Mitigating risk of Fire, Smoke and Fumes

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

This deliverable is produced by the Project P7 "Mitigating Risks of Fire, Smoke and Fumes" of Future Sky Safety and is the final synthesis report of the work performed within its three Work Packages:

- WP7.1 "Understanding and characterizing the fire behavior of primary structures composite materials",
- WP7.2 "Improving material solutions to mitigate fire, smoke and fumes in the cabin environment", and
- WP7.3 "Effects of new materials, technology and fuel systems on the on-board air quality".

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Grant Agreement No.	640597
Document Identification	D7.16
Status	Approved
Version	2.0
Classification	Public

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Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

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Document Change Log

Version	Issue Date	Remarks
1.0	14-06-2019	First formal release
2.0	24-06-2019	Second formal release

Approval status

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Acronyms

Acronym	Definition
ACARE	Advisory Council for Aviation Research and Innovation in Europe
BVID	Barely Visible Impact Damage
CBM	Condition Based Maintenance
CFD	Computational Fluid Dynamics
CFRGC	Carbon Fiber Reinforced Geopolymer Composite
CFRP	Carbon fibre reinforced plastic
CLP	Classification, Labelling and Packaging
COTS	Commercial Off The Shelf
DLR	Deutschen Zentrums für Luft- und Raumfahrt
DMA	Dynamic mechanical analysis
DSC	Differential Scanning Calorimetry
EASA	European Aviation Safety Agency
EC	European Commission
ECS	Environmental Control System
E-ECS	Electrical Environmental Control System
e-nose	Electronic Nose
EU	European Union
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FML	Fibre metal laminate
FSS	Future Sky Safety
FST	Fire/Smoke/Toxicity
GF	Glass Fibre
GFRP	Glass fibre reinforced plastic
GP / GPL	Geopolymer
H2020	Horizon 2020
HR	Heat release
HRR	Heat release rate
IATA	International Air Transport Association

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Acronym	Definition
IFCAS	Industrial cabin air quality Framework based on Continuous Air quality
ISS	International Space Station
JAR	Joint Aviation Regulations
JRI	Joint Research Initiative
MS	Mass Spectrometry
OEM	Original Equipment Manufacturer
OMC	Organic Matrix Composites
P7	FSS Project n°7
PHM	Prognostics Health Management
PID	Photo-ionisation detection
PF	Phenolic Resin (phenol formaldehyde)
rCF	Recycled Carbon Fibre
REACH	Registration, Evaluation, Authorization, Restriction of Chemical
SAE	Society of Automotive Engineers
SD	Smoke Density
SESAR	Single European Sky ATM Research
SRIA	Strategic Research and Innovation Agenda (from ACARE)
TCP	Tri Cresyl Phosphate
TD	Thermal desorption
TGA	Thermogravimetric analysis
VIAQ	Vehicle Indoor Air Quality
VID	Visible Impact Damage
VZLU	Czech Aerospace Research Centre
WP	Work Package

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EXECUTIVE SUMMARY

Problem Area

The objective of Future Sky Safety Project P7 “Mitigating the risk of fire, smoke and fumes” of Future Sky Safety (FSS) is in the long term to support increasing safety - meaning here reducing the number of casualties - with respect to fire related issues (in-flight or post-crash). First, many studies on the current flights have shown that about 50% of the casualties in case of aircraft accidents are linked to situations where fire is involved. Hundreds of casualties 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 Carbon Fibre Reinforced Plastics (CFRP) composite parts in aircraft design, such as fuselage panels, engine carters, engine exhausts,… etc) raises several safety questions with respect to unknown behaviors 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. In the FSS research program, it was decided to address the fire issue as part of Theme 4: “Building the Ultra-resilient Vehicles”. It means that the research work is focused on material and structural questions, and aims at mitigating fire related safety risks when/by introducing new generation of materials in future aircraft design (incl. possible eco-friendly ones). The scope of the present works covers both primary structures materials (the reference being epoxy resin, carbon fibre reinforced polymers) and cabin materials (reference being phenolic polymers, glass fibre reinforced plastics). Considering this focus, it must be noticed that very few test results are available today to the research community, because of evident costs (test facilities, destructive tests, specimens and sensors) and industry confidentiality reasons.

A first part of the P7 project (WP71 - Understanding & characterizing the fire behavior of primary structure composite materials) is then 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. Another objective (WP7.2 - Improving material solutions to mitigate FS&F in the cabin environment) 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, different composite materials have been tested according to prescribed test plan and industrial test protocols. The application of state-of-the art simulation tools (commercial or research tools) is also proposed in WP71 and WP72 to evaluate their capabilities and identify paths for future developments. Last, and since aircraft materials together with architectures, propulsion concepts, etc, will change disruptively in response to the increased air traffic projections and the global environmental issues, WP7.3 - Effects of new materials, technology and fuel systems on the on-board air quality - concerns a thorough study of the cabin air quality of the aircraft cabin of the future.

WP71 - For new aircraft concepts, the application of CFRP is considered here in the primary structure of the wing and the fuselage. The specific concern is for safety issue pertaining to aircraft passengers with

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respect to the fire behavior (incl. mechanical behaviour under high temperature) of these composite materials: enhancing the understanding of carbon/epoxy composite aircraft fire performance would guarantee aircraft occupants a significant safety increase to come out unharmed in case of fire incident or in crash situation.

WP72 – The evaluation of new composite material solutions like Geopolymer and Fibre Metal Laminates with respect to their fire performance requires the use of standard manufacturing protocols and the respect of test requirements and specifications that will make a comparison with the actual industrial solutions possible.

WP73 – Concerning the cabin air quality topic, a broad study covering both the state of the art and possible future developments in the fields of related technologies, societal trends, and competitiveness for industry is proposed, working through a number of subjects such as substances in cabin air and their classification, cabin air sensing and an industrial framework for cabin air quality.

Description of Work

WP71 - Existing testing protocols have been used, adapted, improved or new ones developed (e.g. for charred materials, for compression loadings, for tire debris impacts …) to build up a large experimental database. The works concerned: preparation of test specimens (coupons and panels); standard tests (thermal tests at high temperatures, fire tests …); thermo-gravimetric tests (TGA/DSC, Fast TGA) and complementary BLADE (laser induced) tests (coupons) to operate material degradation/decomposition, measure thermal conductivity tensor and heat capacity of (virgin and) charred material. Fire exposure tests (panels); mechanical and thermo-mechanical tests (quasi-static mechanical and thermo-mechanical tests under tension and compression loadings, in the fibers, transverse and shear directions, in-plane or at the laminates interface) ; dynamic tests (tensile tests at various temperatures (20°C, 70°C, 120°C, and 170°C) ; gas gun tests for tire debris impacts on panels, followed by non-destructive testing, for latter fire exposure tests. A comprehensive analysis of all the test results has then been done: decomposition (under inert atmosphere, under oxidizing atmosphere, under dual atmosphere: inert then oxidative, under inert atmosphere at high temperature ramp), mass loss, gas phases/ species, thermal properties, thermo-physical properties of charred composite laminates, damage (delamination), mechanical properties at material and structural levels (influence of the temperature, influence of the material state - virgin or charred material).

Beside the experimental works, state-of-the art models (thermal, mechanical, multi-physical) in the industry (EMBRAER) and research labs (ONERA) have been surveyed, and some of them operated and assessed based on and by comparison with the previously described test results (materials degradation, thermochemical, thermal (conductivity), thermomechanical responses, etc…). The numerical methods included:

- engineering numerical simulation approaches (EMBRAER) for the modelling of fire effects on composite structures (multidisciplinary, such as coupled CSM/CFD Computational Structural

Mechanics, Computational Fluid Dynamics, etc). A simplified simulation methodology has also been proposed,

- more academic multi-physical (flame, chemical, thermal, …) frameworks (ONERA) for the understanding of complex phenomena and the multiscale modelling of composite materials degradation and panels mechanical behavior.

WP72 – Fibre metal laminates (FML) is a solution mixing thin layers of metal (steel) and composite plies (carbon-epoxy). This kind of solution has been broadly investigated experimentally. Apart from testing the influence of a large number of parameters (stacking sequence, thickness of the metal plies, etc.) on FML specimens fire properties, the compression under fire exposure response of this kind of hybrid metal-carbon composite solution has also been studied. For this purpose, a new Compression Under Fire Exposure (CUFEX) test protocol and apparatus has been designed, set up and used (fire loading, clamping, aperture, etc). Five FLM panel specimens were finally tested.

GeoPolymers (GP) are amorphous aluminosilicate materials that combine low temperature, polymer-like processing with high temperature stability. This combination of properties makes geopolymers an interesting alternative to existing polymeric and ceramic matrix materials and offers a high potential for the development of cost-efficient, ceramic matrix - like composites for applications in the mid to high temperature range. Geopolymers feature high temperature stability and fire resistibility, achieved by low temperature processing, limited generation of toxic fumes and smokes, low thermal conductivity, good specific strength and low price. On the other hand, geopolymer matrix is relatively brittle and its specific gravity is higher than that of organic resins. Due to high alkalinity of uncured resin, range of applicable reinforcement phases is limited to alkali-resistant fibers. Carbon (aramid alternatively) reinforcement was chosen as the optimal option. In the frame of the project, Carbon Fiber Reinforced Geopolymer Composites (CFRGC) were subject of research in undermentioned spheres: Flame resistance, Fire smoke toxicity properties, and mechanical properties (including environmental expositions and impact tests).A particular interest was also paid to the development and use of geopolymer based hard foam as a substitute for state of the art organic core materials.

The use of **bio-fibres** to substitute glass fibres in interior composite materials for aviation (passenger and cargo compartment) could be beneficial for the environmental impact. The same is expected for the application of valuable recycled carbon fibres from cutting waste or end-of-life products via pyrolysis process. As the interest in using ecologically improved materials in aviation is high, it is very important to assess their impact on fire properties. Then, Flax and recycled carbon fibres have been combined and used to manufacture various eco-composite material specimens. Fire and mechanical tests have been performed to evaluate the potential and challenges of these different material combinations. As the geopolymer (GPL) matrix used by partner VZLU shows very good fire properties, another set of material specimens was manufactured - combining the flax and rCF fibers with the geopolymer matrix – and tested according to FAR for cargo compartment (F, ST, HR) and basic flexural tests.

WP73 – The WP73 works investigated the state of the art and developments, including related technologies, in cabin air quality, societal trends in air quality, and competitiveness for industry offered by

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cabin air quality. This study is the final synthesis report of the Future Sky Safety Work Package WP7.3. The WP7.3 team has worked through a number of internal investigations on subjects such as: substances in cabin air and their classification; cabin air sensing; and an industrial framework for cabin air quality.

The state of the art with respect to air quality definition (e.g. wrt constituents) and management, air quality monitoring, air quality contributory factors (material, structural) for aircraft cabin interior (and other applications such as submarines, ISS, automotive) has been reviewed. To address concerns on cabin air quality, a number of air quality monitoring strategies have been suggested, which also served as feasibility studies into the possibility of continuous air quality monitoring in aircraft. Three approaches have been studied: (i) by reporting, (ii) by biomonitoring of personnel, and (iii) by monitoring from measurement of selected substances/ contaminants in the air. To address the need for continuous air quality monitoring in aircraft, some future directions/ strategies have been suggested. A large panel of aspects/ questions, but also challenges and limitations for future methodologies (in-situ real-time or delayed air analysis, computational approaches) and technologies (bleed air, commercial and research sensors), have been considered: e.g. movement of air in cabin (design of cabin, virtual testing, risks analysis); sensors size (miniaturization), type and locations wrt multiple objectives (continuous monitoring of the air quality, fire detection, maintenance); regulatory aspects (to enable effective operational use); human perception; added safety costs. Finally, the exercise included: the identification and adaptation of the best methodology and monitoring equipments (quantitative GC/MS, rack-based instruments, COTS sensors, …) from existing standards; the application of other enclosed spaces air quality related specifications to the aircraft cabin environment; the fine-tuning of contaminants of interest to warranty air quality on aircraft cabin (incl. composite materials flammability and toxicity, temperature and humidity, pressure, …). Eventually, general conclusions and recommendations have been proposed,

A general reflection about the adequate approach (embracing safety, health and comfort) to deal with Cabin Air Quality (CAQ) has been led to configure an industrial framework proposal, framed by the need to have cost defensible solutions. Several issues were addressed: concerns on bleed air contamination; introduction of new materials in cabin environment (e.g. based on REACH regulation); increased air traffic projections but also environment changes, increased awareness and active interaction of citizens/ passengers, etc.; data sharing observatory. A scenario of a citizen based approach for cabin air quality was also addressed, namely to understand how incumbent stakeholders – regulators, operators, OEMs – could use them for overall value creation and safety and health enhancement. Recommendations (aligned with the creation of the Cabin Air Quality Measurement Committee by SAE) have been built up for safety perception and possible research directions to improve CAQ with respect to several general axis: synergies between cabin safety and comfort research; full demonstrators/simulators to support academia studies; CAQ big-data observatory; development of a target specification (species, accuracy, size, etc) for gas sensors; low-cost sensors smart (e.g. e-nose) network; CAQ modelling, with multi-fidelity, simulation framework to enable a holistic CAQ approach; certification cost reduction. Finally a FSS “IFCAS blackbox” concept has been proposed, which gives a generic framework, for instance to place sensors and their processing on-board.

