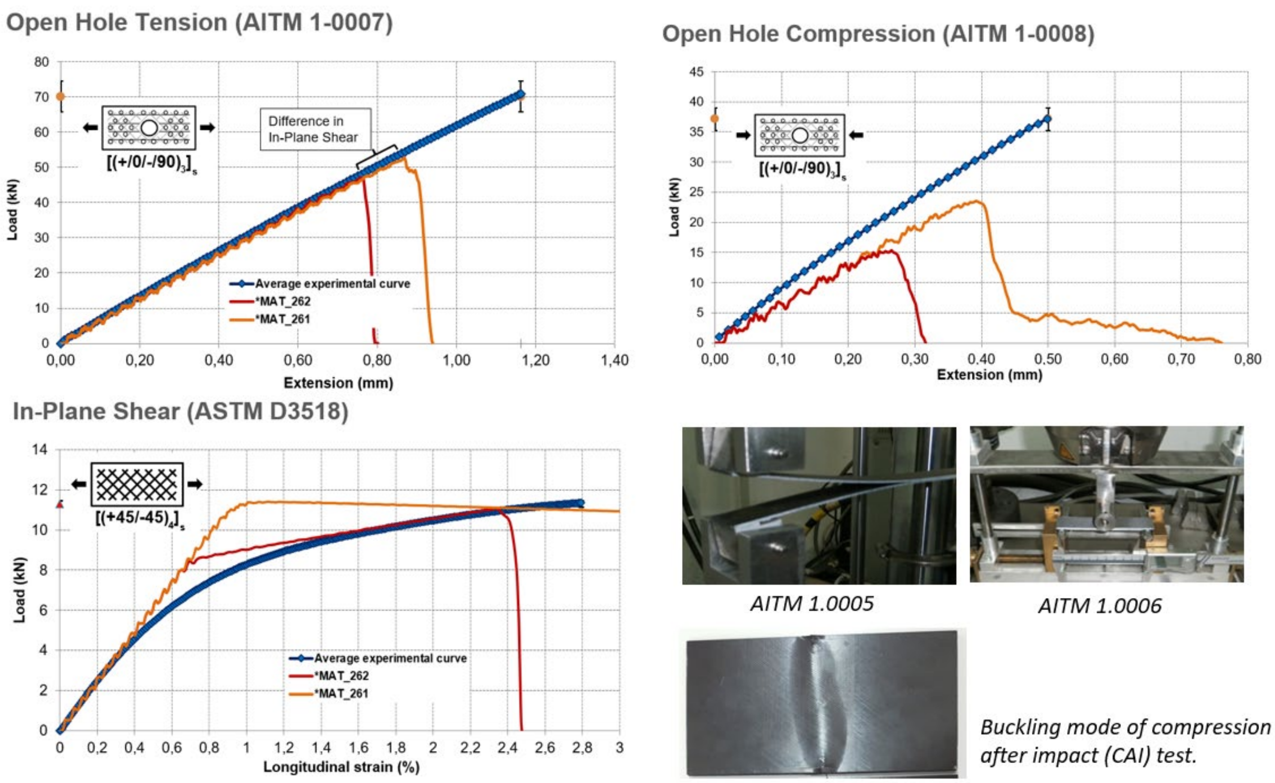


Figure 10: left: OHT, OHC and in-plane shear test; right: fracture toughness and CAI test.

In Figure 10 three more tests have been used for calibration, namely open hole tension and open hole compression test as well as the in-plane shear test. Again, the stiffness in tension can be captured quite well, while the compressive response due to the hole in the coupon is too flexible now. Failure is predicted in both constitutive models too early. A difference in load capacity can be attributed to the calibration of the in-plane shear test.

New constitutive model for composites with damage

A new continuum based anisotropic constitutive model for composites with damage was developed at Brunel University London, based on the spectral decomposition of strain energy with respect to the principle damage modes. This spectral decomposition led to more accurate results, compared to the decomposition of the stiffness tensor. The model was implemented in the LLNL Dyna3d hydrocode and linked with a vector shock equation of state, based on generalized decomposition of the stress tensor into the deviatoric and volumetric parts, see [10].

