Materials for cabin environment protection

Models for material degradation

G. Mirra (LEONARDO), I. Roese-Koerner (DLR), F. Martaus (VZLU), J. Bachmann (DLR), M. Liebisch (DLR)

Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project P7 "Mitigating the risk of fire, smoke and fumes". The main objective of this deliverable is to describe the test program planned to characterize and model some improved material solutions with respect to fire, smoke and fumes mitigation in the cabin environment.

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Acronyms

Acronym	Definition
AITM	Airbus Industries Test Method
ASTM	American Society for Testing and Materials
CFRP	Carbon fibre reinforced plastic
CTE	Coefficient of thermal expansion
DLR	Deutschen Zentrums für Luft- und Raumfahrt
DMA	Dynamic mechanical analysis
DSC	Differential Scanning Calorimetry
GPs	Geopolymers
FAA	Federal Aviation Administration
FML	Fibre metal laminate
FRP	Fibre reinforced plastic
FST	Fire smoke toxicity
HRR	Heat release rate
LAD	Leonardo Aircraft Division
OSU	Ohio State University
RTM	Resin transfer moulding
TGA	Thermogravimetric analysis
TMA	Thermomechanical analysis
VZLU	Aerospace Research and Test Establishment

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EXECUTIVE SUMMARY

Problem Area

Many studies on the current flights show that about 50% of the fatalities in case of aircraft accidents are linked to situations where fire is involved. Hundreds of fatalities could be saved per year if fire effects on the primary structure or in the cabin environment were mitigated. The development of larger, more electric and more lightweight aircraft (with an increase use of Carbon Fiber– Reinforced Plastic (CFRP) composite parts) raises several safety questions with respect to unknown behaviours of the materials and structures when exposed to fire. But the scope of this problem is large, embracing a variety of problems and solutions: the use of fireproof and less toxic materials, the early detection of fire, the simulation of passengers' evacuation, etc.

Future Sky Safety Project P7 "Mitigating the risks of fire, smoke and fumes" will focus on effects of fire on new materials with improved fire properties (production of heat, toxic fumes and smokes), and on the effect of fire on mechanical behaviour that can endanger the passengers' life. The scope of the works will cover both primary structures materials (e.g. epoxy resin, carbon fibre reinforced polymers) and cabin materials (e.g. phenolic polymers, glass fibre reinforced plastics). The objective of WP7.2 is to develop and utilize novel and innovation material solutions with high potential for mitigating risks of fire, smoke and fumes in the cabin environment. To achieve this aim, proposed highly resistant materials will be tested according to prescribed test plan, which will allow to address their mechanical properties with respect to fire exposure. The scope and magnitude of proposed test plan respect industrial safety requirements and usage of state-of-the art simulation tools.

Description of Work

Starting from the test results described in D7.2 , 7.5 and 7.8 analysis activities have been performed in order to simulate the behavior of the materials in fire condition.

Simulation activities have been performed in order to validate the tools and improve them. In particular, the following steps have been followed:

- Verify the tools present in house,
- Improve the tools present in house,
- Validate the tools present in house.

The modelling of the temperature dependent mechanical material properties was achieved and compared to the results of first and second test batches documented in D7.5 [1] and D7.8 [2]. The test behaviour within developed test facility for compression under fire exposure (CuFex, documented in D7.8) was analyzed within FE simulations for the investigated fibre metal laminate specimen (FML).

Results & Conclusions

In conclusion, on the one hand, the test results obtained during the test campaign allowed to collect all the data necessary to improve the FlamePTM tool, thanks to in depth characterization of the tested material , in order to simulate and study the specimen behavior in terms of :

- material degradation: gas produced by the pyrolysis phenomena;
- specimen structural behavior: deformation and stress.

FlamePTM with the improvements described in this deliverable assures a depth simulation of flame penetration tests with the following reported important benefit for aircraft manufacturers:

- Reduce the time and costs of specimen supplying,
- Reduce test time, the experimental activity is minimized to the confirmation of the results for the design approval,
- Reduce the number of development tests and certification tests (cost reduction),
- Reduce the risk associated to the development phase: the refinement is anticipated in the concept phase (cost reduction),
- A wide spectrum of configurations and cases (optimized design) can be investigated.

On the other hand, the simulation model to investigate Fiber Metal Laminates (FML) behaviour within the DLR CuFex facility uses temperature and state dependent material properties. The simulation model uses temperature and state dependent material properties. The insulating pillow effect of the FML could be reproduced by the simulation and the drop of mechanical performance due to the decomposing matrix was studied. Nevertheless, several simplifications were assumed within the FE model and have to be studied within future work to enhance the model.

Applicability

The applicability is dual:

- Verify the reliability of the tool present in house
- On the basis of the experimental results improve the tools in order to simulate in depth the behavior of the tested materials.

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1 INTRODUCTION

1.1. The Programme

The European Commission (EC) Flight Path 2050 vision aims to achieve the highest levels of safety to ensure that passengers and freight as well as the air transport system and its infrastructure are protected. However, trends in safety performance over the last decade indicate that the ACARE Vision 2020 safety goal of an 80% reduction of the accident rate is not being achieved. A stronger focus on safety is required. There is a need to start a Joint Research Initiative (JRI) for Aviation (Future Sky) with a Joint Research Programme (JRP) on Safety, and also for coordination of Safety Research conducted under the Institutional Programs of the European research establishments. The JRP on Safety (Future Sky Safety), established under coordination of the Association of European Research Establishments in Aeronautics (EREA), is built on the relevant European safety priorities as brought forward in Flightpath 2050 and the European Aviation Safety Plan. The program is structured around four main themes with each theme consisting of a small set of projects. Theme 1 (New solutions for today's accidents) aims for breakthrough research with the purpose of enabling direct, specific, significant risk reduction for the two main Accident Categories. Theme 2 (Strengthening the capability to manage risk) conducts research on processes and technologies to enable the aviation system actors to achieve near-total control over the safety risk in the air transport system. Theme 3 (Building ultra-resilient systems and operators) conducts research on the improvement of Organizations, Systems and the Human Operator with the specific aim to improve safety performance under unanticipated circumstances. Theme 4 (Building ultra-resilient vehicles), aims at reducing the effect of external hazards on the aerial vehicle integrity, as well as improving the safety of the cabin environment. In all, Phase 1 of the Programme will address five important safety priorities. The Project P7 "Mitigation the risk of fire, smoke and fumes", contributes to Theme 4 "Building ultra-resilient vehicles" of the Future Sky Safety Programme.

1.2. Project context

The first objective of the P7 project is to increase safety - meaning here reduce the number of fatalities - with respect to fire related issues (in-flight or post-crash). First, many studies on the current flights show that about 50% of the fatalities in case of aircraft accidents are linked to situations where fire is involved. Hundreds of fatalities could be saved per year if fire effects on the primary structure or in the cabin environment were mitigated. Second, the development of larger, more electric and more lightweight aircraft (with an increase use of CFRP composite parts in A/C design, such as fuselage panels, engine carters, engine exhausts, etc) raises several safety questions with respect to unknown behaviours of the materials and structures when exposed to fire. But the scope of this problem is large, embracing a variety of problems and solutions: the use of fireproof and less toxic materials, the early detection of fire, the simulation of passengers' evacuation, etc. And few researches have been funded

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yet by the EU commission on this subject. Compared to the previous 7th PCRD funded project "AircraftFire", on which the JRI one is nevertheless built on, it was decided to address the fire issue in the JRI Safety research programme as part of Theme 4: "Building the Ultra-resilient Vehicles". It means that the research work will be focused on material and structural questions, and will aim at mitigating fire related safety risks when/by introducing new generation of materials in future aircraft design (incl. possible eco-friendly ones). Considering this focus, it must be noticed that very few test results are available today to the research community, because of obvious costs (test facilities, destructive tests, specimens and sensors) and industry confidentiality reasons. A large part of the project will be dedicated to develop and share experimental testing facilities and test results, with a clear partnership added value between EU Research Establishments, Academia and Industry being reached.

Then, there are also concerns about the safety impact on on-board air quality, mainly related to such innovations. For example, aircraft crew has reported health problems that prevent them from working appropriately and which they consider to be due to air quality in the cockpit and cabin of pressurised aircraft. Multiple investigations have been carried out on hypothetical air contamination by oil ingredients and on the potential impact of such contamination on occupants' health, both in short term and in long term. The more general question of any possible kinds of impact on on-board air quality then raised, that can be due for instance to the introduction of new materials in the design that could react with more and more electrical heating systems, fuel systems, or in case of fire which can then be linked to the previously mentioned first objective.

The project will then address on the one hand effects of fire on materials (production of heat, toxic fumes and smokes), and on the other hand effects of fire on structures (burnthrough, strength) that can endanger the passengers' life directly (exposure) or indirectly (evacuation). The scope of the works cover both primary structures materials (e.g. epoxy resin, carbon fibre reinforced polymers) and cabin materials (e.g. phenolic polymers, glass fibre reinforced plastics). Last, the P7 project has been split into three workpackages according to the expected impacts that are claimed for this 3 years research work:

- WP7.1 - aims at improving the knowledge about effects of fire on materials and structures. This sub-workpackage would mainly concern standard epoxy resins and carbon fibres reinforced polymer materials (primary structures),
- WP7.2 - the second one aims at proposing improved materials solutions, mainly to mitigate fire, smoke and fumes. This second workpackage would concern new materials (primary structures and cabin), the properties of which will be compared to standard ones,
- WP7.3 - aims at analysing possible effects on the on-board air quality that the introduction of such new materials in the aircraft structure and cabin could have.

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1.3. Work package context

The objective of WP7.2 is to develop and utilize novel and innovative material solutions with high potential for mitigating risks of fire, smoke and fumes in the cabin environment. To achieve this aim, proposed highly resistant materials will be tested according to prescribed test plan, which will allow to address their mechanical properties with respect to fire exposure. The scope and magnitude of proposed test plan respect industrial safety requirements and usage of state-of-the art simulation tools.

The objective of this investigation concerning fibre metal laminates is the development of FMLs with improved fire properties for the substitution of cabin and structural aircraft materials. This material combination offers the opportunity of a reduced smoke density production with a lower toxic gas content combined with improved mechanical properties during fire.

The objective of hybrid non-woven from natural fibres and (recycled) man-made fibres is to substitute classic cabin materials (glass fibre fabric) with more ecological friendly materials. The use of recycled carbon fibres will enhance the mechanical properties and also improve the fire properties to mitigate the risk of fire and fumes in the cabin environment.

The objective of utilization of geopolymers matrices reinforced by carbon of Kevlar fibers is to test innovative material systems providing no smoke and toxic gas content with sufficient mechanical properties during fire exposure for passenger and cargo linings. Versatility of geopolymers matrices allows their exploitation both on laminate and sandwich structures, where e.g. foams could provide significant impact on mitigating the risk of fire and fumes in the cabin environment.