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In addition, an experimental set-up along the interest for cabin air quality was investigated, developed, and set-up. The first, preliminary experiments with this set-up were carried out.

Results & Conclusions

WP71 – A unique experimental database was produced for T700/M21 CFRP composite material in this project which provides an important number of material properties to the scientific community in order to perform and validate numerical simulations dedicated to the fire behavior and degradation of CFRP materials.

The first part of these results (measurement of the thermal conductivity tensor and heat capacity, thermochemical properties, and some thermo-mechanical properties of the composite material) permitted to assess the specific heat and thermal conductivity of T700/M21 to be a function of temperature, for the virgin material state, on a large range of temperature. The orthotropic properties identified from thermographic measurements have shown a significant temperature dependency.

The second part of the test results (thermogravimetric analysis, measurement of the thermal conductivity tensor and heat capacity of the charred material, mechanical and thermomechanical testing of virgin and charred materials, and decomposition of composite sample with various heating sources) permitted : to identify a thermal degradation model adapted to composite materials, to study more representative thermal loads (compared to those experienced during a fire event), confront kinetic models at low heating rates to high heating rates measurements, etc. For this purpose, a specific protocol has been defined and set up to obtain fully charred (pyrolysed) T700/M21 material specimens.

Finally, the experimental results obtained in this project have been used in order to evaluate state of the art simulation tools (thermal, chemical, …), propose modelling methodologies, and validate them. The main conclusions of these numerical works is that the use of thermo-mechanical modelling in order to obtain a coupled simulation of the real problem is a key factor to predict the behavior of the composite material subjected to representative fire conditions, to help the designer to take decisions related to aircraft fire wall with loads applied and to define geometries and configurations suitable from the point of view of its behavior under generalized fire.

WP72 – GeoPolymer monolithic panels were subjected to flame penetration test per CS25, App.F, Part III with no evidence of flame penetration or smoke generation in case of CFRGC panels. The panels showed very good flame resistance and after-test structural integrity, with no mechanical damage or overt smoke generation. Concerning sandwich test panels, there was no evidence of flame penetration in case of the panels provided with CFRGC skins. Despite a strong blow up (“pillow”) effect, CFRGC sandwich panels showed very good after-test structural integrity.

Considering Fire Smoke Toxicity properties, CFRGC gave significantly better results in comparison with referential glass/phenol. When their static strengths and modules were evaluated (with and without environmental expositions), CFRGC mechanical properties were found to be about the same as these of referential glass/phenol. Drum peel tests of sandwich panels constructed of CFRGC skins and honeycomb /

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foam core were carried out with the foam core specimens providing the best peel strengths. The performed impact tests on the geopolymer based material solutions, once a hybrid carbon-aramid fiber reinforcement is used, showed the highest energy absorb capability and the lowest specific weight from compared materials (incl. reference standard one).

Last, hard structural geopolymer foam proved excellent fire resistivity and almost zero generation of smoke and combustion gases even at long term exposition at 1350°C, but showed higher specific weight-to-strength ratio and brittleness compared to thermoplastic foams.

Non-woven **Flax fibres and recycled carbon fibres** with a bio-based resin system (furan) expressed various potentials and challenges (positive and negative), according to the combinations used, when subjected to the fire and mechanical tests : the additional use of fire retardants, resin additives, fibre sizing and coatings is clearly required to improve their fire and mechanical properties. With a geopolymer resin in combination with rCf, very promising FST and HR results were obtained. A hybrid combination of rCF and flax also showed interesting results despite poor mechanical properties.

Fibre metal laminates (FML) based solutions produced a reduced amount of smoke and toxic gasses, with an improved burn-through resistance, and a very interesting behaviour when compression under fire exposure was tested (using a hydraulic press enhanced by a specimen device that contains a fire load withstanding clamping mechanism, and curved FLM panels). The tests performed also showed the functionality of the new Compression Under Fire Exposure (CuFex) test-stand.

The various test results obtained during the test campaign allowed collecting all the data necessary to improve the material models and numerical simulation tools (e.g. FlamePTM) in terms of prediction of material degradation (gas produced by the pyrolysis phenomena), and specimen structural behaviour (deformation and stress), and propose enhanced modelling strategy to investigate the structural behavior of more complex and representative situations (e.g. compression under fire exposure).

WP73 - There is a continuous development of technological innovations in aircraft such as the electrification of propulsive and non-propulsive power and the development of new cabin air filter technology. These innovations can contribute to improvements in cabin air quality. In addition, there is a growing interest to address complex (cabin) air quality issues related to comfort, health, and safety. Some key guidelines for cabin air quality assessment are given. To further address this interest, the "Industrial cabin air quality Framework based on Continuous Air quality Sensing (IFCAS) is proposed. The core of the IFCAS is a well-placed network of low power, low weight sensors that is distributed across the cabin. Other elements of IFCAS concern the on-board post-processing, storage, and distribution of data during a flight, the storage and sharing of flight data potentially between different stakeholders, and the analysis of the big data that is gathered, potentially combined with modelling and simulations. It is concluded that, depending upon confirmation of stakeholder interest, the development of IFCAS can be started in the near future, while progressively extending it with the latest sensing technologies. Recommendations are given for further research and development of IFCAS to increase its maturity.

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Applicability

WP71 - The experimental database produced in this project provides an important number of material properties to the scientific community. The experimental results obtained in this project should be used in the future to feed and validate numerical simulations dedicated to the fire behavior and degradation of CFRP materials. Moreover the recommendation concerning the thermo-mechanical modelling in order to obtain a couple simulation of the real fire case proposed in this work could be used as a starting point for numerical modelling developments.

WP72 – Among the studied material solutions, **Fibre-Metal-Laminates** (FML) is clearly the most mature technology that could come to be used if needed for aviation load-bearing structures with improved fire resistance behaviour. Once an industrial manufacturing process is proposed and validated, **GeoPolymer** based solutions (resin for fiber reinforced composite plies, foams, sandwich cores, etc) could be used in secondary structures in the future, e.g. as internal linings in cargo or cabin areas, fire bulkheads or temperature exposed pipelines. **Eco-Fibres** still require an important research effort before becoming candidates for an industrial application.

WP73 - Applications of IFCAS are foreseen during flight – for example to reduce the number of false fire alarms - and on different time-horizons after flight, including prognostic health management and condition-based health management, evidence-based answers to concerns, and methodical, engineered approaches to improve comfort and to better design the aircraft to control the air inside the cabin.

The new test protocols and test means developed in FSS P7 can now be used to study any other composite material, and data obtained from these tests can be used to develop physical and material models for improved numerical simulations.

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1 INTRODUCTION

1.1. The Programme

FUTURE SKY SAFETY is an EU-funded transport research programme in the field of European aviation safety, with an estimated initial budget of about € 30 million, bringing together 32 European partners to develop new tools and approaches to aviation safety. The first phase of the Programme research focuses on four main topics:

- Building ultra-resilient vehicles and improving the cabin safety
- Reducing risk of accidents
- Improving processes and technologies to achieve near-total control over the safety risks
- Improving safety performance under unexpected circumstances

The Programme will also help to coordinate the research and innovation agendas of several countries and institutions, as well as create synergies with other EU initiatives in the field (e.g. SESAR,). Future Sky Safety is set up with an expected duration of seven years, divided into two phases of which the first one of 4 years has been formally approved. The Programme started on the 1st of January 2015.

FUTURE SKY SAFETY contributes to the EC Work Programme Topic MG.1.4-2014 Coordinated research and innovation actions targeting the highest levels of safety for European aviation, in Call/Area Mobility for Growth – Aviation of Horizon 2020 Societal Challenge Smart, Green and Integrated Transport. FUTURE SKY SAFETY addresses the Safety challenges of the ACARE Strategic Research and Innovation Agenda (SRIA).

1.2. Project context

Recent studies have shown that, though “fires in flights” as a direct cause represented only 5% of fatalities, “fire/smoke resulting from impact” accounted for 36% of all fatal accidents. Often aircraft occupants have survived the impact only to be incapacitated by toxic fumes and/or heat, e.g. temperatures can rise above 600-700°C after only three minutes [3]. Toxic fumes originate from components such as aviation fuel and combustible materials, producing various gases dependent on the composition of the material.

In recent years the development of more lightweight aircraft has seen an increased use of composite materials in primary structures, e.g. fuselages, as well as secondary and interior structures, such as furnishings. These materials have desirable properties such as corrosion resistance and high strength, however from a safety point of view the use of these materials may require specific controls concerning their behaviour when exposed to fire, or during normal conditions. The project seeks to address this safety aspect within three work packages:

- WP7.1 – The first work package aims to test and thus improve understanding of the effects of fire on these materials,
- WP7.2 – The second work package aims to develop and propose improved material solutions to mitigate fire, smoke and fume,

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- WP7.3 – The third work package aims to investigate the possible effects of new materials and technologies on the on-board air quality with the objective to further improve the air quality.

1.3. Research objectives

The objective of Future Sky Safety WP7 is to increase safety thanks to: O1: the Improvement of knowledge (concerning materials and structures behaviors vs fire) ; O2: the assessment of mechanical/ chemical properties (of heating/burning/degraded materials) ; O3: The evaluation of the fire consequences (incl. toxicity, smoke), and proposition of solutions to mitigate them ; O4: the sharing of a database for future modelling purposes (expensive tests) ; O5: the establishment/ proposition of design recommendations.

1.3.1. WP7.1 Understanding & characterizing the fire behavior of primary structure composite materials

The general objective of FSS work package WP7.1 "Understanding and characterising the fire behaviour of primary structure composite materials (epoxy resins, standard CFRP)" is to enhance knowledge concerning the fire behaviour and performance of CFRP primary structure composite materials, in order to better predict safety and survivability issues in case of fire incident or post-crash situation. Such predictions rely on physical models and numerical tools which need to be developed based on exhaustive materials (characterisation) and components (validation) experimental testing.

The technical objective of FSS WP7.1 is to produce a comprehensive experimental database for a reference material to be shared by the European research community as a basis for material model development regarding the fire behaviour and degradation of CFRP materials:

- At the material level the targeted models concern the prediction of (1) chemical reactions (pyrolysis) due to fire and high temperature exposure, (2) heat diffusion within the degrading material, and (3) mechanical stiffness and strength according to temperature and degradation state,
- At the structural level, the targeted models concern the prediction of the effects of the laminated structure of composite specimens on the chemico-physical and mechanical responses of coupons or panels exposed to fire and high temperature.

The T700GC/M21 material has been proposed to be used in this WP7.1 because a lot of published results already exist about its standard mechanical behavior which the project can build on.

1.3.2. WP7.2 Improving material solutions to mitigate FS&F in the cabin environment

The general objective of FSS WP7.2 is the development of composite materials with improved fire properties in terms of reduction of smoke density production with a lower toxic gas content combined with improved mechanical properties during fire, not presenting mass or cost penalty compared to current cabin and structural aircraft materials, to constantly improve aircraft safety.

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The technical objective of FSS WP7.2 is to investigate concepts of new material solutions for various application cases, meaning here primary structures, cargo or cabin furnishing, and various targeted performances:

- Hybrid laminates of standard composite and metallic layers to reduce smoke density production with a lower toxic gas content combined with improved mechanical properties during fire,
- Natural fibers and (recycled) carbon fibers with enhanced mechanical and fire properties plus reduced environmental impact,
- Geo-polymer matrices (for monolithic composites) or foam (for sandwich panels) for cabin and cargo linings to produce almost zero smoke and toxic gas.

These three kinds of solutions have been selected because of expected advantages compared to current reference solutions, which are glass-fiber phenolic matrix based for interior and aluminium for the fuselage.

1.3.3. WP7.3 Effects of new materials, technology and fuel systems on the on-board air quality

The general objective of FSS WP7.3 is to investigate potential opportunities offered by technical developments, including new materials, which may contribute to enhanced on-board air quality.

The technical objective of FSS WP7.3 is to investigate specific research avenues which include:

- Development of an understanding of the whole chain related to on-board air quality as a basis for recommending economically viable and technically feasible methodologies for ensuring continued air quality,
- Definition of a predictive industrial framework that considers on-board air quality in the context of introduction of new materials, and potential technologies that could monitor and/or correct for air quality changes,
- Investigation of the feasibility of using commercial off the shelf sensors as tools for informing if/when there are any air quality changes as a result of introduction of new composite materials, both in flight and during initial materials evaluation,
- Investigation of a quantitative methodology for evaluating gaseous and volatile emissions from materials used in aircraft under standard operating temperatures.