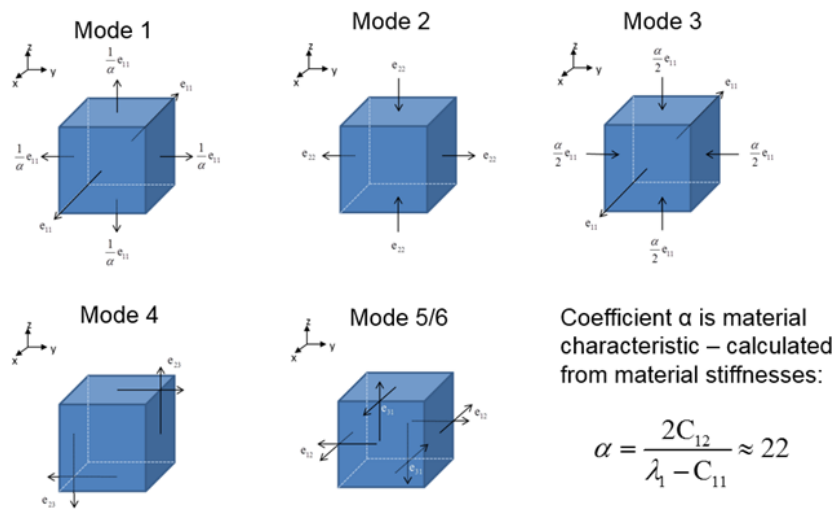


Figure 11: Eigenmodes defined for transversally isotropic material

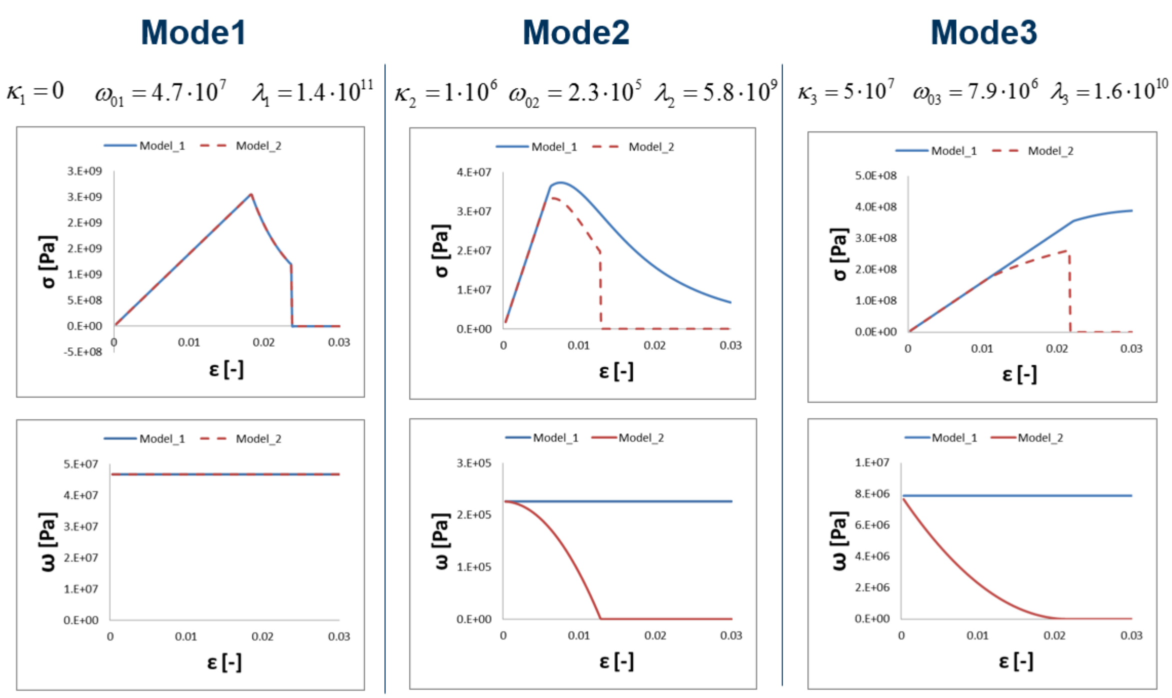
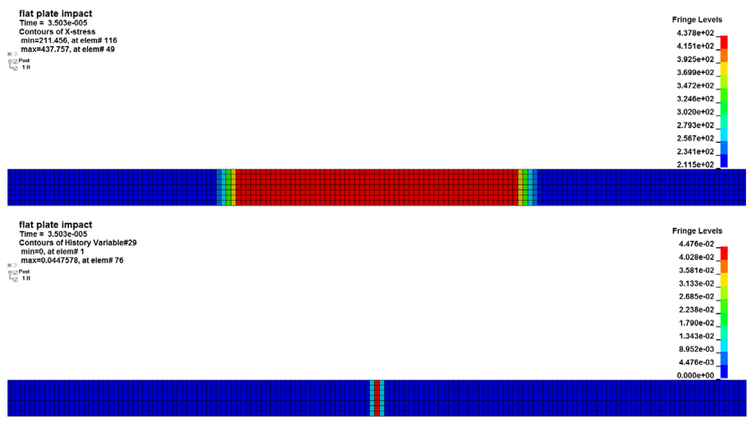


Figure 12: Stress strain and damage strain curves obtained for the first three damage modes

Model verification was conducted using a series of single element tests, where the loading was applied to trigger individual damage eigenmodes for transversally isotropic material, see Figure 11. The material model parameters for elastic response were obtained from the standard quasi-static tests. Damage initiation and damage evolution parameters were obtained from critical damage energy release rates and plate impact tests, respectively. The numerical results for the single element tests were equivalent to the corresponding analytical results, so that the model was successfully verified. A selection of these results is given in Figure 12.