1.4. Research objectives

The main objective of this study is to simulate the behavior of the materials in fire condition, starting from the test results described in D7.2 , 7.5 and 7.8. Simulation activities will be performed in order to validate the tools and improve them. In particular, the following steps will be followed:

- Verify the Tools present in house,
- Improve the tools present in house
- Validate the tools present in house

The simulation of the combined mechanical and fire loading supports is a main objective to improve the understanding of new material solutions. To this, temperature dependent properties measured within first and second test batch as documented within D7.5 and D7.8 should be used. Validation of the developed simulation approach is considered by comparisons to tests within the Cufex facility that are documented within D7.8.

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1.5. Approach

The combination of metal layers and CFRP (fibre metal laminates) can lead to better FST properties. In this project the effect of different thicknesses, numbers and places of the metal layers should be investigated. For this, FMLs with different lay-ups have been manufactured and tested with a special focus on FST properties.

Another approach is to use semi-finished products from natural and recycled carbon fibres in combination with flame resistant geopolymer matrix. Exploitation of polymers matrices in combination with standard composite materials could pave the way to acceptable overall mechanical properties of geopolymers material systems. Application of carbon and Kevlar fibres, hybrid geopolymer – phenolic systems or geopolymer foam should be tested with respect of chosen manufacturing processes from coupon up to linings level.

1.6. Structure of the document

The document is adopting the Future Sky Safety template and general structure.

Chapter 1 covers an introduction summarizing:

- the programme content
- the P7 research objectives and approach

Chapter 2 gives an overview on the tools present in house

Chapter 3 provides an overview of test results described in D7.5 and 7.8 useful for the validation activities.

Chapter 5 provides validation activities

Conclusions and Recommendations are discussed in Chapter 6.

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2 SIMULATION TOOLS

The following two subchapters will give detailed information about the context of the tools present in Leonardo and DLR on the material behaviour in fire conditions.

- In Leonardo has been developed a tool FlamePTM with aim to simulate the flame penetration test required by CS 25.
- In DLR simulation tool has been developed to model the behavior of Fibre Metal Laminates (FML) exposed to combined mechanical and fire loading

2.1. Flame penetration test

2.1.1. Background

In the frame of an aircraft design, composite materials are widely used for interiors applications. Material and specimen (representative of the installation on A/C) used for the development of the interiors panel have to be tested in accordance with the certification requirement.

CS 25 requires that in case of fire on board, the protection of essential systems to a "continued safe flight and landing" has to be guaranteed; for the lining panels (ceiling and sidewall) installed in a Cargo Compartment classified as Class C and E certification rules require that they have to meet the flame penetration test defined by Appendix F Part III.

In details, FAR/CS 25 Appendix F Part III defines that:

- the specimen have to be representatives of the installation on a/c, and where applicable they must include all "features" installed like joints, lights, smoke detector, air outlet etc.;
- the number of specimens (three) required for each installation;
- the acceptance criteria for the test results which are:
  - no flame penetration within 5 minutes after application of flame source;
  - the peak of temperature, measured at 10 cm from the backside surface of the specimen, must not exceed 204°C when tested in horizontal position.

Furthermore, in order to ensure the proper thermal output of the burner, before the starting of the test execution, a calibration phase have to be performed.

Aim of the calibration phase is to verify that the air velocity in the draft tube, the temperature measured by a thermocouples opportunely installed and thermal flux measured by a calorimeter located at a distance of 20 cm from the exit of the burner are in the range required by the certification rule.

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Currently, the only way to predict the failures of certification tests is the engineering test made with the similar equipment. This approach is time consuming and expensive due to the time and the cost necessary to involve a certified laboratory, due to the purchasing of material, due to the cost and time for concept design and manufacturing of the specimen and due to the time and cost for campaign of tests.

For this reason, it was established to develop the method of fire test results prediction based on numerical simulations of specimens deformation.

2.2. Test rig set up

Classical arrangement of the apparatus for horizontal and vertical specimen fire penetration test and for the calibration is shown in Figure 1. It consists of the burner assembly and two specimen mounting stands made of the steel angles. The burner assembly is composed of gun-type burner and the burner cone made from stainless steel sheet.

Figure 1: Flame penetration test - rig

2.3. Flame penetration test model (FlamePTM)

The aim of the model is to simulate the behavior of a specimen in composite material when tested to flame penetration test.

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FlamePTM follow the steps reported below:

- Specimen definition:
    - Geometrical characteristics,
    - Thermo-mechanical material properties,
- Thermo-structural analysis,
- Analysis of the results.

2.4. Fibre Metal Laminates (FML) simulation tool

2.4.1. Background

Within the program FSS a new test facility was developed which is named CuFex (Compression under Fire exposure) facility. The aim of the test stand is to investigate the changing mechanical behavior of materials within a fire scenario. The test is not considered to be part of any qualification but to learn about the specific behavior within such a scenario and to identify promising new material solutions. Since measurements cannot be conducted in sufficient accuracy for such fire scenarios, a numerical tool is intended to support the investigations.

The simulation tool that is developed in parallel to the tests aims to improve the knowledge that is generated through the tests. It aims to learn about occurring effects within the materials and the degrading structural behavior over the duration of a test. Details that might be investigated within the simulation could be effects due to thermal and chemical degradation caused by the fire, thermal expansion effects that occur at material sections close to the burnt area, proceeding of heat conduction and others. A validation of the tool by experimental results (measured temperatures, loads, displacement) is therefore important. Furthermore, if validated, the tool might be used to change the setup of the investigated material, for instance its composite layup. Following simulation based sensitivity studies could decrease testing effort and help to identify further improved material solutions.

2.4.2. CuFex Setup

A hydraulic press was enhanced by a specimen device that contains a fire load withstanding clamping mechanism. The clamping is conducted by a potting of concrete material that is located inside a steel mold. The concrete potting material clamps the specimen against out-of-plane deformation. In-plane compression loads are applied through the face of the mold. The tested specimens have a dimension of 200mm length, a 120mm width and a radius of 245mm. A length of 40mm at each side is located inside the potting and thus the specimen field exposed to fire will have quadratic dimensions of 120mm side length. An additional aperture is available to reduce the area that is exposed to the flames. The specimens are curved to avoid structural collapse due to stability (buckling).

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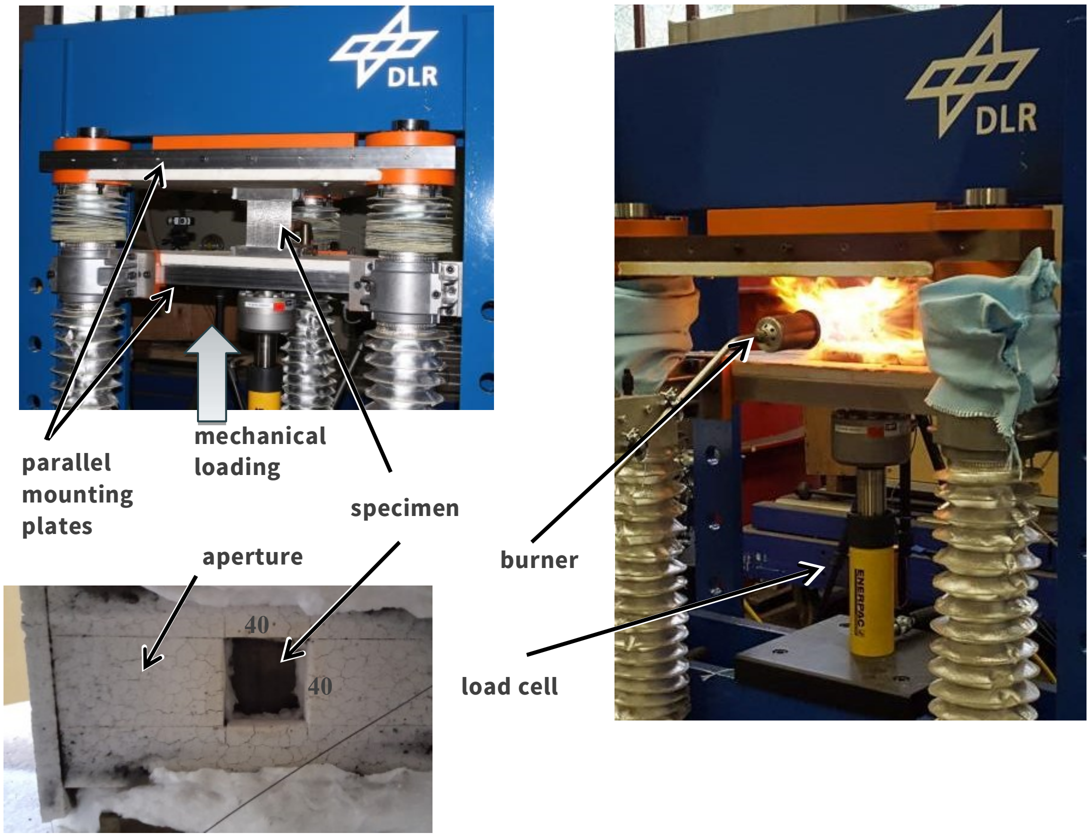

Figure 2: Cufex facility: clamped specimen (left) and while testing without aperture (right)

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3 EXPERIMENTAL TEST RESULTS

3.1. Test results

3.1.1. Materials chemical and thermomechanical characteristics

First batch tests have been executed also, as described in chapter 3.3 of ref.[1], to evaluate materials chemical and thermomechanical characteristics. Materials reported below have been tested:

- Carbon fabric 200g/m2, plain/GP resin L30,
- GURIT PHG 600-68-37 style 7781 prepreg.

Thermal properties of carbon geopolymer (C-GP) and glass phenol (G-P) resin composites were tested by three methods of thermal analysis: SDT (thermogravimetry), DSC (differential scanning calorimetry) and DMA (dynamical mechanical analysis). The thermogram of C-GP exhibits a long time weight loss which is probably caused by moisture evaporation, and combustion of carbon fibres which begins at about 600°C. G-P behaves differently; the degradation of organic resin starts at 300°C and only glass fibres remain at 600°C. Dynamical mechanical properties were measured by DMA up to 250°C.

In Figure 3 the DCS, DMA and SDT curves are shown. The thermal decomposition process was characterized in TGA experiments conducted in an inert atmosphere as well as an oxidative atmosphere at various purge flow rates.