1.4. Proposed research approach

1.4.1. WP7.1 Understanding & characterizing the fire behavior of primary structure composite materials

The mean to reach the FSS WP7.1 technical objective described in §1.3.1 was to use original ONERA in-house test protocols or to develop new ones in order to provide unknown or uncertain data, for state-of-the art numerical model assessment and future improvement if needed. In particular the interlaminar toughness, the compression and bending stiffness, and the residual strength after impact, under fire or

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high temperature exposure, are the kind of unusual structural properties which are of interest in this part of the project.

Two batches of tests have been planned: initially, the first one dedicated to the use of existing unusual test protocols and the development of new ones for more accurate or simply missing material data, and the second one dedicated the completion of the material data and for obtaining structural data.

In terms of project management, FSS WP7.1 was split into 3 tasks, a large effort being put on T7.1.2 (material and structural tests):

- T7.1.1. Definition of tests, manufacturing of test coupons and panels, preparation of tests (incl. instrumentation), led by CEiiA,
- T7.1.2. Test and model the thermo-chemical, thermo-physical and thermo-mechanical properties of composite materials according to temperature, fire exposure (time), and material state (virgin and charred), led by ONERA,
- T7.1.3. Test and model resilience to temperature/fire effects at structural levels (incl. on damaged panels), led by CASA.

1.4.2. WP7.2 Improving material solutions to mitigate FS&F in the cabin environment

To achieve the FSS WP7.2 objective described in §1.3.2, candidate material solutions have been tested according to a prescribed test plan, which allows addressing their properties with respect to fire exposure. The scope and magnitude of the proposed test plan respect industrial safety requirements and usage of state-of-the art simulation tools. Tests have been performed, and a new compression under fire exposure test has been developed to investigate the performance of some solutions at structural level (panels).

Two batches of tests have been planned: initially, the first one dedicated to the study of the basic properties of different material solutions, and the second one dedicated to the most promising solutions for the completion of the material data and for obtaining structural data.

In terms of project management, FSS WP7.2 was split into 3 tasks, a large effort being put in T7.2.1 (manufacturing of the unusual materials):

- T7.2.1. Definition of tests, manufacturing of specimens, preparation of tests (instrumentation). Led by VZLU,
- T7.2.2. Development and test of new materials, fire retardants and fire protections concepts, led by DLR,
- T7.2.3. Modelling of material degradation with respect to fire, smoke and fumes in the cabin environment, led by LEONARDO.

1.4.3. WP7.3 Effects of new materials, technology and fuel systems on the on-board air quality

To achieve the FSS WP7.3 objective described in §1.3.3, the FSS WP7.3 team has first worked through a number of internal investigations on: substances in cabin air and their classification; cabin air sensing; and an industrial framework for cabin air quality. Results from investigations have been shared frequently

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within the team. Discussions on the results have led to the initiation of further investigations. Part of the investigations in FSS WP7.3 also concerned the development of an experimental set-up along the interest for cabin air quality. In addition, first experimental results with this set-up were obtained.

In a second loop, the results from the first works have been collated and reviewed again against the latest developments and insights about the fast-changing air quality topic: some of them being confirmed, other updated, extended or rewritten from a different perspective.

In terms of project management, FSS WP7.3 was split into 4 tasks, an almost balanced effort being put in the 4 different tasks:

- T7.3.1. Definition of methodological framework, led by NLR,
- T7.3.2. Study of possible safety impact on on-board air-quality according to various innovations: materials (structures, engines, cabin), technology (more electrical aircraft), and fuel systems, led by EMBRAER,
- T7.3.3. Study of concepts and feasibility of sensors and analytical methods to detect, measure and monitor gaseous and volatile emissions from composite materials, led by CRANFIELD University,
- T7.3.4. Proposal of general solutions to improve air quality, led by CAA (UK).

2 DESCRIPTION OF WORK

2.1. WP7.1 Understanding & characterizing the fire behavior of primary structure composite materials

Existing testing protocols have been reviewed (FSS D7.1), used, adapted, improved or new ones developed (e.g. for charred materials, for compression loadings, for tire debris impacts …) to build up a large experimental database. The works (FSS D7.4 & D7.7) concerned: preparation of test specimens (coupons and panels) ; standard tests (thermal tests at high temperatures, fire tests, …) ; thermo-gravimetric tests (TGA/DSC, Adethec, Fast TGA) and complementary BLADE (laser induced) tests (coupons) to operate material degradation/decomposition, measure thermal conductivity tensor and heat capacity of (virgin and) charred material. Fire exposure tests (panels); mechanical and thermo-mechanical tests (quasi-static mechanical and thermo-mechanical tests under tension and compression loadings, in the fibers, transverse and shear directions, in-plane or at the laminates interface) ; dynamic tests (tensile tests at various temperatures: 20°C, 70°C, 120°C, and 170°C) ; gas gun tests for tire debris impacts on panels, followed by non-destructive testing, for latter fire exposure test. A comprehensive analysis of all the test results has then been done: decomposition (under inert atmosphere, under oxidizing atmosphere, under dual atmosphere: inert then oxidative, under inert atmosphere at high temperature ramp), mass loss, gas phases/ species, thermal properties, thermo-physical properties of charred composite laminates, damage (delamination), mechanical properties at material and structural levels (influence of the temperature, influence of the material state - virgin or charred material).

Beside the experimental works, some state-of-the art models (thermal, mechanical, multi-physical) in the industry (AIRBUS D&S) and research labs (ONERA) have been surveyed, and some of them operated and assessed based on and by comparison with the previously described test results (materials degradation, thermochemical, thermal (conductivity), thermomechanical responses, etc) (FSS D7.9). The numerical methods included:

- engineering numerical simulation approaches (AIRBUS D&S) for the modelling of fire effects on composite structures (multidisciplinary, such as coupled CSM/CFD Computational Structural Mechanics, Computational Fluid Dynamics, etc). A simplified simulation methodology has also been proposed,
- more academic multi-physical (flame, chemical, thermal, …) frameworks (ONERA) for the understanding of complex phenomena and the multiscale modelling of composite materials degradation and panels mechanical behavior.

A more detailed synthesis of the works performed in the FSS WP7.1 work-package is available in FSS D7.12 deliverable "Primary structure materials - Final report on the characterization and modelling of materials fire behavior".

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2.2. WP7.2 Improving material solutions to mitigate FS&F in the cabin environment

A first set of candidate new material solutions have been surveyed and some of them selected for testing according to standard test specifications (FSS D7.2): Hybrid non-woven, Fibre metal laminates (FML), and Geo-polymers (GP). Panels and specimens have been manufactured for the tests (standard tests and others). Many different kinds of tests have then been performed: smoke density, toxicity, heat release, flame propagation and flame penetration tests; but also mechanical tests at various temperatures (DMA, SDT and DSC tests; tensile, compression, shear tests and flexural tests).

The results (FSS D7.5) have been analyzed to further select and study relevant material solutions. During the second batch of tests, Fiber Metal Laminates and Geo-polymers based material solutions have been further studied (FSS D7.8). A new approach has been considered: eco-fibers based composites (natural fibers, recycled carbon fibers and a hybrid combination of both) with Geo-polymer matrix. Specimens, panels and sandwich panels have been manufactured for the tests (standard and others). A specific test protocol has been developed, set up and operated (Compression under Fire Exposure, CuFex), to perform compression tests on composite panels during fire exposure. New kinds of tests have been performed on FML and GPs: further fire effluents and smoke optical density tests, flame penetration test, mechanical tests (impact tests, drum peel tests, compression tests, CuFex tests). The new eco-fiber based solutions have been tested partially the same way the FML and geo-polymer based solutions were in the first batch of tests. Besides, compositions and manufacturing technique of geo-polymer foams have been developed. Basic mechanical and fire resistivity tests were carried out. Geo-polymer foam is a promising candidate to replace toxic products emitting honeycombs and thermoplastic foams in sandwich structures. Works focused on improvement of fiber/matrix interfacial properties of geo-polymer composites have been started: wettability of fibers and fiber-matrix adhesion are factors that could improve mechanical properties of geo-polymer laminates. Various methods of physical and chemical treatment of fibers have been tested (plasma, acid etching, heat treatment). Precisely controlled heat treatment has shown to be the most promising technique for fibers preparation.

Last, sensitivity of laminate layup variations have been evaluated to compare the different solutions at material and structural levels, to establish their performances and limitations, to conclude about their respective advantages and drawbacks, and to give recommendations of use. They were also analyzed/processed to calculate the material characteristics useful to simulate material degradation and to define the data necessary for the flame penetration model validation (FSS D7.10).

A more detailed synthesis of the works performed in the FSS WP7.2 work-package is available in FSS D7.13 deliverable "Improving material solutions to mitigate fire, smoke and fumes in cabin environment – final report".

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2.3. WP7.3 Effects of new materials, technology and fuel systems on the on-board air quality

The state of the art with respect to air quality definition (e.g. wrt constituents) and management, air quality monitoring, air quality contributory factors (material, structural) for aircraft cabin interior (and other applications such as submarines, ISS, automotive) has been reviewed (FSS D7.6). To address concerns on cabin air quality, a number of air quality monitoring strategies have been suggested, which also has served as feasibility studies into the possibility of continuous air quality monitoring in aircraft. Three approaches have been studied: (i) by reporting, (ii) by biomonitoring of personnel, and (iii) by monitoring from measurement of selected substances/ contaminants in the air. A dedicated review about new concepts of sensors has been performed (FSS D7.3). To address the need for continuous air quality monitoring in aircraft, some future directions/ strategies have been suggested. A large panel of aspects/ questions, but also challenges and limitations for future methodologies (in-situ real-time or delayed air analysis, computational approaches) and technologies (bleed air, commercial and research sensors), have been considered: e.g. movement of air in cabin (design of cabin, virtual testing, risks analysis); sensors size (miniaturization), type and locations wrt multiple objectives (continuous monitoring of the air quality, fire detection, maintenance); regulatory aspects (to enable effective operational use); human perception; added safety costs. Finally, the exercise included: the identification and adaptation of the best methodology and monitoring equipment (quantitative GC/MS, rack-based instruments, COTS sensors, …) from existing standards; the application of other enclosed spaces air quality related specifications to the aircraft cabin environment; the fine-tuning of contaminants of interest to warranty air quality on aircraft cabin (incl. composite materials flammability and toxicity, temperature and humidity, pressure, …). Eventually, general conclusions and recommendations have been proposed (FSS D7.6).

A general reflection (D7.11) about the adequate approach (embracing safety, health and comfort) to deal with Cabin Air Quality (CAQ) has been led to configure an industrial framework proposal, framed by the need to have cost defensible solutions. Several issues were addressed: concerns on bleed air contamination; introduction of new materials in cabin environment (e.g. based on REACH regulation); increased air traffic projections but also environment changes, increased awareness and active interaction of citizens/ passengers, etc.; data sharing observatory. A scenario of a citizen based approach for cabin air quality was also addressed, namely to understand how incumbent stakeholders – regulators, operators, OEMs – could use them for overall value creation and safety and health enhancement. Recommendations (aligned with the creation of the Cabin Air Quality Measurement Committee by SAE) have been built up for safety perception and possible research directions to improve CAQ with respect to several general axis: synergies between cabin safety and comfort research; full demonstrators/simulators to support academia studies; CAQ big-data observatory; development of a target specification (species, accuracy, size, etc) for gas sensors; low-cost sensors smart (e.g. e-nose) network; CAQ modelling, with multi-fidelity, simulation framework to enable a holistic CAQ approach; certification cost reduction. Finally a FSS "black-box" concept have been proposed, which gives a generic framework, for instance to place sensors and their processing on-board.

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A more detailed synthesis of the works performed in the FSS WP7.3 work-package is available in FSS D7.14 deliverable "On-board air quality – final report on the effect of new materials".

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3 SYNTHESIS OF RESULTS

3.1. WP7.1 Understanding & characterizing the fire behavior of primary structure composite materials

3.1.1. Experimental results on tape CFRP T700/M21 material

The material studied in FSS WP7.1 work-package is a CFRP (Carbon Fibre Reinforced Polymer) material made of T700 carbon fibers and M21 epoxy resin. The composite specimens are laminated coupons or panels with different stacking sequences accd. to the material properties of interest.