The constitutive model was used for modelling a stress wave propagation problem, where the formulation was not suffering from instability due to localization, which is typically observed in the FEM based continuum damage mechanics models. Contour plots of stress and damage variables for one test case are shown in Figure 13, whilst Figure 14 shows results obtained with the material model with different mesh densities.



a)

b)

Figure 13: Stress (a) and damage (b) distribution in the bar modelled with 151 elements in the loading X direction; time $t = 3L/2c$

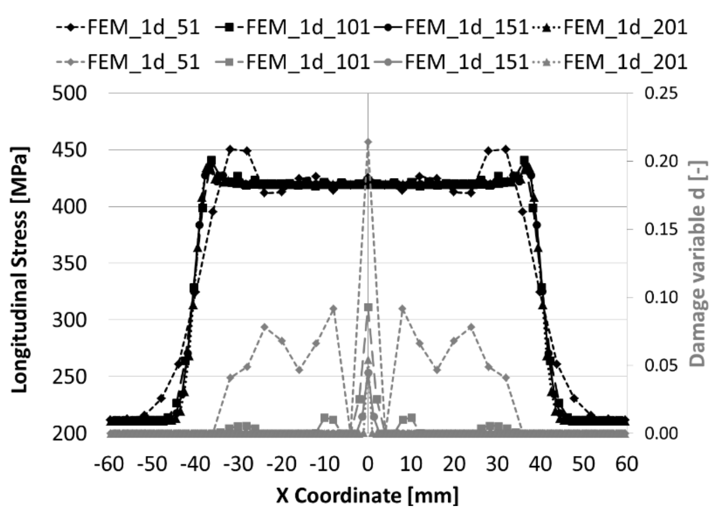


Figure 14: Stress and damage distribution in the bar modelled with four mesh densities; time $t = 3L/2c$

Numerical model validation was conducted by modelling a hard-projectile impact on a 6mm thick composite panel (400mm x 400mm), for which the corresponding experiment was conducted within the project EXTREME. The target panel consisted of 23 unidirectional plies, which were 0.26mm thick, with stacking sequence $[-45/0/+45/\underline{90}]_{3S}$. The projectile was a steel ball bearing of 12mm in diameter. Two impact cases above the ballistic limit of the panel were modelled, with the normal impact speed of 307m/s and 1200m/s respectively. The simulation results for delamination distribution through the thickness of the target panel (damage mode 5 stored on hisv#34) are shown in Figure 15. The shape of the damaged zones obtained in the simulations agree well with the experiments, which is for the lower speed localized in the vicinity of the crater and of hourglass-like shape for the higher speed impact case. The discrepancy in the maximum diameter of the damage zones between the numerical and experimental results is within 10%, which demonstrate current capabilities of the new material model.