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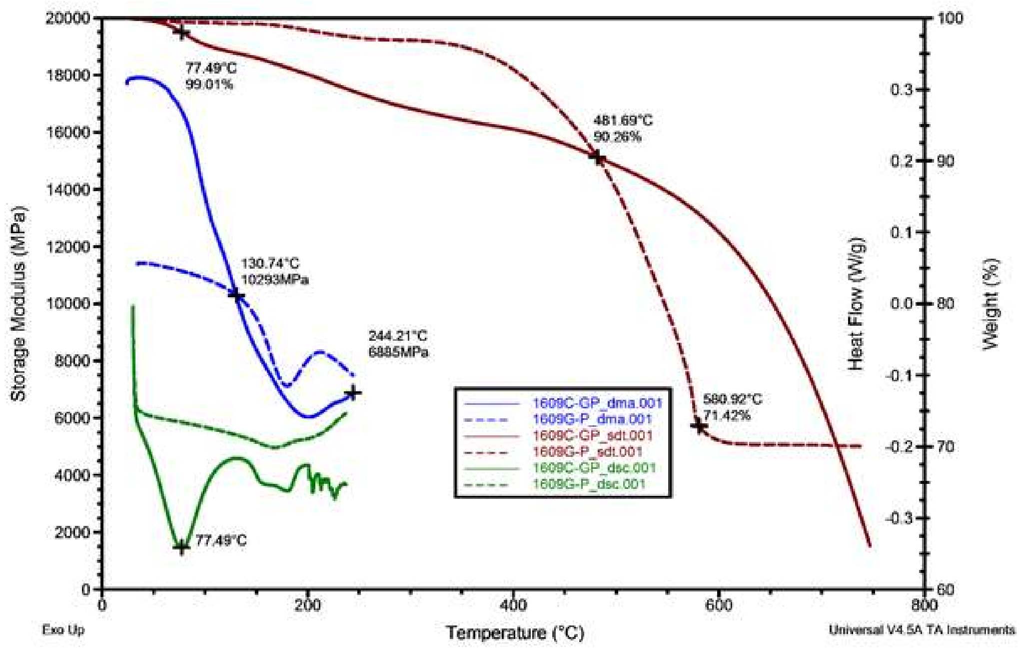

Figure 3: DMA (bending), SDT and DSC curves of carbon/geopolymer (C-GP*) and reference glass/phenol (G-P). DMA 5°C/min, DCS 10°C/min, SDT 20°C/min.**

3.1.2. Flame penetration test results

Flame penetration tests have been executed during the test campaign detailed in D7.5 and 7.8 (ref. [1]). Test results have been analysed and the data necessary for the validation activities have been extracted. The validation activities are detailed in chapter 5.

3.1.3. Fibre Metal Laminates (FML)

Mechanical material properties of the pure CFRP and the FML were measured with respect to temperature. They are documented in detail within D7.5 and D7.8. The results of the Cufex test (compression loading under fire exposure) are documented in D7.8.

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4 DEVELOPMENT ACTIVITIES

The aim of this paragraph is to show the implementation activities carried out in order to improve the FlamePTM.

In particular, the aim of the activity has been the implementation of a model to simulate the pyrolysis mechanism in order to introduce in the CFD model the effect of the reaction of the gas produced by the pyrolysis mechanism with the flame, and the consequence effect on the thermo-structural behavior of the tested specimen.

The activity has been executed in the following steps:

- Experimental data examination;
- Implementation of the pyrolysis model
- Simulation of the Thermogravimentric test analysis
- Tool validation through numerical experimental comparison analysis.

The CFD model developed has been validated by simulating the Thermogravimetric test analysis executed on G-P test specimen reported in ref. [1].

In Figure 4 and Figure 5 comparison analysis between experimental test results and CFD model results has been shown. The model allows to simulate the effect of the flame on the material characteristics due to the pyrolysis phenomena. In the model has been defined the reactions due to the pyrolysis of the solid. Gas composition has been extracted from the ABD0031 test executed by VZLU.

Analyzing the results, the little discrepancy between the two curves are due to the fact that the CFD model do not simulate in depth the preliminary material degradation due to the degradation of organic resin that starts at 300°C.

The pyrolysis model for G-P material herein described and for C-GP material have been integrated in the FlamePTM tool.

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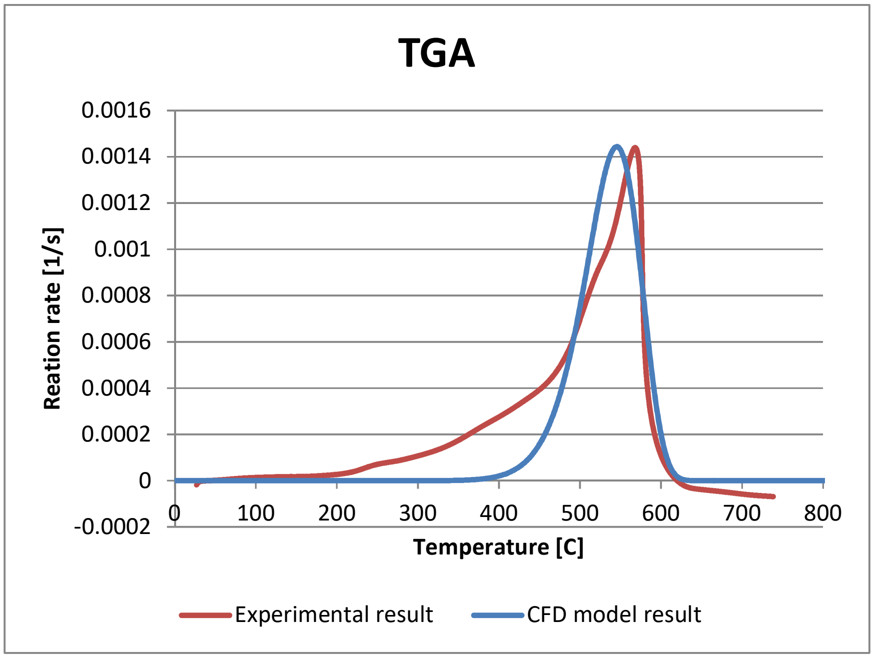

Figure 4: Comparison analysis – Reaction rate

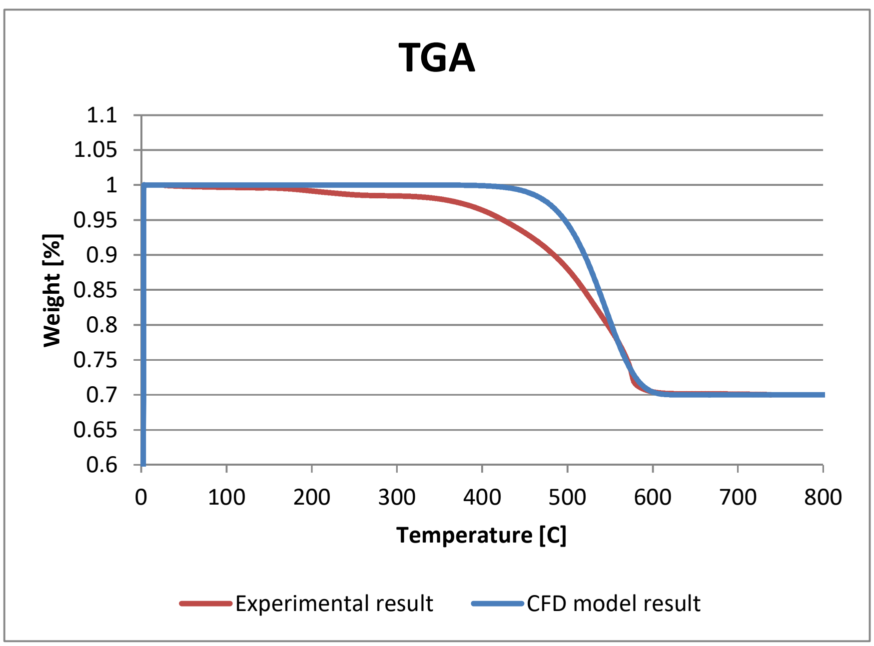

Figure 5: Comparison analysis – Loss of weight

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5 TOOL VALIDATION ACTIVITIES

5.1. Flame penetration test validation tool

FlamePTM validation activities have been carried out by comparing the simulation tool results in terms of temperature field and thermos-structural behavior of test specimen with the test results detailed in ref.[1] and ref.[2].

In particular in order to gather temperature data in correspondence of the specimen surface VZLU performed a dedicated test applying sixteen thermocouples in defined points. The thermocouples location have been opportunely defined, on the basis of the flame temperature pattern.

VZLU defined a new thermocouples installation technique in order to measure the temperature for the tool validation activities. The new technique consists in the installation of the thermocouples embedded in the test specimen (see Figure 8).

In Figure 6 and Figure 7 are shown the location of the thermocouples used during the test described in ref.[3]. In Figure 8 test results are shown in terms of temperature in correspondence of the thermocouples.

Unfortunately, on this composition we did not evaluate the fastening plane necessary to fix the specimen in the test rig. In fact, this fastening plane consists of steel plates (high conductivity), on which the test specimen laying during the test. Therefore, analyzing the data shown in Figure 8 and the position of each thermocouples (see Figure 6 and Figure 7) it was clear that temperature measurement points 1,2,3, 4, 5, 10, 12, 13, 14,15, 17, 18 and 19 are influenced by fastening plane.

Therefore, for the model validation activities the temperature measured with thermocouples 6, 7, 8 and 9 was selected. In Figure 10 and Figure 11 the comparison analysis between the experimental test results and the model results are shown.

As shown in Figure 10 and Figure 11 FlamePTM results are more instable compared to the test results, probably is due to the different time step between the acquisition tool used during the test and the model. Furthermore, in the model, oscillation of the temperature field has been detected during the simulation of the flame generated by the burner. By the way, FlamePTM results have an acceptable correlation with the experimental results. The model thermocouples and the test rig thermocouples give the same temperature pattern. Furthermore, Figure 12 shows FlamePTM results compared with experimental results (flame map).