3.1.1.1. Material behaviour (at the ply level)

The fire behaviour of composite materials is very complex because the thermal and mechanical responses are combined to temperature-activated chemical decomposition (pyrolysis). As a consequence, a key step in a material properties characterization process is to assess decomposition mechanisms and kinetics as a function of temperature, heating rates and atmosphere. Thermo-Gravimetric Analysis, a conventional technique has been used to do so. The experimental device used by ONERA in the FSS P7 project combines the mass loss measurement with heat flux assessment in order to simultaneously identify the heat of reactions. When conventional devices have a heating rate range usually lower than $150\ K/min$, ***ONERA has performed TGA measurements at very high heating rates (up to $\mathbf{1200\ K/min}$)*** using a device previously developed for space application. This has been done to cover in FSS WP7.1 the whole range of thermal loadings that T700/M21 could experience when exposed to fire. All measurements were analysed and post-processed using an ONERA toolbox: kinetic parameters have been characterized and relevant decomposition mechanisms have been defined. The gas phase released by T700/M21 decomposition was characterised using an isothermal pyrolyser combined by GC-MS (Gas Chromatography – Mass Spectroscopy).

In parallel the previously mentioned temperature and heating rates of the composite material constituents is driven by the anisotropic heat diffusion within the laminate due to the fiber reinforcement as a response to the heat flux generated by the fire source. Before any decomposition occurs, optical surface properties make it possible to determine how much heat is absorbed by the material surface and how much heat is lost by radiation with the surrounding atmosphere. Specific heat and thermal conductivity coefficients that characterize heat diffusion within the material could then be properly analysed, here for unidirectional and quasi-isotropic stacking sequences. Since conventional techniques would fail to provide these coefficients because of the 3D behaviour or the heterogeneous composition of T700/M21, ***a specific test facility (BLADE facility)*** previously developed by ONERA to study composite materials ***has been used in FSS WP7.1 to obtain these coefficients*** (which depend on the temperature). This ONERA BLADE facility provides a pure (laser based) radiative heating at the material surface of a specimen located in a temperature and pressure-regulated test chamber. Compared to a fire/flame test, the heat source is here fully controlled and characterised and the test conditions are completely regulated. The thermal response is measured using non-intrusive quantitative infra-red thermography.

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But these specific heat and thermal conductivity coefficients also depend on the material decomposition state. ***The specific heat and thermal conductivity coefficients of T700/M21 charred material has also been characterized*** with the BLADE facility. For that purpose TGA measurements have been used to properly define the T700/M21 charred states, and a protocol has been defined to prepare T700/M21 charred coupons.

In FSS WP7.1 ONERA has also characterized the mechanical properties of T700/M21 composite material with respect to the environmental temperature and to the material degradation state. Regarding the mechanical properties of the laminate ply, various experimental setups have been used in order to to do so for a large range of strain rates and temperatures: DMA testing device (1-10 Hz, 20-300°C), electromechanical testing devices (0.5 and 100 mm/min, 20-240°C) and servohydraulic testing devices (5mm/min up to 2m/s, 20-170°C) equipped with climate chambers. Various UD configurations have been tested to characterise the longitudinal, transverse and shear properties of the composite material. The properties of the interfaces between the plies have also been studied to characterise the influence of the temperature on the interlaminar toughness: ENF tests have been performed on a specific test bench existing at ONERA (INJECT) which is based on the concept of injecting an electric current into the specimen in order to increase its temperature thanks to the quite high electric resistance of carbon/epoxy laminates. With the use of this experimental facility, the interface properties have been obtained at different temperature (20°C and 80°C).

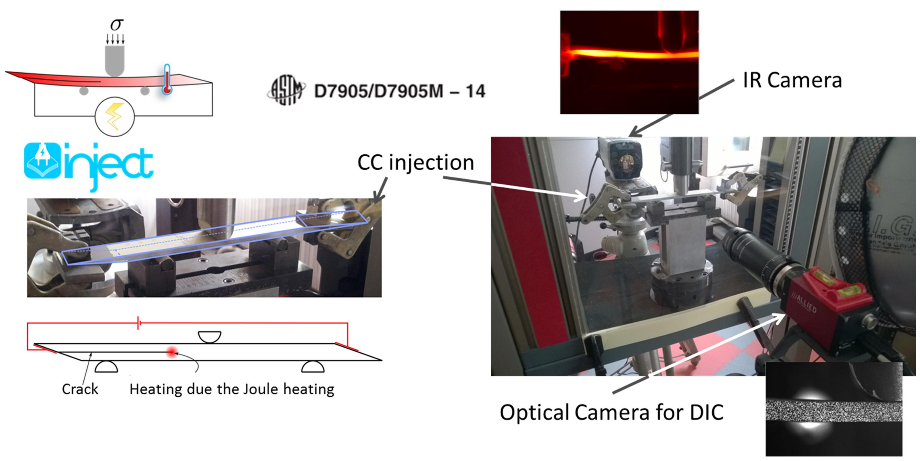

Figure 1 - Inject facility used to study the influence of the high temperature on the fracture toughness of composite materials

3.1.1.2. Thermo-structural behavior of T700/M21

Once a pyrolysis model identified and validated thanks to a pyrolysis solver (MoDeTheC, from previous research works at ONERA) against the experimental database provided by the BLADE facility, the next step to study T700/M21 fire behaviour (and to compare with numerical simulations) was to expose test specimens to a laboratory gas burner while performing simultaneous measurements to investigate the interaction of the gas phase released by the composite decomposition with the flame generated by the burner. ***The FIRE facility has been developed at ONERA in previous research for this purpose***. The thermal

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response of a T700/M21 material panel unexposed surface has been measured during FSS WP7.1 tests while the mass loss and the unexposed surface deformation being recorded in order to correlate the temperature evolution with the decomposition reaction activation and the damage onset and growth.

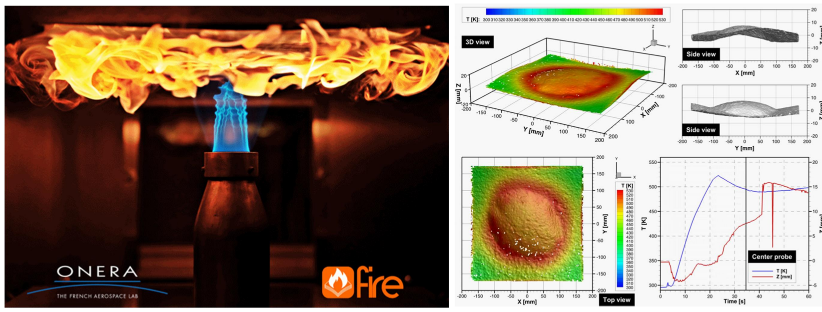

Figure 2 - 3D reconstruction of temperature measurements on the back surface of a composite laminate exposed to fire (FIRE facility @ONERA)

The gas phase release and ignition have been observed using high resolution photographic images (voir Figure 3).

Figure 3 – Overview of the successive events occurring during the fire exposure onto the composite test coupon with the FIRE facility

Standard fire tests have also been performed in this FSS WP7.1 work-package by Airbus D&S. Classical test conditions have been chosen with a fire duration of 15 minutes based on specific normative conditions applicable to aeronautic structures when submitted to fire. The temperature evolution on the cold and hot faces of T700/M21 panel has been monitored with infrared thermography. The main results of these tests have been that the flame did not pierce the panel during the test, that a high emission of fume has been observed, and that a small separation between fibers on the flame side of the T700/M21 panel has been observed.

3.1.1.3. Fire response of T700/M21 delaminated structural panels

Last, the response of T700/M21 composite laminated panels to fire exposure (gas burner) before and after a tire debris impact (with more or less delamination damage) has been studied in FSS WP7.1 in order to evaluate if what extent an initial impact damage would have an effect on the fire

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resistance/performance of such panels. The tests have been instrumented in order to possibly serve (if some effects are observed) as validation cases for future thermo-structural numerical simulations. For the purpose, ONERA used a gas gun to perform tire impacts, the existing test facility being slightly modified to set up displacement or strain field measurements (DIC) during impacts (to get data for later comparison with simulations). A series of impacts between 100 m/s and 200 m/s were performed, with NDT being used to characterize the size of delamination damage. The impacted T700/M21 panels have then been fire tested afterwards on the ONERA FIRE test bench (gas burner). For the higher impact velocity, internal damage in the composite plate can be observed. In that case the fire response of the composite can be slightly modified. As the internal damage topology can be off-centered, the internal damage can thus affect the gas release at the material surface as a consequence of an off-centered thermal response. At the beginning of this experiment, the internal thermal conditions within the laminate are non-uniform. Delamination induced by the impact prevents heat to diffuse through the area where cracks are located. The thermal insulation of the cracked layer causes the temperature on the surface exposed to fire to rise faster in the damaged area. The gas phase is released first in the damaged area and the ignition occurs earlier in the experiment.

Figure 4 - Internal damage induced by impact affecting the gas release and ignition on the material surface

Another effect of the internal damage induced by the impact can be observed for damages located in the first surface ply on the side exposed to fire. Non-destructive inspection shows small cracks on the surface of some coupons. Experimental results show that the gas phase is released preferentially through the surface crack due to the impact loading.

3.1.2. Modelling results of T700/M21 test cases

A detailed bibliography review dedicated to current state of the art of thermal and thermomechanical models and simulation tool has been done. This bibliographic study has been completed by two detailed case studies proposed by ONERA and AIRBUS D&S.

The ONERA contribution to the assessment of pyrolysis and fire response T700/M21 properties and state-of-the-art models for composite materials has consisted in numerical simulations of some T700/M21

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thermo-structural tests using the ONERA MoDeTheC solver previously mentioned, together with obtained T700/M21 material properties. The simulations have shown the interest (increased accuracy of predictions) of introducing different aspects in the numerical models/simulation tools, such as (1) the anisotropic heat diffusion coefficients for heterogeneous materials such as composite materials, (2) the energetic contribution of (endothermal or exothermal) decomposition reactions, (3) the gas phase formation and transport within an anisotropic porous medium, and (4) the anisotropic thermo-physical properties evolution as a function of temperature and decomposition state using advanced homogenisation methods to define bridging function between virgin and charred states during decomposition.

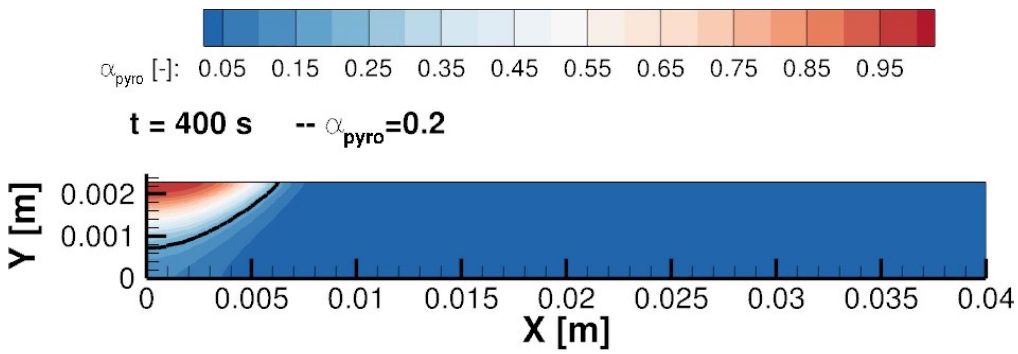

Figure 5 - Final pyrolysis evolution function field of the T700GC/M21 ISO simulation exposed to a 101.2 kW/m^2 laser beam (ONERA MoDeThec Solver)

AIRBUS D&S's contribution in FSS WP7.1 modelling works has consisted on the application of a simplified methodology for fire testing prediction of standard fire tests on composite loaded panels. This simplified methodology relies on the use/definition of (1) simplified thermal boundary conditions, in particular a flame model based on the repetitivity of thermal hot face map on a standard fire test, and a convection model based on constant heat transfer coefficient dependent on the cold face flow speed), (2) a thermal characterization on an intact panel and a degraded panel, (3) the assumption of a direct relation between thermal and mechanical degradation, (4) the definition of simplified failure criteria based on cold face temperature map evolution through test, and (5) the confirmation, by dedicated and especially monitored tests, of the adequacy of these assumptions for a typical composite configuration in a typical load range. Then a thermal (only) transient problem resolution is performed to establish the cold face temperature map evolution, and determine the failure time based on the failure criteria defined. Last, the thermomechanical problem is solved, with the same assumptions, to evaluate impact of secondary effects that may influence the panel response (large deformations with impact on thermal contact between elements).

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3.2. WP7.2 Improving material solutions to mitigate FS&F in the cabin environment

3.2.1. Experimental results on new material solutions

3.2.1.1. FML

Fibre metal laminates (FML) have been investigated as a possible solution to improve the current CFRP material behavior within a fire scenario. This improvement would be produced by steel layers that are integrated into the CFRP laminate. The steel layers act as gas barrier for decomposed material parts resulting in thermally insulating behavior. To investigate and underline this benefit, subjects of research have been smoke toxicity and smoke density tests, as well as burn through tests with respect to varying layups. It has been shown in FSS WP7.2 work-package that the metal layers acting as gas barrier significantly reduce the generation of smoke and toxic gasses. Moreover, the burn through resistance is improved allowing increased duration of mechanical performance of the structure.