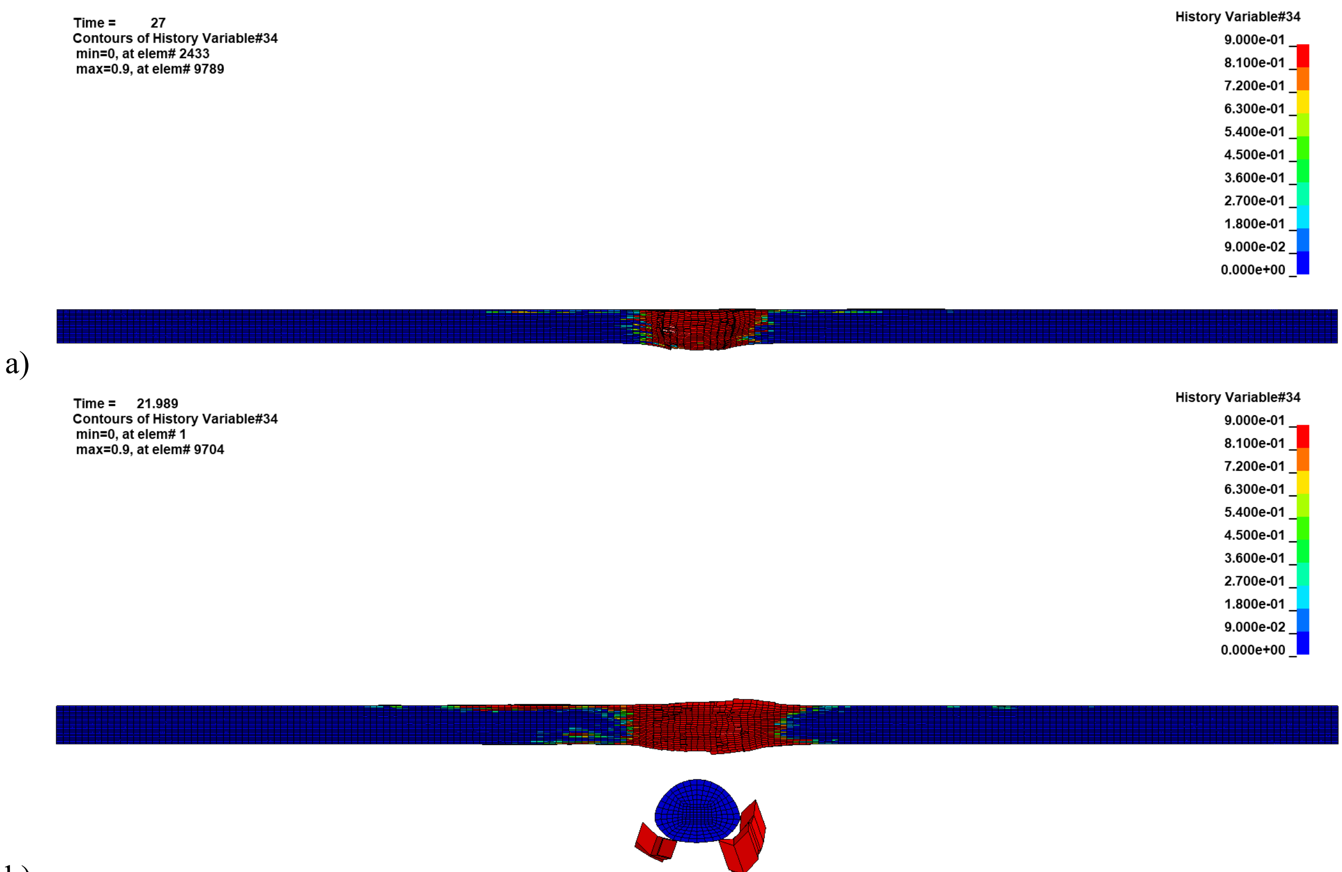


Figure 15: Delamination through thickness obtained in the simulations of impact at (a) 307m/s and (b) 1200m/s

Modelling of validation structures

Soft Body Impact (SBI)

A generic CFRP-Fan Blade is subjected to a soft body gelatin impactor at 190 m/s. The impact test setup is illustrated in Figure 16, where a gas gun of the University of Dresden (TUD) is used to accelerate the soft projectile (diameter = 100mm) with an impact angle of 50°.