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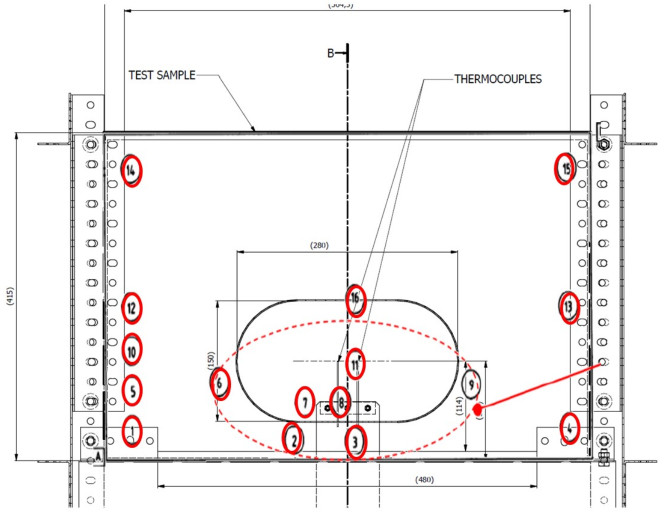

Figure 6: Thermocouples location – surface exposed to the flame

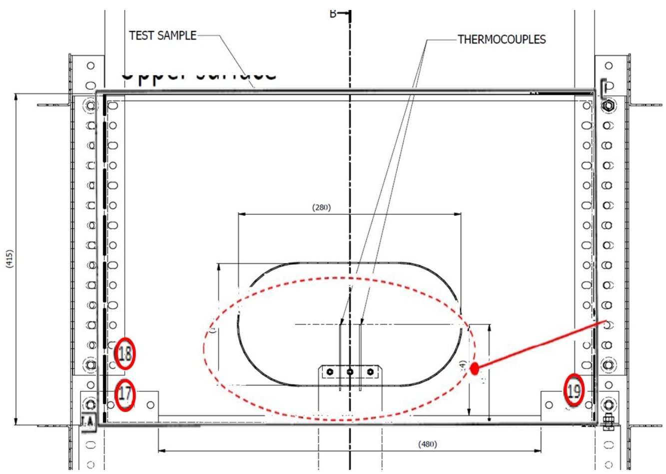

Figure 7: Thermocouples location – surface not exposed to the flame

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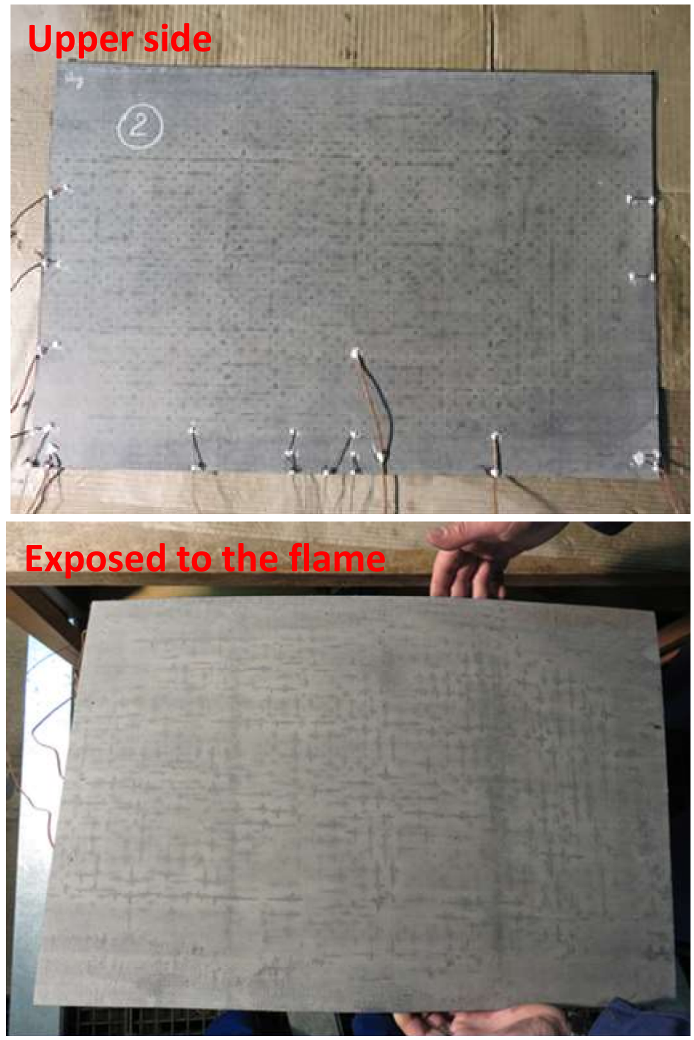

Figure 8: Specimen thermocouples installation

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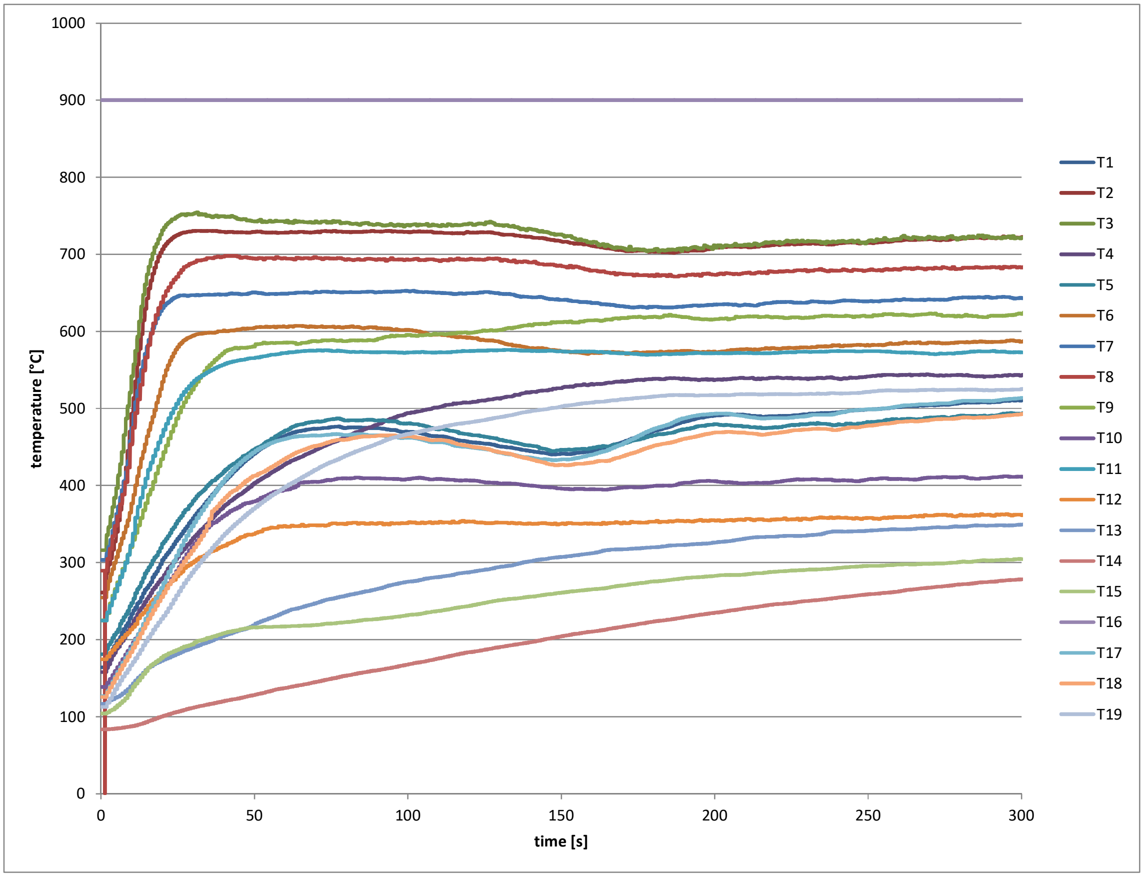

Figure 9: Temperature measured on thermocouples – Experimental results

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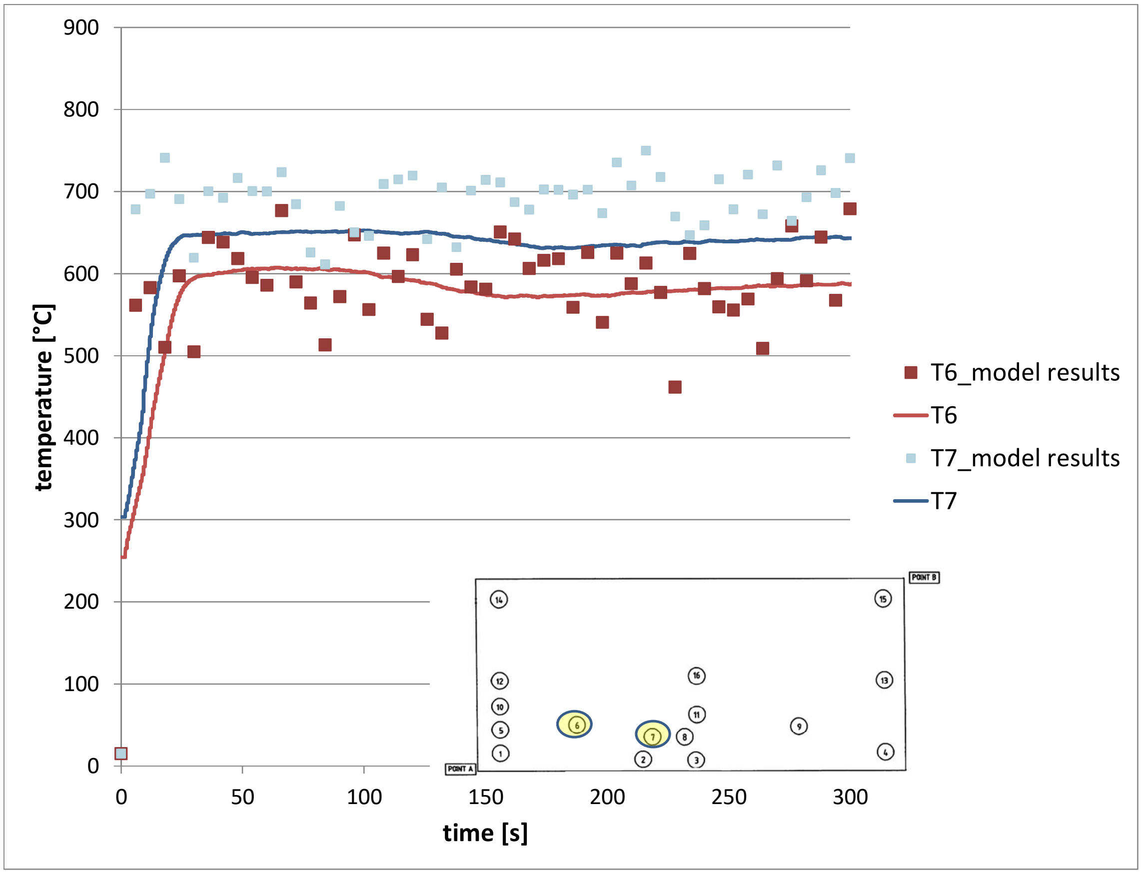