Furthermore, the new test facility (CuFex) developed in FSS WP7.2 work-package has permitted to investigate the mechanical performance of FML under axial compression while exposed to fire. This test is intended to study the insulation effects, how material degradation proceeds and if the material can still be expected as load carrying in such a scenario. Since manufacturing and testing is a huge effort a simulation method has also been developed which has decreased the testing effort and has given a grip on the mechanical degradation process of FML within a fire scenario. To realize these simulations, the steel and CFRP properties have been characterized with respect to their temperature dependency. The material characterization has also led to increase knowledge about FML materials.

The Compression under Fire Experiment (CuFex) has been designed by enhancing a hydraulic press 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 mould. The concrete potting material clamps the specimen against out-of-plane deformation. In-plane compression loads are applied through the face of the mould. The tested specimens can 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 flame. The tested specimens in FSS WP7.2 were curved ones to avoid structural collapse due to stability (buckling). Five FML specimens have been tested, four of them with an aperture and one without. The specimens with the aperture have shown a “pillow-effect”, insulating gases that are trapped between the steel layers within the laminate.

3.2.1.2. Geopolymer

For ‘non-flammable’ shall be considered such substances that does not burn, smolder or carbonize at normal pressure by the action of fire or high temperature. It is known that most inorganic substances feature these properties. Thus application of inorganic based fiber composites is the possible way to meet the WP7.2 objectives. Indeed, if appropriate lightweight, fire-resistant (e.g. carbon) fibers are applied in conjunction with inherently non-combustible inorganic matrix, there is an opportunity to get materials

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featuring new level of fire and FST safety. Candidates for such material are geo-polymer compounds. Geo-polymers are a class of totally inorganic, alumino-silicate based ceramics. They are rigid gels, processed under relatively ambient conditions of temperature and pressure into semi-crystalline glass-ceramic materials. In WP7.2 Carbon Fibre Reinforced Geopolymer Composites (CFRGC) properties (flame resistance, fire smoke toxicity properties, mechanical properties including environmental expositions and impact tests) have been investigated. Particular interest has been paid to the development of geo-polymer based hard foam as a replacement of state of the art organic core materials.

Monolithic CFRGC test panels have been manufactured and tested wrt flame penetration, burn length and smoke generation (tests per CS25). During the tests, there was no evidence of flame penetration, burn or smoke generation of the panels which have also shown very good after-test structural integrity. Sandwich CFRGC (skins) - thermoplastic foam and Nomex® honeycomb (core) test panels have also been manufactured and tested wrt flame penetration resistivity. Strong blow up (“pillow”) effect has been first registered which has been partly eliminated by applying metal frame on the panels edges. No other damages have been detected and sandwich panels have shown also very good after-test structural integrity. In many aspects the geo-polymer based panels demonstrated better properties compared to a reference glass/phenolic solution.

Concerning the other standard tests (toxicity, mechanical stiffness and strength, peel strength of sandwiches) which have been performed: (1) the monolithic CFRGC solutions have shown a significant sensitivity to hot-wet exposition in case of shear strength, other mechanical properties being found to be about the same as these of referential glass/phenolic solutions, (2) the geo-polymer foam which has been developed has shown to be brittle but proved excellent fire resistivity, with almost zero generation of smoke and combustion gases even at long term exposition at 1350 °C and (3) sandwich CFRGC (skins) - thermoplastic foam and Nomex® honeycomb (core) specimens with a geo-polymer adhesive provided better peel strengths compared to other tested adhesive solutions. Last, impact tests have been conducted on different “raw” GP or hybrid based panel solutions: worse VID (Visible Impact Damage) and BVID (Barely Visible Impact Damage) values have been found compared to referential standard (glass/phenolic) material solutions. This poor impact resistance has been improved thanks to an improved wettability treatment of fibers by the geo-polymer resin, and by incorporation of more ductile aramid or flax fibers into the composite lay-up. This hybrid geo-polymer composite structure has also proved enhanced energy absorption capability and the lowest specific weight compared to the other tested solutions. On the other hand, insertion of ductile organic (aramid, flax) layers caused enhanced generation of smoke at flame penetration tests.

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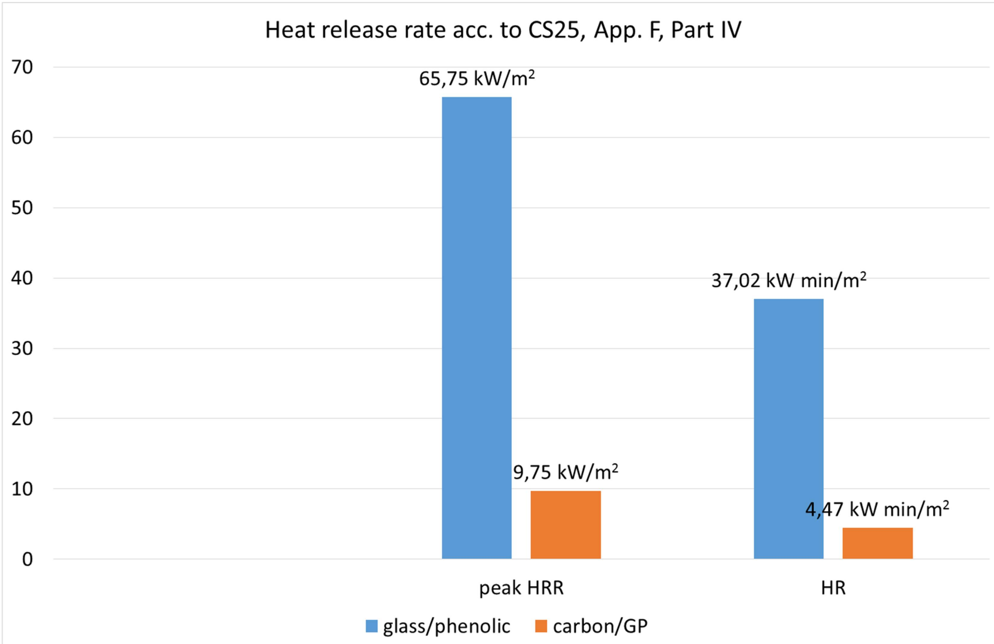

Figure 6 - Comparison of Heat Release Rate and Heat Release values of carbon/geopolymer composite with referential glass/phenol

3.2.1.1. Eco-reinforcements

As the reduction of ecological impacts is getting more and more attention as important factor for future transport activities, it has been another approach of FSS WP7.2 to assess the potential of ecological improved composite constituents in cabin environment for their effect on fire, smoke and toxicity. The use of bio-fibres to substitute glass fibres in interior composite materials for aviation (passenger and cargo compartment) could be beneficial for the environmental impact. The same is expected for the application of valuable recycled carbon fibres from cutting waste or end-of-life products via pyrolysis process. As the cellulosic natural fibres increase the calorific value, it is important to assess their impact on fire properties on composite level. For this purpose semi-finished products from natural fibers (flax) and recycled carbon fibers in combination with different matrix systems have been tested in FSS WP7.2 work-package. Simple mechanical tests (flexural) and different fire tests from aviation standards (Flammability, Heat Release, Smoke & Toxicity) have been used to evaluate the performance of eco-reinforcement based material systems.

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Figure 7 - During the 12 sec vertical flammability test (glass fibre + phenolic resin reference (left), recycled carbon fibre + geopolymer (middle) and flax + geopolymer (right))

Flax and recycled carbon fibres have been used to manufacture non-woven reinforcements. A promising bio-based resin system (furan) that exhibits comparable characteristics to state-of-the-art phenolic resin has first been used as matrix for the composites. Fire and mechanical tests have shown the potential and challenges of different material combinations. When using 100% recycled carbon fibers as reinforcement, the fire and mechanical properties have been shown to be very promising, while the heat release is still too high to fulfil the demanding aviation requirements. The use of flax fibers in a hybrid with rCF or as sole reinforcement has highlighted considerable challenges to fulfil the fire requirements: such material solutions would require additional use of fire retardants. Their mechanical properties and weight as cabin environment materials should also be improved, maybe thanks to resin additives, fiber sizing and coatings.

In a second step, a geo-polymer (GPL) matrix has been used as matrix system. Fire tests according to FAR for cargo compartment (F, ST, HR) and basic flexural tests have been conducted to show the potential advantages and challenges of such material combinations. Very promising FST and HR properties have been obtained for the rCF nonwoven with geo-polymer matrix with clear advantages compared to the state-of-the-art glass fibre phenolic resin (GF-PF) combination, e.g. all toxic gases could be reduced. Flammable flax fibers embedded in geo-polymer matrix show good flammability values and toxic gases below the limit. Depending on the amount of flax fibers used in the composites, the heat release limit has been exceeded. Flame retardants would again be required in these cases to meet aviation interior lining requirements. Hybrid combination of outer layers from rCF and inner layers of flax have shown promising FST and HR results in the range of the GF-PF reference, but the mechanical properties would need to be improved (e.g. by a better fibre-matrix adhesion).

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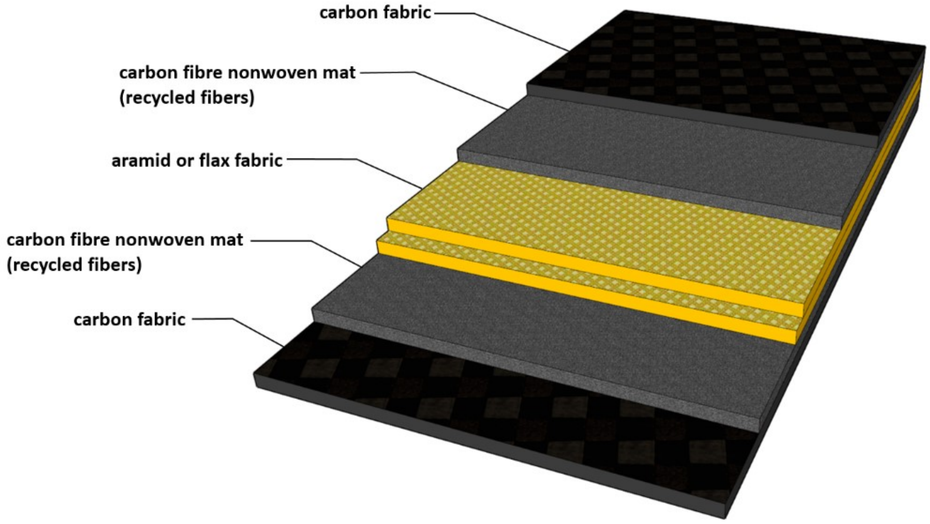

Figure 8 - Lay-up of the geopolymer test panel containing layers of recycled and ductile (natural) fibers

3.2.1. Modelling and simulation results

Flame penetration tests of a monolithic geo-polymer panel and a carbon geo-polymer (foam) sandwich panel have been modelled and simulated using the FlamePTM tool. The use of the FlamePTM tool could bring important benefits to aircraft designers: a reduced need of input tests and test specimens for the model development (hence reduced time and cost), a reduced design and certification cycle thanks to numerical simulations, a reduced risk in the development phase (refinement can be anticipated in the concept phase), and a possible numerical optimisation (rapid calculations). To assess these numerical capabilities, all the data necessary to improve the FlamePTM pyrolysis models have been collected from the characterization of the carbon and geo-polymer materials during the FSS WP7.2 previous test campaign. The implementation of a model to simulate the pyrolysis mechanism for G-P material and for C-GP material have been integrated in the FlamePTM tool in order to introduce the effect of the reaction of the gas produced by the pyrolysis mechanism with the flame in the CFD model, and the consequence effect on the thermo-structural behavior of the tested specimen. The specimen behavior in terms of (1) material degradation (gas produced by the pyrolysis phenomena) and (2) structural behaviour (deformation and stress) has been simulated.

Concerning the behaviour of a FML panel within the CuFex facility, simulation model has been developed which uses thermal and mechanical dependent material properties. The insulating pillow effect of the FML has been reproduced by the simulation, and the drop of mechanical performance due to the decomposing matrix has been studied. A modelling strategy has been developed in FSS WP7.1 work package to investigate the structural behavior of FML with respect to simultaneous fire and mechanical loading. To decrease computational effort, the simulation has been conducted by sequential heat transfer and mechanical analysis. The comparisons of simulation and CuFex-experiment have shown reasonable agreement. The simulation of the combined mechanical and fire loading has also supported the better understanding of the new material solution, helping for further improvement such as optimized layups and decrease of expensive testing effort.