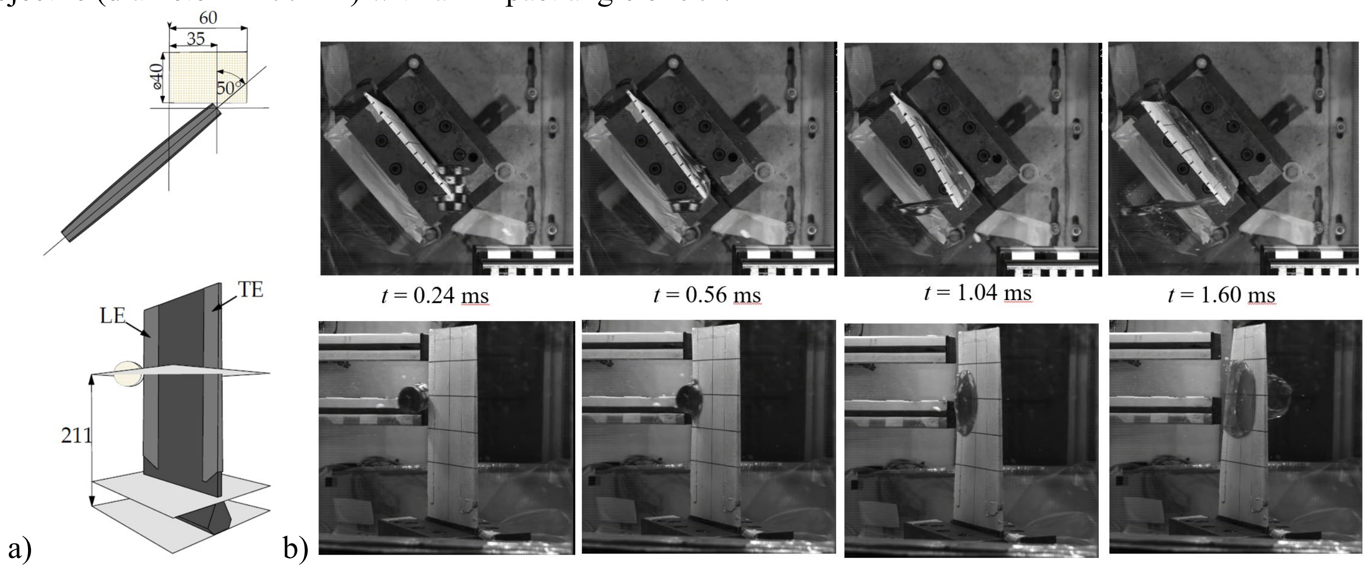


Figure 16: a) Impact test set-up and b) testing sequence

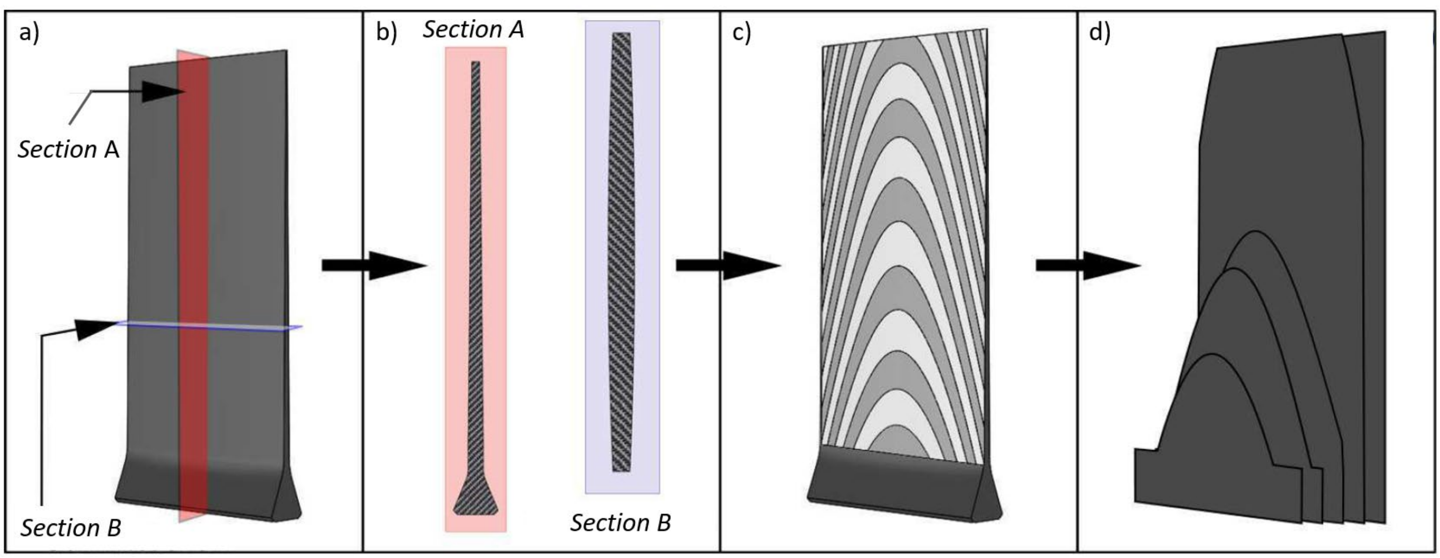


Figure 17: Illustration of the complex layer geometries for the generic fan blade: (a) positioning of the cross-sections; (b) cross-sections; (c) areas with the same number of layers; (d) derived exemplary ply geometries