Figure 10: Comparison analysis between model results with experimental results

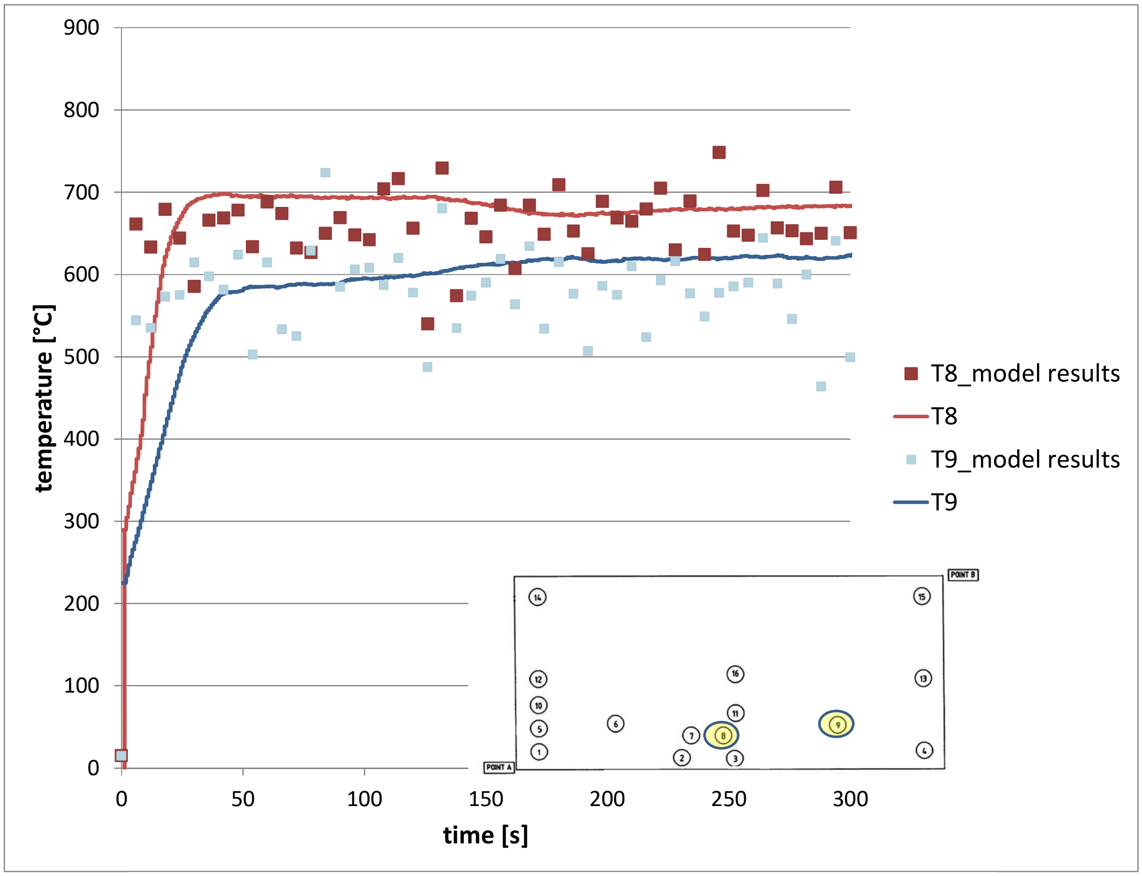

Figure 11: Comparison between model results with experimental results

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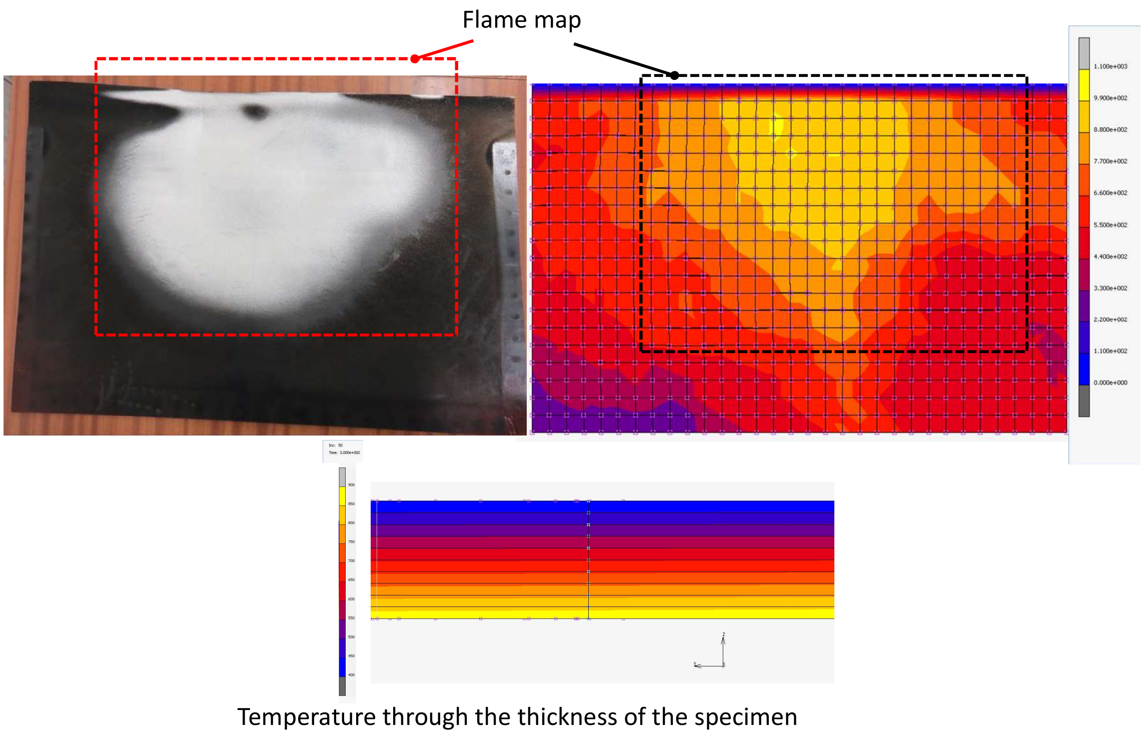

Figure 12: Temperature pattern

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5.2. Fibre Metal Laminates (FML) validation tool

5.2.1. FE-model and modelling strategy

The intention of the FE-model is to further investigate the structural behavior examined within the CuFex tests. A first simplified FE-model representing a unit cell in the center is aimed to investigate the sensitivities of the thermal system and thermal parameters within a heat transfer analysis (HTA). Later, a second model is used to show further influences of in-plane heat conduction and transient heat propagation. To decrease calculation time, the full model is reduced to a symmetric partial model.

Following, sequential mechanical analyses are carried out to model the degradation of structural load carrying capabilities. A single mechanical step uses the temperature distribution at a certain time step of the heat transfer analysis (symmetric partial model) and derives the according mechanical properties by the material model. A maximum load can be determined from the load shortening curves. The temperature distribution is constant within this single analysis step. Repeating the mechanical analysis for several time steps of the thermal analysis will lead to a buckling load reduction as a follow-up to progressing decomposition and degradation.

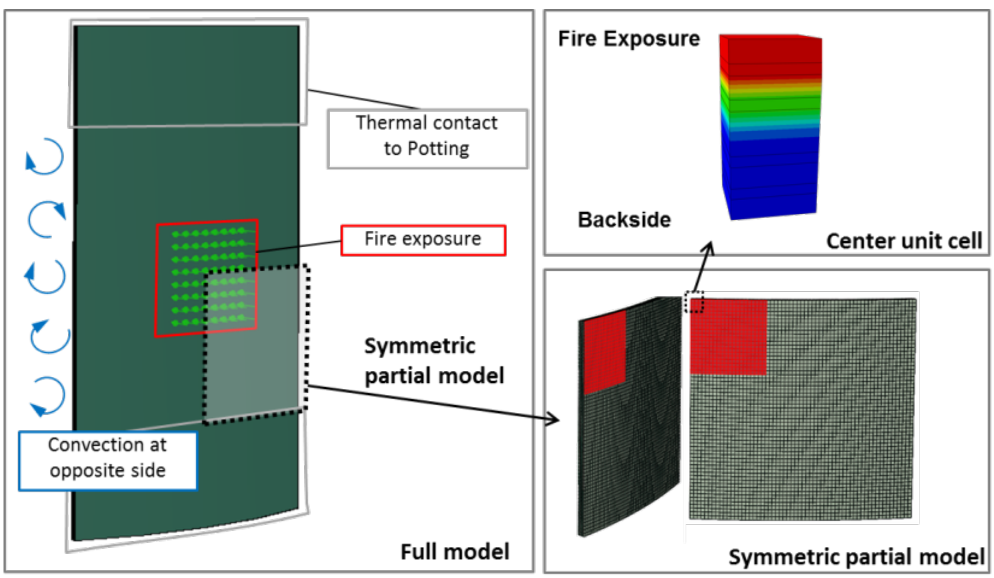

Figure 13 : Overview to the FE-models used and boundary conditions applied

During fire testing deformations occur as a result to thermal strains but also due to the decomposition of the matrix between the metal layers. The developing gasses are trapped between the metal layers and lead to a pillow effect. Modelling of this pillow effect was an initial aim to develop further understanding of the resulting mechanics. Unfortunately, the resulting computational effort for simulating the inflation process was not acceptable due to local state and property changes and the resulting deformations. According to that, respective assumptions and simplifications are made, such as the mentioned mechanical analysis for a constant temperature state at a certain time within the test.

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Further assumptions are mentioned in section 4.2.1.1. The material models used and the assumed thermal and mechanical material behavior over the temperature are outlined in section 4.2.1.2.

5.2.1.1. Boundary conditions

The thermal boundary conditions are shown in Figure 13 at the full model. Since the frontal side is insulated by an aperture, only the center region with a dimension of 40mm x 40mm is used for heat introduction. The heat introduction is modelled by surface film condition and is assumed to be constant over the selected area. The sink temperature of 1200°C was defined according to the approximate temperature of the burner flame measured during calibration tests. The film coefficient was selected to 100W/K. For a specimen at room temperature, this results in a heat flux of 120kW. This value could be validated by measurements within burner calibration.

The area next to this center region is modelled by adiabatic boundary conditions. This assumes that the insulation around the fire exposed area is nearly perfect with negligible heat losses. The rear face is assumed to show natural convection to air at room temperature and ambient radiation to room temperature. Within the present study the thermal contact to the potting is neglected. For the future, this boundary condition could be studied in more details to include a transfer of heat from the specimen to the potting, if needed.

To respect the pillow effect, the properties of trapped gasses from decomposition (shown within the following section 4.2.1.2; Table 5, T > 337°C) are divided by a thickness factor k_t. The factor is used to consider the inflation caused by the gas formation. An increased layer thickness generates the insulation effect. Within the FE-model, the decomposed layer does not increase its thickness within the present modelling strategy. This is why the thickness factor k_t is used. The factor ideally has the size of relative thickness increase and produces smaller conduction coefficients. Since conduction is a linear phenomenon, the insulation effect through increasing thickness is therefore modelled by reduced conduction coefficients. The value of k_t is initially assumed to be 10. The sensitivity will be studied within the level of the centre unit cell model.

The mechanical analysis (MA) uses a static temperature distribution derived from a chosen time step of the heat transfer analysis. Over the duration of the MA the temperature is constant. The load is applied at the lower side of the structure through a given displacement U. All other Degrees Of Freedom (DOF) are zero at this plane. The DOF at vertical plane distant to the fire exposed area are not constrained. The constrained DOF of the symmetry planes are shown in Figure 14.