3.3. WP7.3 Effects of new materials, technology and fuel systems on the on-board air quality

3.3.1. Pathway towards Improved Cabin Air Quality

Aircraft architectures, including propulsion concepts, will change disruptively in response to the increased air traffic projections and the global environmental issues (e.g. electrification of propulsive and non-propulsive power). Safety should not be compromised by these disruptive changes. In parallel, there is a growing interest to address complex (cabin) air quality issues related to comfort, health, and safety. This context has allowed for a thorough review of the aircraft cabin of the future, including the cabin air quality of the future on which this research has been focussing. Of course, innovations can and should contribute to improvements in cabin air quality, for instance through the development of new cabin environmental control system, air filter technologies, etc.

In FSS WP7.3 work-package the review of state of the art and recent developments, including related technologies, in cabin air quality, societal trends in air quality, and competitiveness for industry offered by cabin air quality has led to confirm the interest for some recommendations or maybe safeguards (if not regulations) before the introduction of new materials (e.g., nanomaterials) in cabin environment. A continuous cabin air quality sensing could then be a pathway, as long as (1) a knowledge-based definition of Air Quality is established, (2) a general industrial framework exists, and (3) the technology permits.

Methodological guidelines for Cabin Air Quality assessment have first been proposed to increase scientific understanding and to develop business cases: (1) the common purpose of the cabin air quality assessment should be identified in detail with relevant stakeholders and experts, (2) sensor-based methods would be preferred for cabin air quality assessment, supported by human-based information, and (3) conclusions drawn about the human aspect of the cabin air quality assessment should be placed in the perspectives of other factors and events outside the cabin and of air quality in other environments. These guidelines have led to the following results.

3.3.2. Assessment of Air Quality (sensing technologies)

The focus of FSS WP7.3 work-package has been put on the assessment of the cabin air quality by sensing, but other means have also been explored (e.g. human-based information). Specific works has been carried out on experimental characterisation of air quality with COTS sensors, which has demonstrated the applicability of commercial off-the-shelf (COTS) gas sensors to make quantitative measurements of volatile and gaseous emissions from different materials at operational and elevated temperatures, once combined with laboratory analytical modelling techniques. The works has allowed the characterisation of gas emissions from composite materials inside an air-tight tube furnace that could be operated up to 1200 °C.

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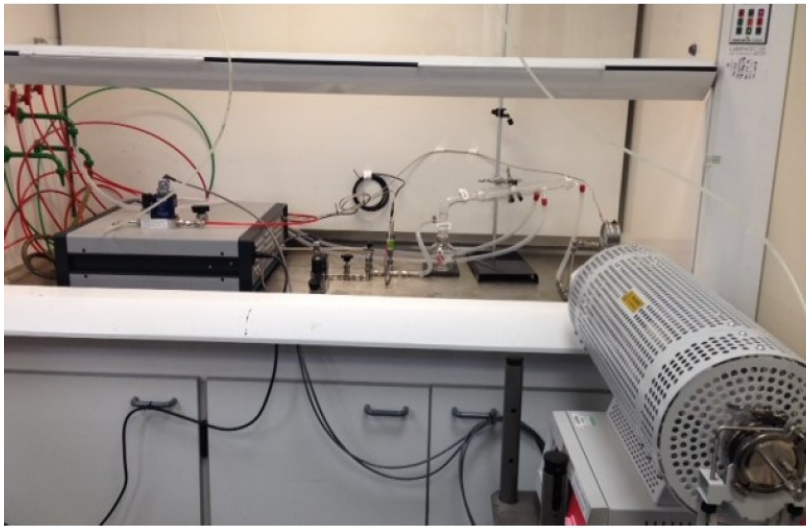

Figure 9 - Experimental apparatus for characterisation of gas emissions at elevated temperatures in realtime using commercial gas sensors and thermal desorption tubes

In the end, the information gained throughout this preliminary investigation has allowed identifying technology capable of detecting potentially hazardous emissions, and the limitations encountered with their use. The sensors have demonstrated a good performance to real-time detection of gases, working consistently over long periods of time (hours). A cross-response of sensors to a range of volatiles has also been pointed out, which would need to be taken into account while investigating and implementing gas sensors into a cabin environment.

Since modelling is needed to link the emission rate in such tests with a possible concentration in the real ECS and elsewhere in the cabin, an ECS (Environmental Control System) model has been extended in order to enable such quantitative investigation of the potential for new materials to affect cabin air quality (if at all). The results of emissions experiments with tested materials can be combined with the modelling developments. Limits on the acceptable concentrations of different substances can also be applied, through the model, to define acceptable limits in the laboratory tests.

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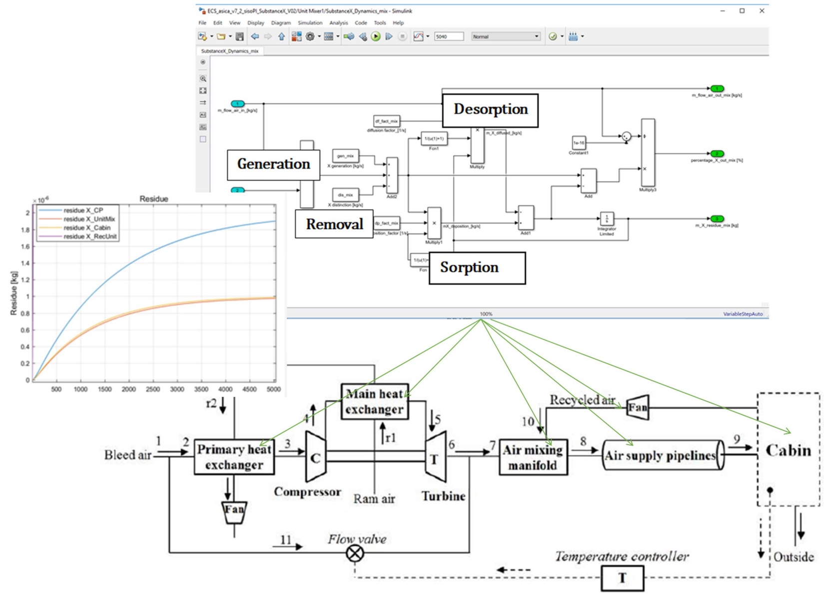

Figure 10 - Cabin air quality building block for aircraft environmental control system (ECS) model with. ECS schematic from literature[1]. Verification of the integration of the building block

Last, the experience of using COTS sensors in FSS WP7.1 work-package has fed into specifications for the sensors in any IFCAS (see next paragraph).

3.3.3. Industrial framework for continuous air quality sensing

An "Industrial cabin air quality Framework based on Continuous Air quality Sensing" (IFCAS) has been finally proposed. The core of the IFCAS would be a well-placed network of low power, low weight sensors that is distributed across the cabin. Other elements of IFCAS would concern the on-board post-processing, storage, and distribution of data during a flight, the storage and sharing of flight data potentially between different stakeholders, and the analysis of the big data that is gathered, potentially combined with modelling and simulations. It has been suggested that, depending upon confirmation of stakeholder interest, the development of IFCAS could be started in near future, while progressively extending it with the latest sensing technologies. Recommendations have been given for further research and development of IFCAS to increase its maturity. All the more as the on board air quality framework could evolve in the future because of: (1) civil society initiatives such as a citizen-based observatory for cabin air quality, (2) the development of multi-fidelity cabin air quality modelling and simulation and (3) the possible future combination of inner (IFCAS flight data) and outer (lab, virtual) data.

[1] H. Yin et al., "Modeling dynamic responses of aircraft environmental control systems by coupling with cabin thermal environment simulations," Build. Simul., vol. 9, no. 4, pp. 459–468, 2016

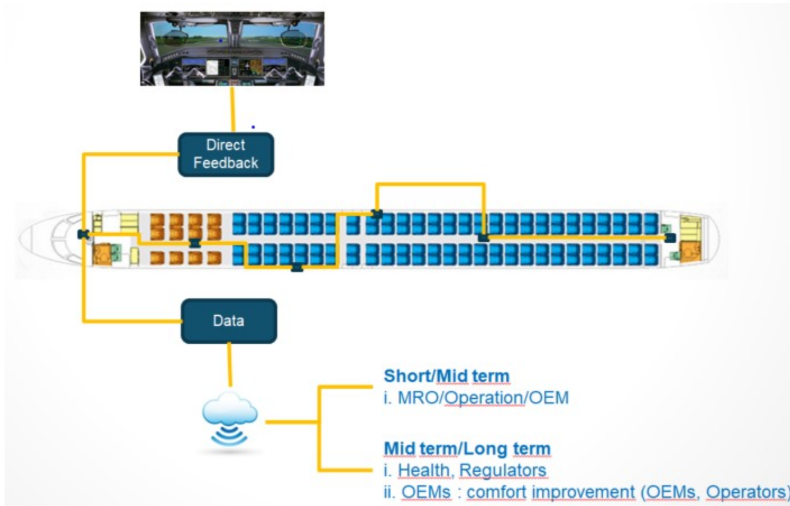

Figure 11 - IFCAS concept architecture (cabin/cockpit pictures Embraer)

Possible applications of such IFCAS are foreseen during flight and on different time-horizons after flight, including prognostic health management and condition-based health management, evidence-based answers to concerns, and methodical, engineered approaches to improve comfort and to better design the air inside the cabin. The FSS WP7.3 preliminary feasibility analysis of IFCAS has been further investigated by deepening the concept. This investigation identified challenges for effective use of the IFCAS data such as: (1) how to ensure high-level of quality of the IFCAS data, including the human interface, in case this would be used on-board, in order not to compromise safety, and (2) transform opportunities offered by common management of IFCAS data into an effective use in further data analysis.

4 SPECIFIC EXPLOITATION ACTION

In year 2018, in frames of FSS WP7.2, a geopolymer-based panel was manufactured and tested. It was designed as a 406 x 610 mm flat panel to facilitate CS25 App. F, Part III flame penetration test. Lay-up of the panel represented hypothetical interior panel of CS23 or CS25 certified airliner. The emphasis was placed on the design of a lightweight, cost effective and well impact resistant structure. Basic information are available also in technical reports D7.10, D7.13, D7.16 and reminded in §3.2.1.1. Following this work, it was proposed and approved to further developing these works into the design and manufacturing of a structural demonstrator, as an exploitation action for FSS P7.

4.1. The basic concept of demonstrator

An actual interior panel of the CS 23 certified, Czech made regional turboprop was selected to be the FSS WP7.2 structural demonstrator, and more specifically the emergency exit door panel was identified as the optimal choice – it is a relatively complex part featuring window cutout and dimple of the opening lever. Originally the part is made by autoclaving of qualified glass-phenolic prepreg. The demonstrator was not thought to be an exact copy of the original and certain level of design freedom was accepted. Several moldings of this demonstrator were manufactured for different purposes: in particular several composite materials solutions were used for the structural skins. More details (drawings, materials, layups, etc.) about these different moldings are presented in D7.16.

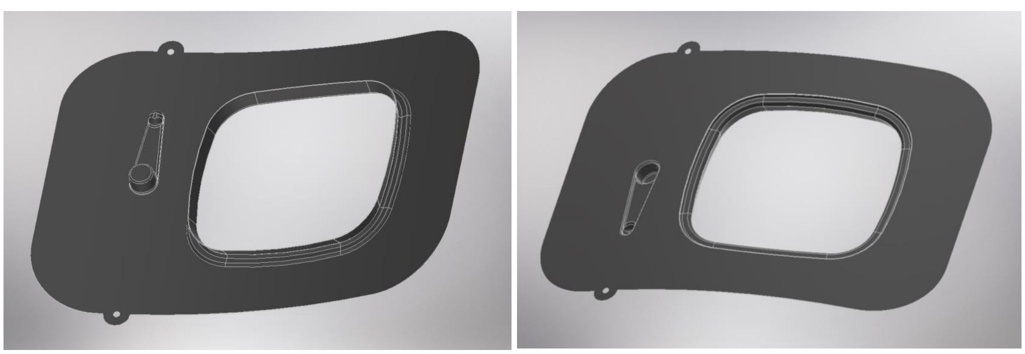

Figure 12: Design of the first demonstrator – inner (left) and outer side (right)

For manufacturing the demonstrator, a serial mold was leased from the original part manufacturer (LA Composite, Prague). The mold is of standard design, negative, two piece, made of glass / epoxy temperature resistant composite (Airtech TMR 2001A / TMH 2001B resin system).