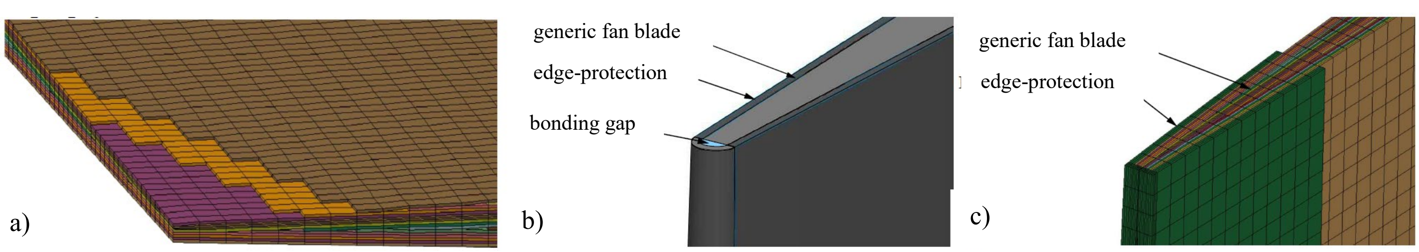


Figure 18: a) Hexaeder mesh of the generig fan blade; b) edge-protection structures; c) simplified representation for impact analysis

The generic fan blade has a double curved topology and requires therefore a complexly tailored ply book of the CFRP single plies (Figure 17). For meshing an in-house tool (OptiPly) at TUD was used, which generates a homogeneous and hexaeder-only based mesh for individual ply stacks. Simplifications have been used to represent the edge-protection structures. The bonding gap and the roundings are not modeled. Only the stiffness of the edge-protection elements and the adhesive failure between the edge-protection structures and the generic fan blade is considered to be relevant (Figure 18).

The impactor was model by SPH with constitutive data provided by the project partner TUD and the blade was set up and simulated with the calibrated material data from the coupon tests. Due to slight deviations in the spatial discretization between the model and the hardware experiment the dynamic response of the test differs from the simulation. Some stages of the simulation results are given in Fig. 19. It is believed that weaknesses in the compressive behaviour of the simulation model as well as slight variations in the impact velocity and location be the reason for the mismatching deflections at later points in time. Further investigations focusing on more validation structures will release any further weakness of the modelling proposal.