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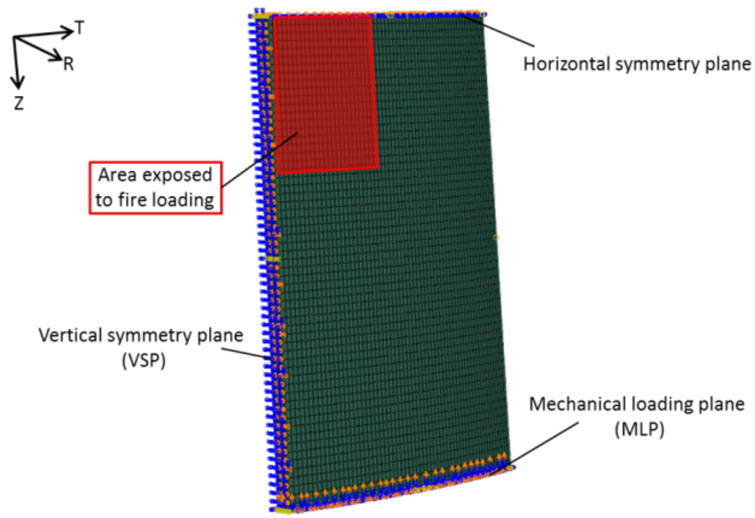

	MLP	VSP	HSP
U_R	0		
U_T	0	0	
U_Z	U		0
UR_R	0	0	0
UR_T	0		0
UR_Z	0	0	

Constrained DOF

Figure 14: Mechanical Boundary Conditions for the symmetric partial model

Summarising, the modelling approach was simplified for capturing the process of decomposition (conf. 4.2.1.2), the presence of fibres after resin decomposition and the thermal influence of the pillow effect as explained above (through thickness factor k_t)

Throughout the studies, scientific questions were raised which could not be studied in detail within this project and therefore shall be part of future research. Explicitly, it concerns interactions between deformations and thermal loading, exothermal effects, thermal expansion effects, delamination and deformations as a follow-up to the pillow effect (pressure through trapped gasses).

5.2.1.2. Material modelling

The thermal material properties are used in the heat transfer analysis. The centre unit cell depends only on the through thickness values while the symmetric partial model also requires in-plane properties.

Thermal properties

Within Literature [3], the decomposition energy of approximately 378800 J/kg is used to model the decomposition, and a decomposition temperature of about 350°C was determined. The data in [3] is based on glass/vinyl ester laminates. Since the measurement of decomposition energy and temperature is still an open task, the decomposition energy of the present CFRP resin material is estimated at around 350000 J/kg, and the decomposition temperature of 327°C (600K) is assumed. The time dependency of the decomposition is ignored. To model the decomposition, a temperature range between 327°C and 337°C was allocated to withdraw the decomposition energy. Within this range of

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10K, the specific heat was increased instantaneously to withdraw the heat as described in values in Table 2. Directly above 337°C the specific heat was set to values of the gas, which is explained in the following (cf. Figure 15).

To model the insulating effect of the FML and the trapped gases that are developed through the decomposition of the CFRP layers, thermal properties of the gasses need to be provided. To this a Toxicity test according to ABD 0031 was performed at the start of the project measuring the HCl, HF, SO2, NOx, CO, HCN content. The test method is equal to the smoke density test (CS/FAR Part 25), but at the end of the test, gas content is captured and the amount of toxic gases evaluated. The results are listed within Table 1.

Table 1: Results of Smoke toxicity test according to ABD 0031, gas parts measured and evaluated ratios

in ppm	HCN	CO	NO_x	SO_2
Test 01	n.a.	125	21	25
Test 02	10	51	5	4
Test 03	20	105	32	35
Test 04	8	94	19	21
Average in ppm	12.60	93.75	19.25	21.25
Part ratio	8.58%	63.84%	13.11%	14.47%
Molar Mass	27g/mol	28g/mol	30g/mol	64g/mol
Molar fraction	6.94%	53.54%	11.78%	27.74%

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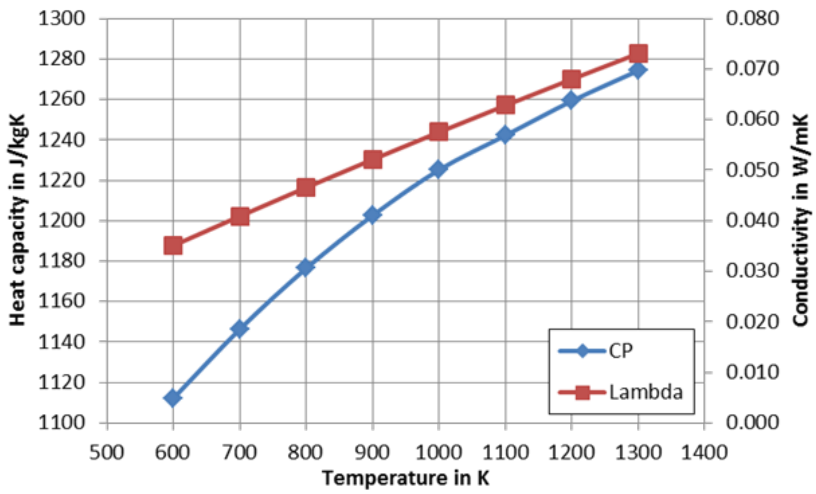

Figure 15: Thermal properties of the developing gasses

The gas composition is used to derive the thermal properties of the trapped gases (specific heat c_p and thermal conductivity λ) over the temperature. This assumes that the gas composition is equal to Table 2 and does not change with progressing test duration. Moreover, a constant volume and no mass loss are expected.

The thermal conductivity used in thickness direction below glass transition are based on measurement results. Above glass transition but below decomposition the thermal conductivity in thickness direction are assumed to λ_3=0.3W/mK. The values are based on data from similar materials. The in-plane conductivity is dominated by fibre values, it is assumed to λ_1= λ_2=6.0W/mK. Since the fibres are still present after matrix decomposition, the in-plane conductivity is assumed to be constant.

Summarizing, the thermal properties used are shown in Table 2.

Table 2: Thermal properties used within the Cufex-Simulation (lin. inc. = linear increasing), the thickness factor thickness factor k_t (explained in 4.2.1.1) is not included

T in °C	20	100	190	200	327	327.01	337.0	337.01	1000
$\lambda_{1,2}$ in W/mK	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
λ_3 in W/mK	0.58	0.61	0.63	0.3	0.3	0.3	0.047	lin. inc.	0.076
c_p in J/kgK	770	linear increasing			850	35000		1110	1270

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Mechanical properties

The modelling of the mechanical properties was conducted based on the first batch test results documented in [1] and [2].

Material models from the literature are implemented to achieve temperature dependent material behaviour within simulations. Gibson [4] as well as Mahieux and Reifsnider [5] developed formulas to describe the mechanical properties depending on the temperature. They are given by:

Gibson: $$P(T) = \frac{P_U + P_R}{2} - \frac{P_U - P_R}{2}\tanh\left(k\left(T - T_g\right)\right)$$

Mahieux and Reifsnider: $$P(T) = \left(P_g - P_r\right)\exp\left(-\left(\frac{T}{T_g}\right)^{m_1}\right) + \left(P_r - P_d\right)\exp\left(-\left(\frac{T}{T_d}\right)^{m_2}\right)$$

Gibson's formula [4] and the equation based on Mahieux and Reifsnider [5] both formulate functions representing a general property P before and after a state change, for example the glass transition or the decomposition in dependence on the temperature at which the state change occurs. Moreover, both functions need one or multiple fitting parameters. In the present studies, the fitting parameters were chosen based on comparisons to the DMA results from the first batch testing reported in [1] and [2]. Gibson's model was used to model the behaviour until decomposition. The model uses k as fitting parameter and the indices U and R for the properties in unrelaxed (room temperature) and relaxed state (past state change), respectively. The model based on Mahieux and Reifsnider [5] was used additionally to model the decomposition state change. The equation therefore uses two fitting parameters, m_1 for the glass transition term and m_2 for the decomposition term. The parameters used are shown in Table 3 with g, r and d denoting the properties in glassy, rubbery and decomposed state, respectively. T_g and T_d are the glass transition temperature and the decomposition temperature.

Both models showed a rather poor agreement to the measurement for the properties that are not applied in fibre direction. Therefore, a modification was introduced by a linearly temperature dependent P_g (property at room temperature) that decreases with increasing temperature by the amount denoted by "q".

$$P_g = P_{g*} - q \cdot \Delta T$$

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Such modification of the models is implemented to depict the resin dominated behaviour within glassy state. The corresponding curves of the material properties are denoted by "modified". The material properties are shown in Figure 16 to Figure 20.

Table 3: Parameters used to model the mechanical temperature dependent material behavior

P	g *	R	d	T_g	T_d	q	k	m_1	m_2
$E_{UD,0}$	164000MPa	15000MPa	0MPa	200.0°C	327.0°C	0 MPa/K	0.079	34.2	20.0
$E_{UD,90}$	9000MPa	1000MPa	0MPa	200.0°C	327.0°C	8MPa/K	0.04	20.0	10.0
G_{UD}	7000MPa	500.0MPa	0MPa	180.0°C	327.0°C	20MPa/K	0.05	30.0	50.0
E_{FML}	105000MPa	22000MPa	0MPa	200.0°C	327.0°C	0 MPa/K	0.42	20.2	20
G_{FML}	22000MPa	2000MPa	0MPa	200°C	327.0°C	60MPa/K	0.05	30.0	50.0

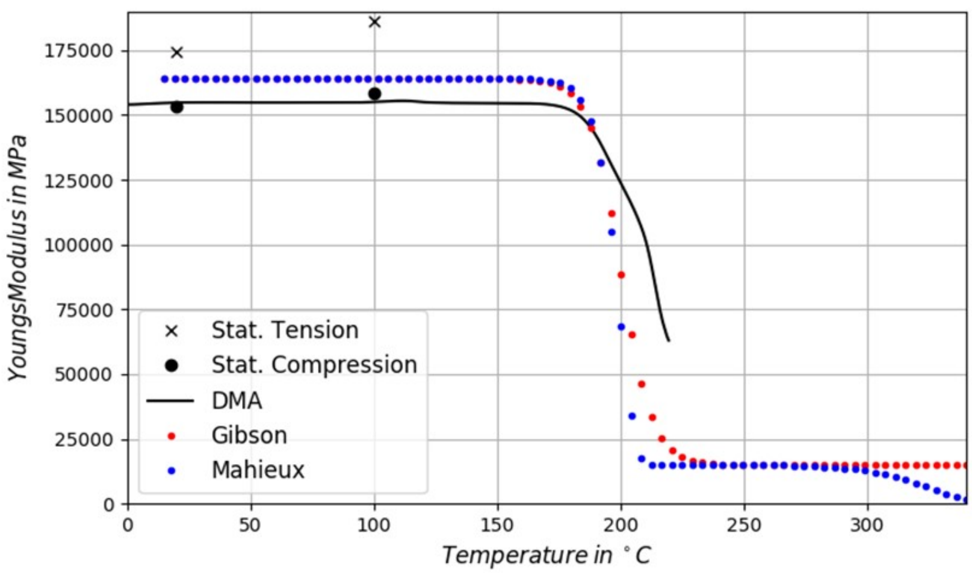

Figure 16: Comparison of material model and measurements: Young's modulus of CFRP in fibre direction