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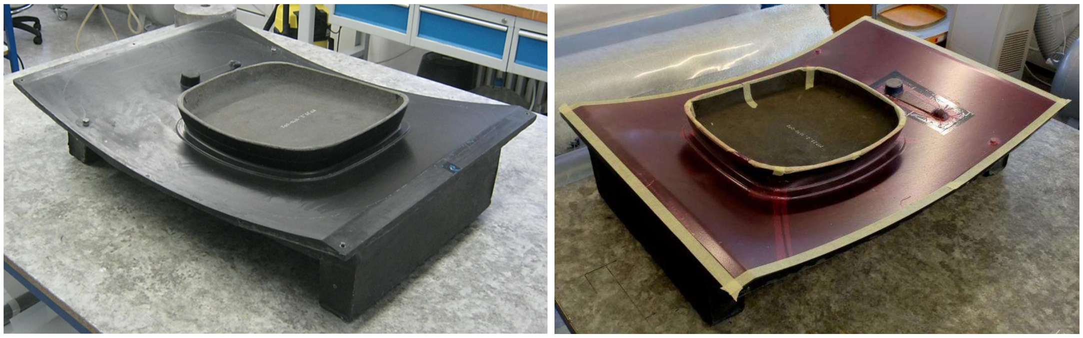

Figure 13: The raw (left) and protected by aDiatex A5000 release film (right) mold of the first demonstrator

4.2. Materials solutions and process used for the FSS WP7.2 demonstrators

The corrugated geopolymer-carbon fibers sheets based honeycomb was manufactured using 1 layer of 20 g/m^2 carbon nonwoven + 1 layer of 60 g/m^2 carbon plain fabric / GPL30 geopolymer resin. A geopolymer foam the specific weight of which is approx. 230 kg/m^3 was used to realize the chamfered edge needed to complete the sandwich design. The layer of the first variant of the demonstrator (molding A) is given in the figure below.

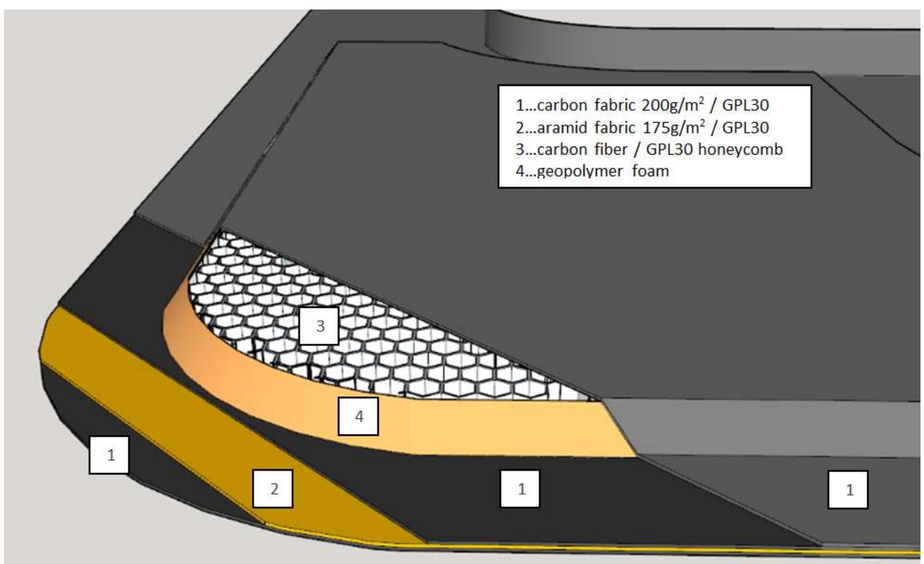

Figure 14: Lay-up scheme of the structural demonstrator (molding A)

The composite sandwich skins of the demonstrator were made by wet-laminating method using standard vacuum bagging process. The honeycomb core was then first assembled and bonded on the cured outer skin, and the inner skin post-cured prior to final demolding and painting. The weight of the trimmed molding A (without surface finish) was finally 770 g. The first molding was done for validating the process and showing of the concept purposes.

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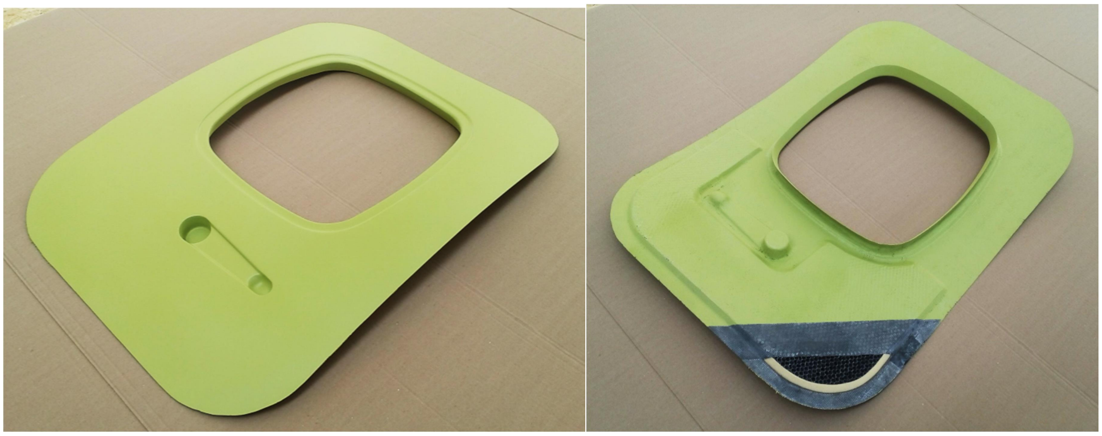

Figure 15: Outer (left) and inner (right) side of the molding A (surface filled and painted)

4.3. Materials variants of the FSS WP7.2 demonstrators

The second molding B was meant for the flame penetration test (the transparent window was replaced by a 0,5 mm stainless steel panel, and the test duration was prolonged to 10 minutes instead of standard 5 mn). The lay-up and manufacturing process was identical with molding A (except one layer which was made of 200 g/m^2 carbon plain fabric). No filling or painting was carried out on this part. The weight of the trimmed molding B (without surface finish) was 793 g.

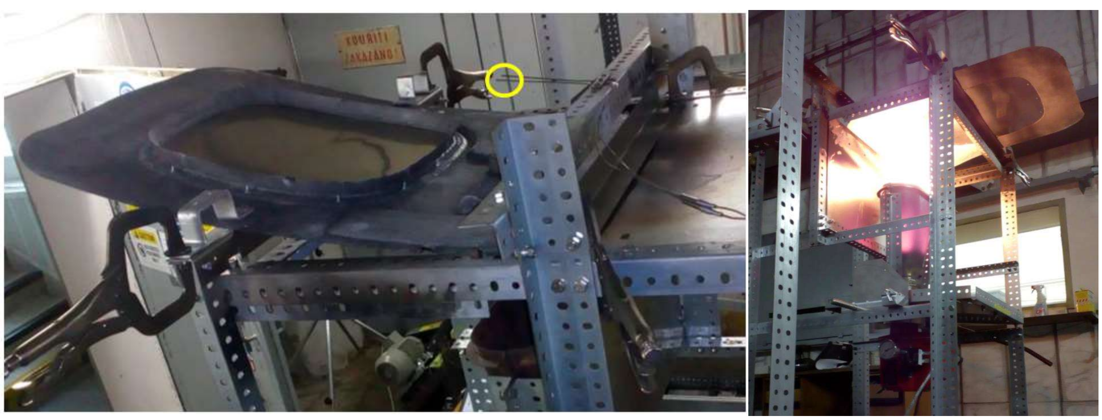

Figure 16: Flame penetration test per CS 25, App. F, Part III - Two thermocouples (in yellow circle, see left) were set 100 mm above the back surface

The figure below presents the flame penetration test results with molding B. After the test, no visible changes have been registered on the molding, except of colour change and warpage of the edges. Due to application of geopolymer honeycomb, no sandwich “pillow effect” was registered. The molding has maintained integrity and very good stiffness. The temperature above the back surface (4 inches) passed the max. allowable temperature per CS25, APP. F, Part III (204^{o}C / 400 °F), for an average flame temperature about 970 °C.

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Figure 17: Molding B after 10 minutes of the flame penetration test - Exposed side (left) and back side (right)

A 3rd variant (molding C) of the structural demonstrator was manufactured using a carbon-aramid hybrid fabric KORDCARBON CA 164 P - 120 (164g/m^2) as base fiber reinforcement, mainly to reduce weight. Flame penetration test (CS25, App. F, part III), vertical test (CS25, App. F, part I) as well as smoke density and toxicants tests of the new geopolymer - carbon - aramid material were performed in order to check that the presence of aramid fibres does not impair significantly the FST properties of the composite parts (all the test results have passed standards requirements and highly surpassed referential glass-phenol). Once verified this point, the final lay-up for molding C was chosen identical with molding A except the fact that the reinforcement material for the different layers are made of the hybrid where the aramid fibers were located as a separate layer between the carbon layers for molding A: the weight of trimmed molding C (without surface finish) was finally 623 g.

The 4th and last version of the demonstrator (molding D) was meant as a referential one made of GURIT PHG 600-68-37 T2 glass-phenolic prepreg and AIREX R82.60 foam. The lay-up of the molding is described in D7.16. The final weight of the trimmed molding D was 776 g. A comparison of the costs of the two last versions of the demonstrator is given below.

Table 1 - Informative comparison of molding C vs. molding D material costs

Molding variant	Main structural material	Structural material price incl. VAT (100 g)	
C (carbon / aramid / geopolymer)	carbon - aramid hybrid fabric KORDCARBON CA 164 P 164 g/m^2	7,44 €	7,84 €
	GPL 30 resin	0,4 €	
D (glass / phenol prepreg)	GURIT PHG 600-68-37 T2 prepreg	8,24 €	8,24 €

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5 CONCLUSIONS

5.1. WP7.1 Understanding & characterizing the fire behavior of primary structure composite materials

Concerning the objectives defined for Future Sky Safety WP7 (see §1.3. Research objectives) the research effort performed in this FSS WP7.1 work-package have contributed the achievement of at least three of these objectives. First, the experimental results have increased the knowledge concerning CFRP material behaviours vs fire, for instance the influence of temperature but also temperature rise rate on the pyrolysis mechanisms has been demonstrated. Second, the results obtained in this work-package has allowed assessing the mechanical properties of heating/burning/degraded material and/or panels for an aircraft standard CRFP tape material through numerical simulations of 2 case studies, and has pointed out future axis of improvement. Third, the public results can now be shared to build up a public experimental database on T700/M21 material: the experimental database produced thanks to this FSS WP7.1 work-package is unique and provides an important number of material properties to the scientific community in order to improve the models and validate numerical simulations dedicated to the fire behaviour and degradation of CFRP materials.

The first output from WP7.1 is the production of knowledge concerning the fire behaviour of primary structure composite materials. The main conclusions of these works (which are expected to be published in scientific journals) are that:

- the specific heat and thermal conductivity for the virgin T700/M21 material, and its orthotropic properties (identified from thermographic measurements) are dependent on the temperature, and the oxidation reactions are dependent on the temperature rise rate (ramp),
- a thermal degradation model adapted to composite materials could be identified thanks to Thermo Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) experiments. To improve accuracy of predictions, kinetic models for high heating rates must be developed and identified out of the conventional thermally thin assumption especially if one wants to predict significant local thermal non-equilibrium measurements,
- concerning numerical simulation tools, the main conclusions of the FSS WP7.1 works are that the use of thermo-mechanical modelling in order to obtain a coupled simulation of the real problem is a key factor to more accurately predict the behavior of composite CFRP materials submitted to fire under real conditions.

The second output from WP7.1 is the production of a comprehensive experimental database for a reference material (T700/M21) to be shared by the European research community as a basis for material model development of the fire behaviour and degradation of CFRP materials. All the experimental results obtained in the work-package are summarised in FSS D7.12 synthesis report. For each property studied, a clear reference is made to the different documents in which the methodology, the experimental results

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and the analysis are properly described. All the FSS WP7.1 test data are available in extensor in two deliverables: FSS D7.4 and FSS D7.7:

- FSS D7.4 deliverable is mainly dedicated to the measurement of the thermal conductivity tensor and the heat capacity, the thermochemical properties and some thermo-mechanical properties of the T700/M21 CFRP tape material,
- FSS D7.7 deliverable is mainly dedicated to the thermogravimetric analysis, the measurement of the thermal conductivity tensor and the heat capacity of charred material, mechanical and thermomechanical testing of virgin and charred materials and decomposition of composite sample with various heating sources. The mechanical and thermomechanical behavior of the virgin material have been characterized on a large range of temperatures that makes it possible to perform coupled thermo-mechanical simulations. New test protocols/results are available: heating rates of TGA measurements have been extended to reach thermal loads of the same order of magnitude than those experienced during a fire event. A preparation protocol to reach a fully charred (pyrolysed) state of the material has been set up and successfully carried out to obtain a thermal and a mechanical characterization of the T700/M21 charred state,
- nevertheless, some tests standards are still clearly missing before such complete characterisation of the thermal degradation of composite laminates is accepted.