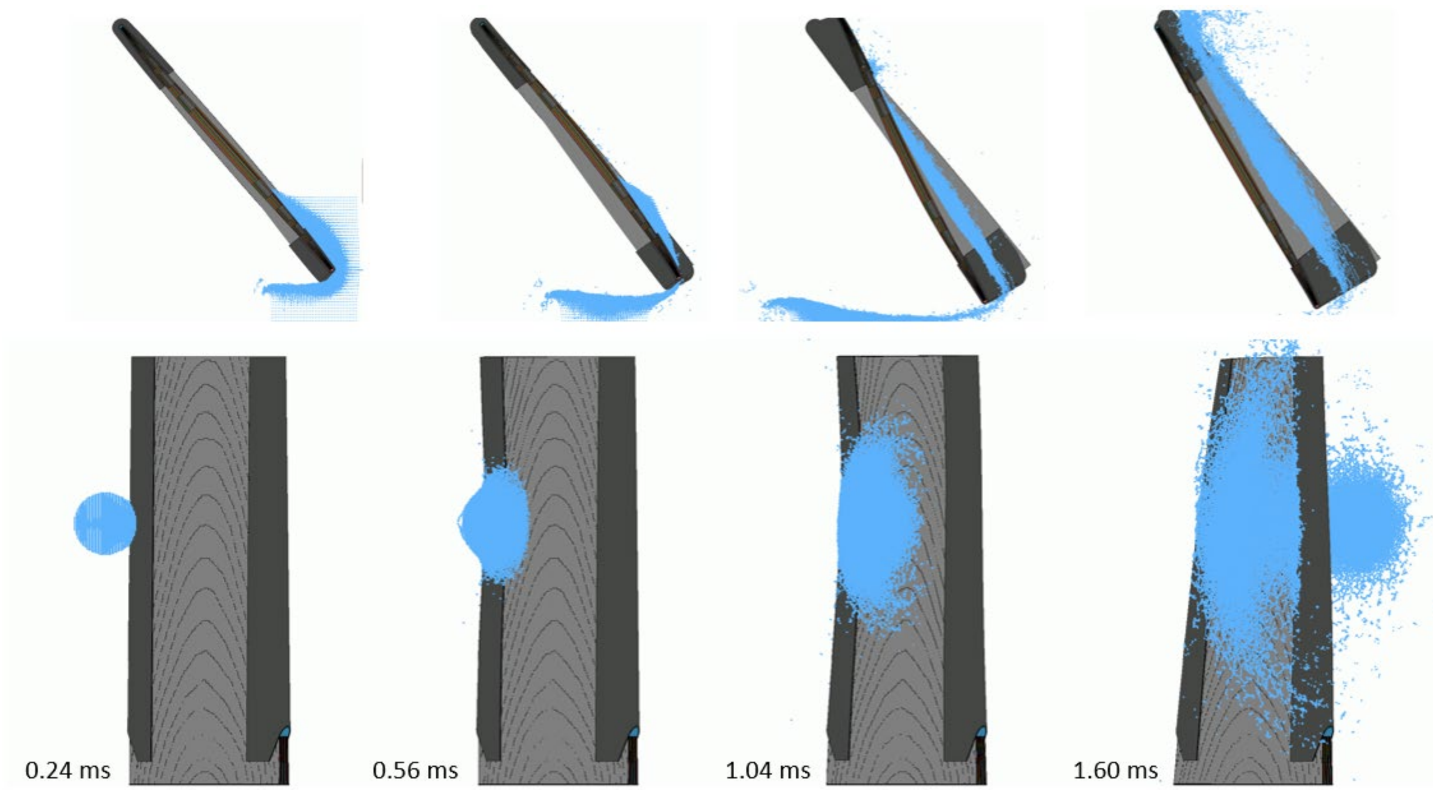


Figure 19: Impact on fan blade top view view and side view

Leading Edge Impact (LEI)

Another validation structure that was build, tested and simulated within the EXTREME project is the leading edge (LE) of an aero-plane wing section. The leading edge had a symmetric layup at the tip of $[45/0/45/0/0/45/0/45]_{sym}$ with appox. 0.2mm thick plies gradually opening to a honeycomb (OX 3.0pcf, t=3/8") filled section of $[45/0/45/0/0/45/0/45/HC]_{sym}$. The structure was linearly fixed to a test rig as depicted in Figure 20, right. For the impact a bird of 0.91kg (85mm x 170mm) was shot at two identical structures with 70.2m/s (LE1) and 83.3m/s (LE#2).

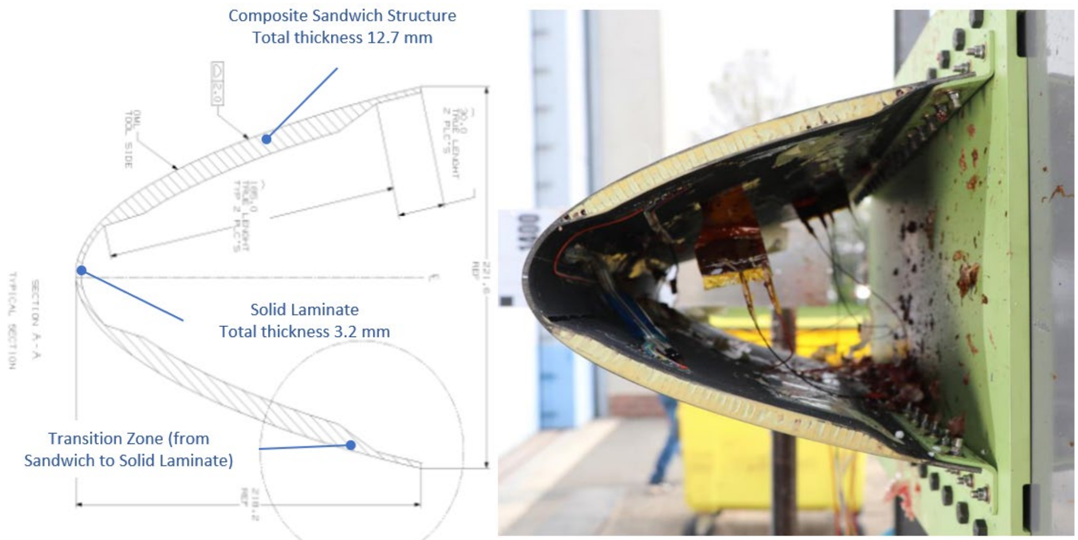


Figure 20: Geometry of leading edge structure

Since no visible damage was experienced a second shot on LE1 with higher speed, namely 101.9m/s, was performed. The impact location of this shot was lower than in the previous tests, i.e. the bird was not aligned with the edge centerline. Now, cracking and crack opening on the front edge of the structures was visible.

The modelling followed the same ideas as in the previous example; however, now cohesive elements were embedded in between the individual plies to capture delamination effects. Again, the bird was modeled by SPH discretization. Since there was no significant damage in the simulation of an impact speed of 70.2m/s, the virtual structure was loaded also with a second impact of 101.9m/s. The results are depicted as sequence of standstill snapshots in Figure 21. fracturing and damage on the outside in compression is triggered. Furthermore, on the inside surface fracturing is as well observed which is qualitatively corresponding to the experimental investigations.