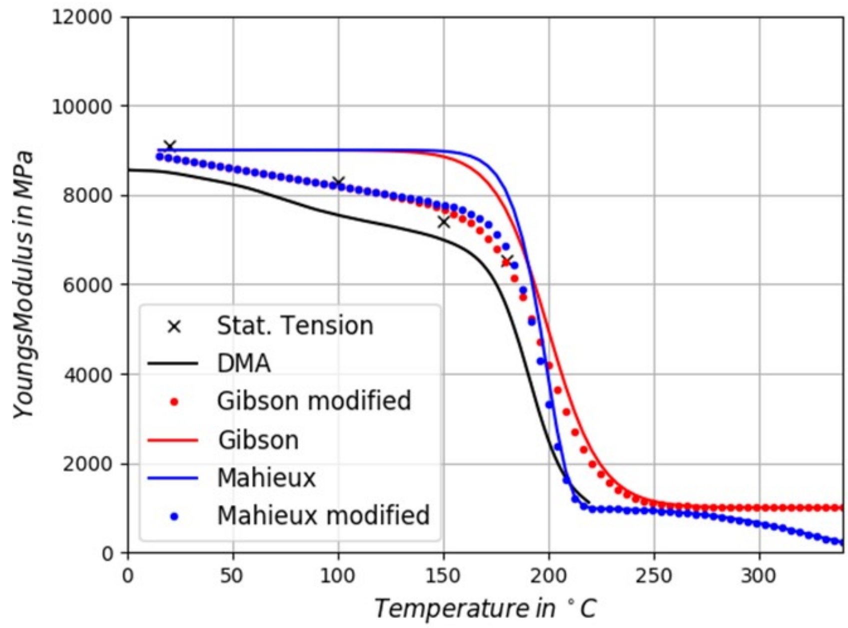

Figure 17: Comparison of material model and measurements: Young's modulus of CFRP in transverse fibre direction

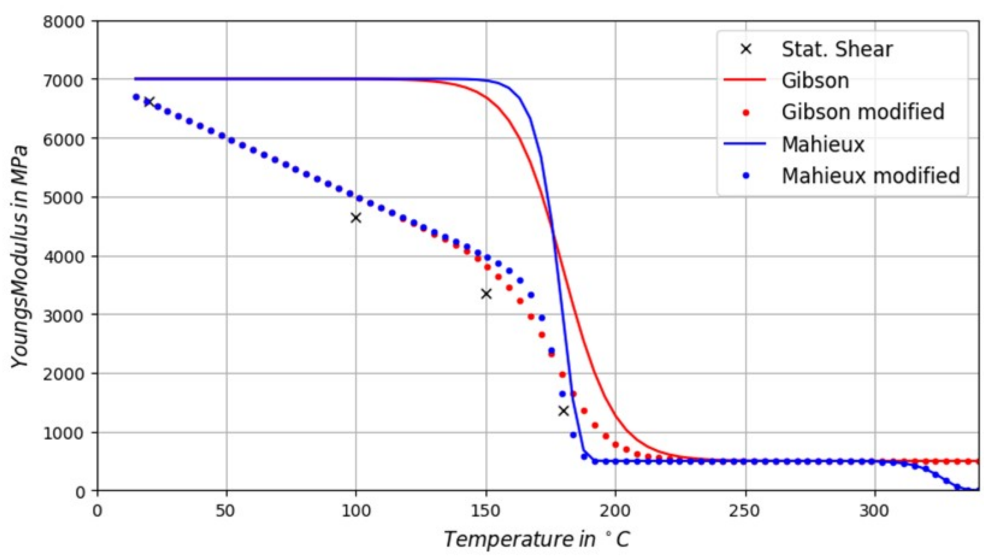

Figure 18: Comparison of material model and measurements: Shear modulus of CFRP

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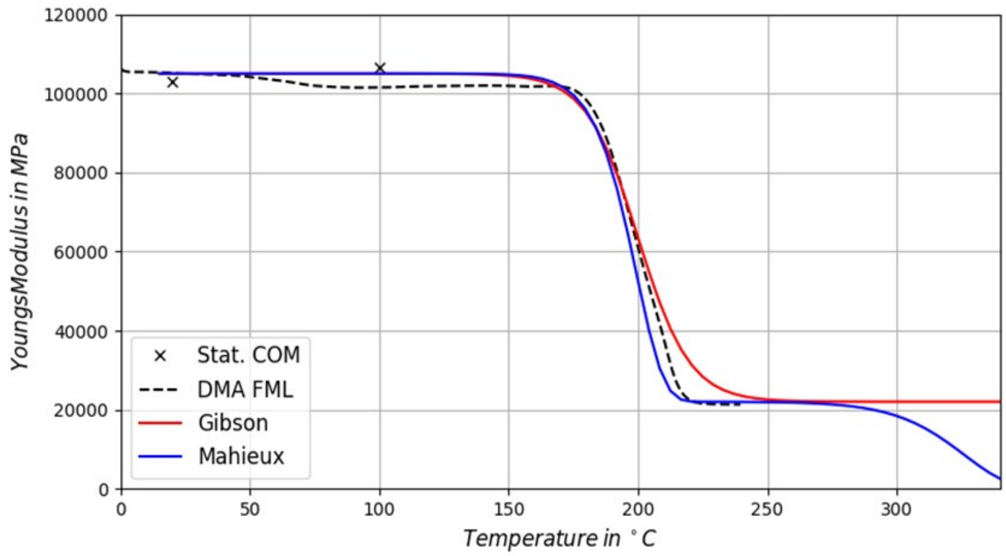

Figure 19: Comparison of material model and measurements: Young's modulus of FML

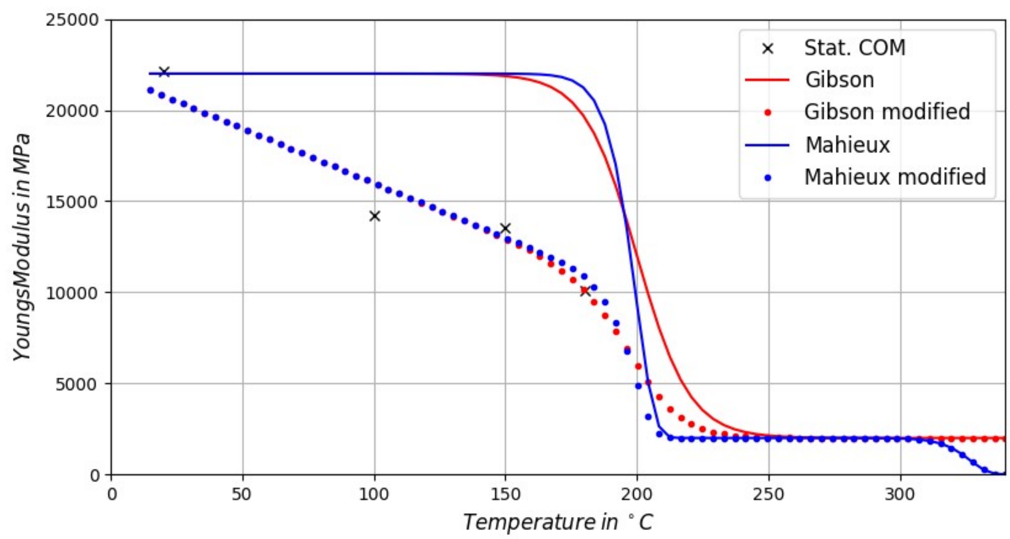

Figure 20: Comparison of material model and measurements: Shear modulus of FML

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5.2.2. Results and discussion

To initially test the applicability of the present simulation strategy, heat transfer analyses were conducted at the center unit cell model. A first comparison with test results is shown in Figure 22. Here both versions (v04 and v05) did use a decomposition temperature of 300°C (573K). In reference to Literature (e.g. [3]) this value appears too low. Within Table 2, an updated value of 327°C /600K) is provided. Finally, measurements are required to ensure the correct values. The difference between the models v04 and v05 was made in the modelling of the first layer. The developing gasses of the first layer will not be trapped. Assumably, the gasses will escape to the ambiance. Thus, the first layer should not be considered to perform any insulating behaviour. This change was made between model v04 and model v05. For further understanding of the behaviour, the temperature history for all nodes over the thickness of the centre unit cell model v05 is shown in Figure 21. Point A shows the onset of decomposition of CFRP layer 1 which is the outermost layer to the fire exposure. Point B shows the onset of decomposition of CFRP layer 2. The layer between 1 and 2 shows increasing temperature values from that which is a consequence of the progressing decomposition. At point C the third CFRP layer starts to decompose.

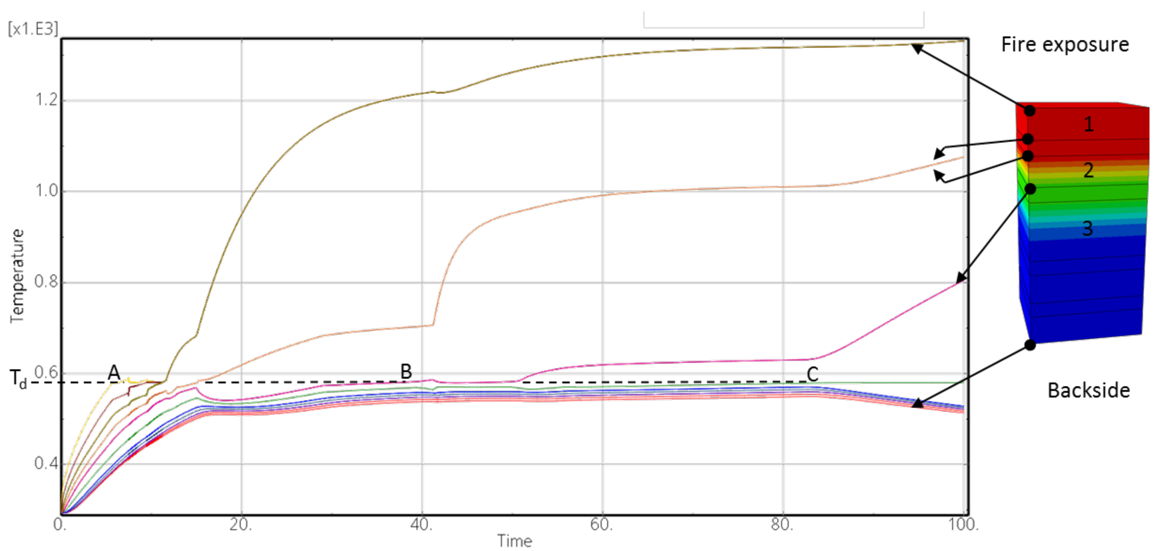

Figure 21: Temperature history evaluated at all nodes over the thickness for the centre unit cell (CUC) model v04

The partial structural model (PSM) within the version v04 was only solved up to approximately 10.5 seconds test duration. As a consequence to the state changes, changing material properties and the local heat introduction, low increments were needed resulting in a huge calculation time (several days up to the latest point of PSM v04, cf. Figure 22). At this stage, the idea of a thermo-mechanically coupled analysis was discarded for the current project. PSM v07 was conducted with increased element sizes using the material properties denoted in Table 2. The calculation duration could be reduced to

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approximately 6h by that. Nevertheless, further studies have to be carried out in order to significantly reduce the computation effort with respect to the predictive quality of the model. Part of such studies is increased element sizes, the element choice, the setup of analysis incrementation and others. Figure 23 shows the temperature distribution after a step time of 10.5s.