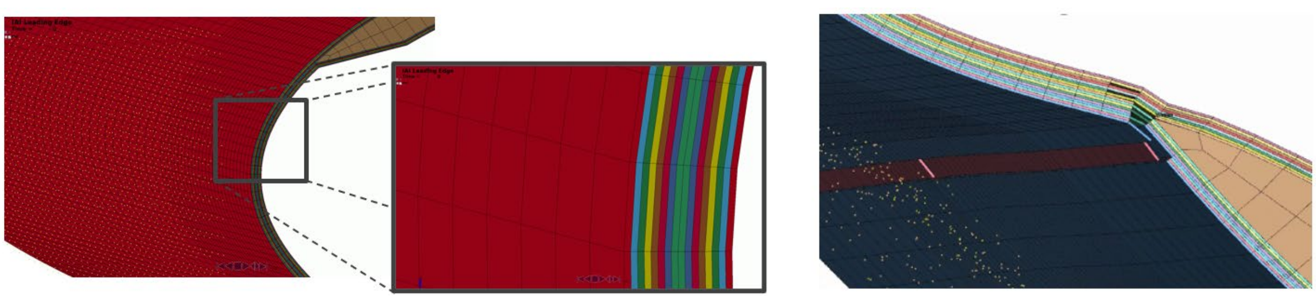


Figure 21: Discretization of LE with layered solid and cohesive elements as well as fracture mode at peak deformation

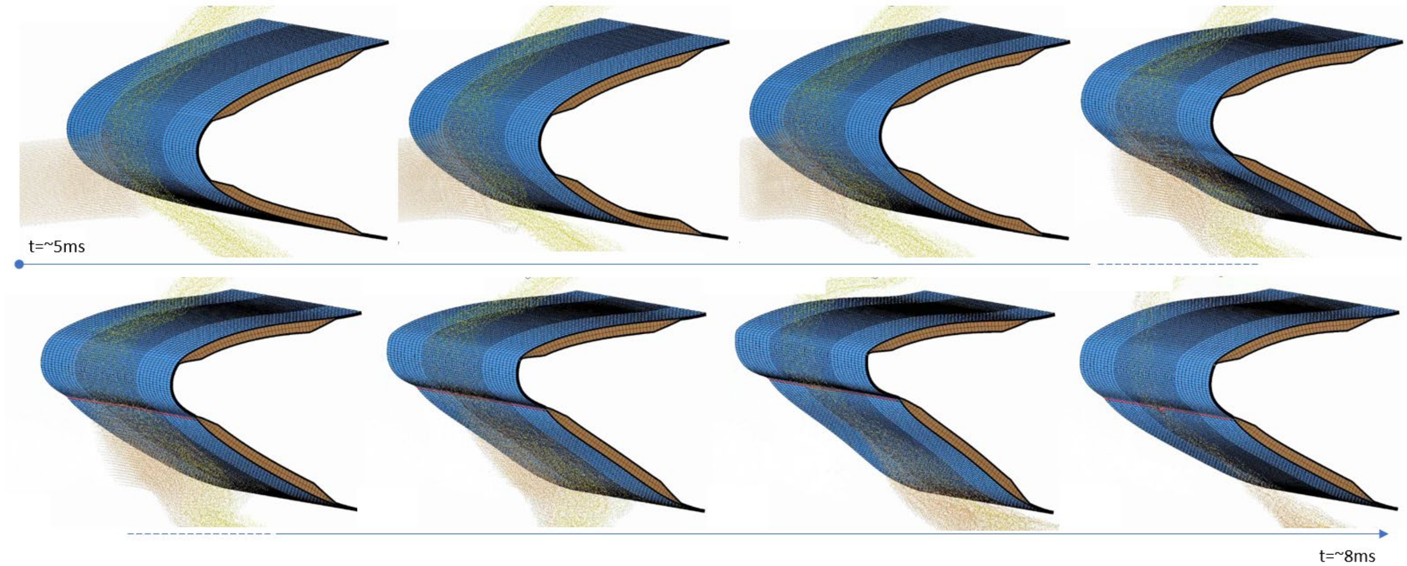


Figure 21: Sequence of pictures of second impact on LE1 structure.

Conclusions

This contribution gave a quick overview on the EXTREME project funded by the European Community within the Horizon2020 framework. This support is greatly acknowledged. Only a small part of the project was covering structural mechanics and the extensive work done in the field of simulation technology in various fields of application cannot be present in this format. Hence the authors only showcased some of the work done within EXTREME, especially some aspects of modelling that is thought to be most interesting to the audience. The validation structures as well as the testing of them was finished rather late during the project which is why sever validation is still an ongoing task. It remains a challenge to calibrate the structural and constitutive models even better and maybe find another modelling approach to capture the various effects seen in some of the coupons as well as in the various validation structures more accurately. This will be focus of future work.

Acknowledgment

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