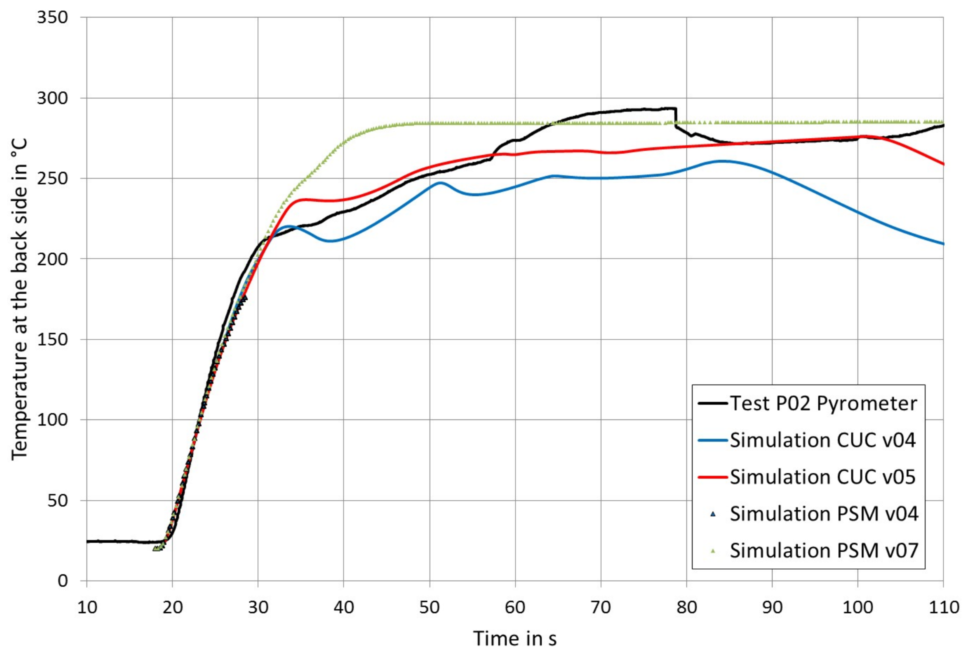

Figure 22: Comparison of CuFex test backside temperature measured by a pyrometer and the backside temperature evaluated from simulation models for the center unit cell (CUC) and the partial symmetric model (PSM)

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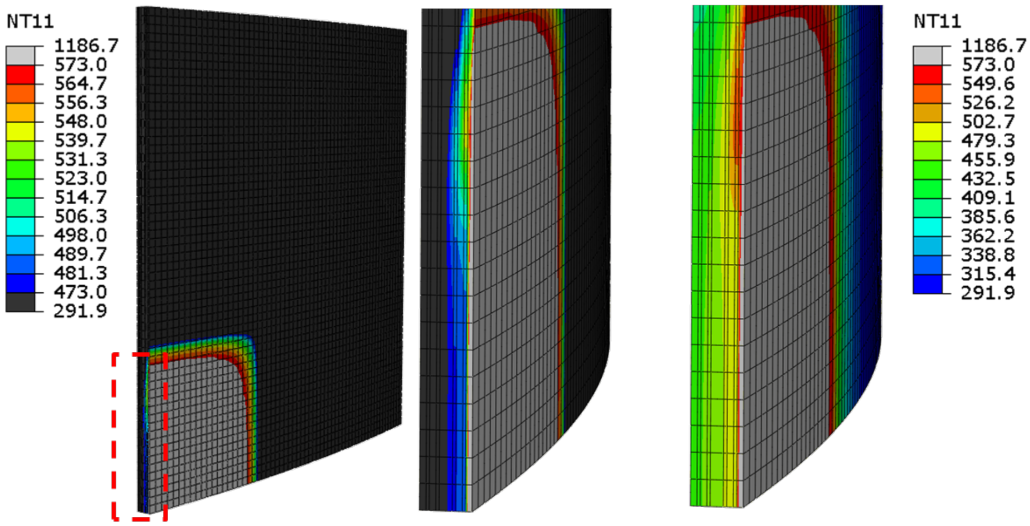

Figure 23: Symmetric partial model after 10.5s of fire exposure: The scaling of left two models pictures shows the temperature rage $T_g < T < T_d$

To investigate the mechanical behaviour by the proposed simulation strategy, multiple MA's are conducted. Figure 24 shows the drop of mechanical performance due to degrading material properties using the PSM v07 model as basis. Compared to the experimental results shown in D7.8 [2] the drop of the load-shortening curve seems to be low. This could be a result to several reasons. The aperture did allow the flame to hit a bigger area and thus the real degradation is lower. The simulation does not consider delamination, e.g. of the plies that are close to the heated ones but not fully degraded. This is an important point for the stability behaviour of the structure. The simulation values thus seem too high. Moreover, yet the simulation does not include thermal expansion effects which would also decrease the pathway of the load shortening curves exposed to fire. The integration of the mentioned points are possible topics of future work.

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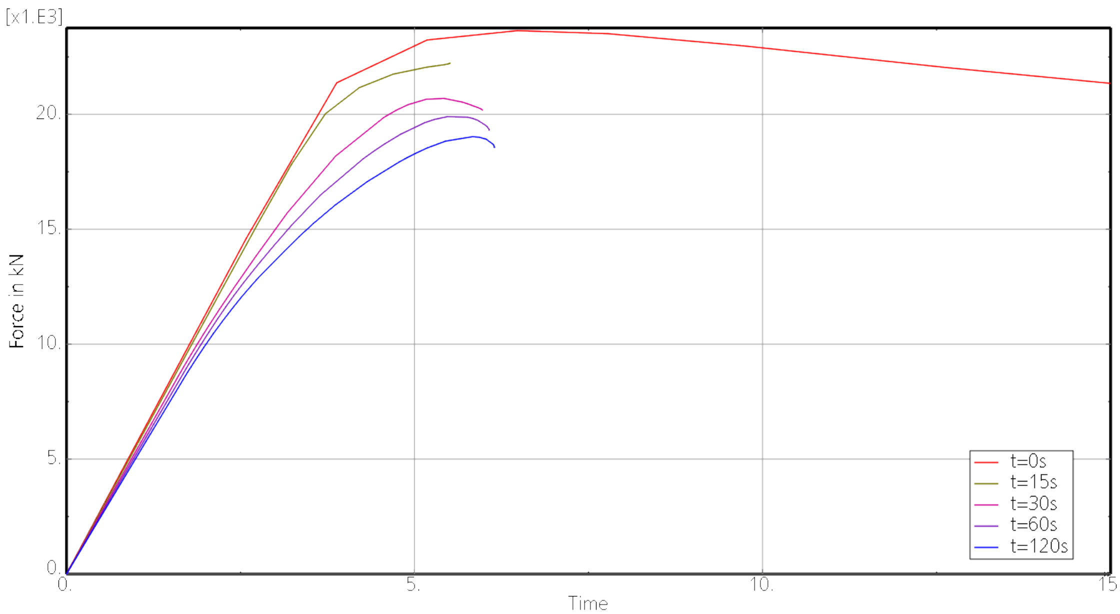

Figure 24: Comparison of load shortening curves after increasing duration of fire exposure

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6 CONCLUSIONS

In conclusion the test results obtained during the experimental campaign allowed to collect all the data necessary to improve the FlamePTM tool, thanks to in depth characterization of the tested material, in order to simulate and study the specimen behavior in terms of :

- material degradation: gas produced by the pyrolysis phenomena,
- specimen structural behavior: deformation and stress.

Structural analysis results have not been reported in the present deliverable because of the negligible deformation detected with the model. It is due to the fact that the flame penetration test is a static test and the only structural effect is due to the effect of the gas produced in the specimen. It has not been considered in the model.

FlamePTM with the improvement described in this deliverable assures a depth simulation of flame penetration test with the following reported important benefit for aircraft manufacturers:

- Reduce the time and costs of specimen supplying,
- Reduce test time, the experimental activity is minimized to the confirmation of the results for the design approval,
- Reduce the number of development tests and certification tests (cost reduction),
- Reduce the risk associated to the development phase: the refinement is anticipated in the concept phase (cost reduction),
- A wide spectrum of configurations and cases (optimized design) can be investigated.

The simulation model to investigate FML behaviour within the CuFex facility uses temperature and state dependent material properties. The insulating pillow effect of the FML could be reproduced by the simulation and the drop of mechanical performance due to the decomposing matrix was studied. Nevertheless, several simplifications were assumed within the FE model and have to be studied within future work to enhance the model.

The simulation of the combined mechanical and fire loading supports the understanding of new material solutions. Further enhancements of the simulation strategy could lead to identify further improved material solutions such as optimized layups. Furthermore, this leads to a decreased effort of expensive testing.

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7 REFERENCES

[1] D7.5: New materials for fire protection in cabin environment – Test results first batch

[2] D7.8: New materials for fire protection in cabin environment – Test results second batch

[3] Feih S. et al. (2007): Modelling the compression strength of polymer laminates in fire. In: *Composites: Part A* 38, p. 2354-2365, doi:10.1016/j.compositesa.2007.04.013

[4] Gibson, A. G. (2005): Laminate Theory Analysis of Composites under Load in Fire. In: *Journal of Composite Materials* 40 (7), S. 639–658. DOI: 10.1177/0021998305055543.

[5] Mahieux, C. A.; Reifsnider, K. L. (2001): Property modeling across transition temperatures in polymers: a robust stiffness-temperature model. In: *Polymer* 8 (42), S. 3281–3291. DOI: 10.1023/A:1011230620286.

[6] R 6739 Composite Panel Test Alfa Cs-25 Appendix F Part III

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