The third output from WP7.1 is the assessment of the mechanical properties of heating/burning/degraded material and/or panels from the tests previously mentioned for the purpose of better designing aircraft standard CRFP tape material primary structures. FSS D7.9 deliverable contains a detailed bibliography dedicated to current state of the art in the field of thermal and thermomechanical simulations. The bibliographic study is completed by two detailed case studies proposed by ONERA and AIRBUS D&S, with a confrontation of experimental results to research and industry state-of-the-art models and simulation tools respectively:

- methodologies have been proposed to use the proposed models for the simulation of the thermal and chemical behaviors for few selected test cases, then for fire testing predictions. It was shown that the analysis of structural simulation results could provide a useful estimation of the degradation state of the composite materials summited to fire and other boundary conditions, to support decision making (geometries, configurations) by the designers,
- for instance, the experience related to monolithic composite fire testing when loaded through common fitting assemblies determines that the main failure usually occurs in the joint between load introduction device (fitting) and the composite. This joint is typically a fastened connection (bonding joint is not a non-destructively inspectable procedure and not actually accepted by EASA). Once having decomposed real loading cases on a fastened joint as a sum of two basic load cases(in-plane and through-the-plane cases), the characterization, test and correlation with the

simulations of each of these two basic configurations may give enough information to propose a simplified analysis of a complex fitting-composite configuration,

- this part of the work has led to the following recommendations: (1) implement the new models into suitable simulation platform software would make it easier to carry out coupled-simulations, (2) generate a thermo-mechanical model by means of finite element method representative of the behavior of materials submitted to applied loads, temperature and degradation would increase numerical efficiency, (3) work out problems taking into account the thermal and mechanical interactions, first thermally uncoupled, followed by coupled, would improve understanding and analysis, and (4) establish a systematic procedure to perform correlations of simulation models with results obtained in laboratory tests would be highly appreciated.

In terms of ***outlooks and perspectives***, now that tests, models and simulation methodologies have been exhaustively studied at the material, structural detail or simple panel levels focussing on a single composite material, two possibilities are offered for further proposals:

a) the response of more complex structural components should be addressed following the building block approach philosophy. In particular the models and simulation tools could be used to evaluate the structural behaviour of composite stiffened panels, especially under combined fire exposure and compression loading. The research could include preliminary numerical design of a structural test, incl. structure specimen and (adaptation of) test apparatus/rig. Several structural specimens/tests of increasing complexity might of course be needed in order to permit the detailed analysis of difficulties related to the change of structural scale. The tests results would then be of great interest for the research and industry community to challenge and compare the capabilities of different models and softwares at this complexity level,

b) the tests protocols, new models and methodologies could also be applied to other materials (for instance the new ones that have started to be studied in FSS WP7.2) which is under discussion.

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5.2. WP7.2 Improving material solutions to mitigate FS&F in the cabin environment

Concerning the objectives defined for Future Sky Safety WP7 (see §1.3. Research objectives) the research effort performed in this FSS WP7.2 work-package has contributed to the achievement of at least three of these objectives: (1) the Improvement of knowledge concerning unusual materials but also structures (e.g. under combined compression and fire loadings) behavior vs fire, (2) the assessment of identified mechanical/chemical properties to model these new material behavior and their structural response, (3) the evaluation of potentialities offered by several families of hybrid structural solutions of different maturity levels to reduce fire consequences (incl. toxicity, smoke) in the cabin environment: e.g. fiber metal laminates, hybrid recycled carbon and natural fibers, and geo-polymer based (as a matrix or foam) carbon reinforced solutions.

The first output of FSS WP7.2 concerns:

- The screening of a set of basic candidate improved materials thanks to a large panel of experimentations which have permitted to confront expectations (in terms of fire resistance, smoke and toxicity but also mechanical properties) to reality, and have enlightened manufacturing capabilities or difficulties. Material solutions have been compared to standard glass/phenolic current materials for cabin environment, but also analysed wrt to their potentialities for cargo applications. Significant improvements have been demonstrated with some of these material solutions, that have led to the decision to evaluate their performances at the structural level,
- The structural assessment of a selection of hybrid solutions, mainly fiber metal laminates and geo-polymer foam based carbon sandwich panels has been reached. A new CuFex test rig to study compression behaviour of structural panels under fire exposure has been designed, set up and can be used to evaluate such structural solutions. However, testing of structural concepts such as sandwich composites or stringer structures has to be approved.
- Routes for further improvements have been identified wrt to observed weaknesses, and some of them already tested. But a lot still remains of course to be done to fully consider applicability for commercial aircraft design.

The second output of FSS WP7.2 concerns other considerations beside the fire, smoke and toxicity properties of the studied new material solutions:

- In terms of manufacturing techniques, standard methods as hand lamination, “wetpreg” or standard prepreg can be used but applicability of infusion processes is still limited. In terms of costs, the new material solutions and current glass/phenolic (for cabin environment materials), or current monolithic CFRP (for primary structures) would be comparable,
- In terms of ecological and sustainable aspects, direct and indirect advantages have been highlighted when using natural fibers, recycled carbon fibers, geo-polymer or bio-based resins, instead of current solutions. To make all the benefit from these material solutions,

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combinations/hybridizations have to be further studied and final formulations improved and optimised.

The third output of this FSS WP7.2 work-package concerns the demonstration of the interest and possibility to further improve existing simulation models and tools thanks to more complete and research sets of experimentations like those performed in this project. Several ways of improvements have been illustrated, either by proposing methodologies for coupling different tools (in softer or stronger ways), or by extending capabilities of dedicated multi-physical codes with enhanced material models (e.g. pyrolysis models). Improvements would concern accuracy and robustness of predictions, but also computational efficiency for structural design and numerical optimization.

In terms of ***outlooks and perspectives***, the possible combination of natural and recycled fibres with geopolymer matrix which has been demonstrated in this project could be further studied in the frame on follow-on projects:

a) Generally, the weak fibre-matrix adhesion is a challenge for the use of geo-polymers in combination with natural fibres and recycled carbon fibres. Cold plasma treatment to activate the fibre surface could be a solution. Furthermore, the influence of moisture must be carefully considered as geo-polymers are partly water based system. Flexural tests with pre-dried specimens are recommended to assess possible differences. GPL resin features a strong basic pH (>11) until it hardens which takes normally few hours until the pH factor of cured resin drops to neutral value. The effect on sensitive natural fibres by alkalinity should be observed in detail.

b) The pore content needs to be better controlled in future manufacturing trials in order to get a better assessment of the performance potential. The embedding in a fire resistant geo-polymer matrix alone is not enough to protect the fire sensitive cellulosic flax fibres. It has to be explored, if a better composite quality with reduced pore content is able to improve the heat release results considerably. If not, the addition of flame retardants is needed to fulfil the demanding aviation requirements. A possible way to enhance mechanical and fire properties could be a hybrid composite. The example of rCF outer layers and flax inner-layers shows very promising results. Generally, for application in aviation interior linings, the highest attention should be given to the reduction of the panel weight. This is the most effective way to reduce the environmental footprint by lowering the kerosene consumption during the use -phase. A Life Cycle Assessment (LCA) is recommended to compare possible variants with the state-of-the-art.

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5.3. WP7.3 Effects of new materials, technology and fuel systems on the on-board air quality

Concerning the objectives defined for Future Sky Safety P7 (see §1.3. Research objectives) the research effort performed in this FSS WP7.3 work-package have contributed to the achievement of 2 of these objectives: (1) the experimental method for evaluation of the elevated temperature consequences of new material on air quality (toxicity), and (2) the establishment/proposition of recommendations for the definition of an on-board air quality industrial framework. Once implemented this framework would provide the data and thus enable a step change in the scientific understanding of on-board air quality under relevant conditions. This would address the current globally growing interest in complex air quality issues, including the air quality in the cabin. Based on the increased scientific understanding improved designs of the cabin air can be developed. Such framework can already be used on shorter time horizons for improved operation of aircraft and mitigation of risks.

The first output of FSS WP7.3 is the delivery of a broad bibliographic review and analysis of numerous topics of interest to better formulate and address the cabin air quality question as it is today and maybe will be in a near future: new concerns and incident reports of course, specificities of cabin environment or similarities compared to other confined or even unconfined environments, possible emissions from different (new) sources in interaction with cabin air, regulatory aspects, cabin air quality assessment methods with a focus on assessment by sensing, currently available air quality sensors and their application in the cabin environment, current directions of research in air quality sensors. One of the conclusions is the growing global interest to address complex cabin air quality issues related to comfort, health, and safety.

The second output of FSS WP7.3 is the design (from existing standards) and set up of a prototype lab test equipment based on the use of commercially off-the-shelf sensors/instruments, to enable real-time quantitative investigation of potential emissions from cabin materials under operating or elevated temperatures. The test bench allows also for sampling and further delayed analysis, for which TD-GC-MS has been applied. Low concentration detection capabilities have been demonstrated for a series of well-known toxic gases and volatiles. The experimental methodology also offers the ability to test COTS sensors for detection of those volatiles. The test bench allows for integration of additional COTS sensors. Having established a methodology for potential assessment of materials, a wider range of new materials and testing of an increased number of samples would provide greater detail to inform materials selection and design.

The third output of FSS WP73 is the method for extending global ECS models to capture the main dynamical phenomena involving substances. Global ECS models are commonly applied in industry to develop control elements of the ECS. One such extended global ECS model has been obtained as a verification of the method. Such model enables transfer of the results of the laboratory environment in the second output to the aircraft cabin environment and vice versa. Other applications of the extended global ECS model are in the context of the framework in the fourth output.

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The fourth output of FSS WP73 concerns recommendations and methodological guidelines for cabin air quality assessment. To address the growing interest in complex cabin air quality issues the feasibility of a pathway has been concluded that would permit to build a global framework, involving the aircraft industry and the other stakeholders, including regulation authorities and civil society, to assess, measure, and monitor cabin air quality. Thanks to the insights obtained on sensor developments, the feasibility of this pathway could be concluded, based as well on the investigations on the initial concept architecture for such framework and the opportunities for data-recording on-board aircraft. The placement of cabin air quality sensors is facilitated by extended global ECS models, see the third output.

The proposed "Industrial cabin air quality Framework based on Continuous Air quality Sensing (IFCAS) would make use of "big data" emerging analysis techniques, and of the combination of real and virtual data. The IFCAS framework could be exploited for PHM/CBM or improvement of in-flight cabin management. In a longer time frame, IFCAS data could be used as well for validated multi-fidelity cabin air quality modelling and simulation, exploiting the third output. Multi-fidelity cabin air quality modelling and simulation may be used to design the cabin accordingly, to mitigate risks. Business models and value propositions for operators and other stakeholders should be studied further.

These outputs from WP7.3 have been reported in two public deliverables:

- FSS D7.6 deliverable is the major report on the bibliographic review (first output) with an extensive review of cabin air quality monitoring strategies, mainly based on sensing.
- FSS D7.14 deliverable is the final report on on-board air quality, in which the bibliographic review (output 1) has been completed and the second, third, and fourth outputs are described.

In terms of ***outlooks and perspectives***, considering the previous conclusions, possible topics for follow-on projects have been identified.

a) *The first one* would consist in carrying out further fundamental research on possible configurations, use and governance of IFCAS as a big data observatory for cabin air quality. This would take into account synergies with other big data initiatives in aviation such as FSS Risk Observatory and EASA big data initiative. It would also take into account the trends on the ECS and cabin of the future in disrupted aircraft and engine configurations, on the quantified self and on air quality in other environments. This project would help stakeholders, such as OEMs, operators, and regulatory agencies to prepare to exploit IFCAS.

b) *The second project proposal* would concern the development of a target specification for gas **sensors to operate in the aircraft cabin environment within the proposed IFCAS "black box", the** design and set-up of an embedded prototype. This would require cross-industry discussion and agreement. The target specification could be used to allow flexibility between different airlines (for example on which species to detect) and yet provide a common test strategy for sensor providers (for example concerning the environment(s) they should operate in). It would therefore allow sensors to be compared on a consistent basis.

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c) *The third project proposal* would concern the **ongoing development of the COTS system** to (i) analyse and compare a wider range of sample types including the new materials developed towards the end of this project, (ii) develop the system further to be able to support work at higher temperatures or establish an upper operating limit, (iii) extend the range of sensors within the system to detect in real time a wider range of possible gases and volatiles, specifically looking for those gases more likely to arise at higher temperatures as a possible result of combustion, (iv) link the quantitative results with modelling so as to predict the effect on air quality with a given area and thermal profile of material.

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5.4. Conclusions and outlook about the FSS WP7.2 exploitation action

Realization of the geopolymer based structural demonstrator (window panel) as exploitation action for FSS WP7.2 has permitted to prove:

- The manufacturability of real aircraft interior part of inorganic, geopolymer based composite material. Standard serial molds as well as common vacuum bag manufacturing procedure have been applied with no complications,
- The exceptional fire resistance and negligible smoke emission of geopolymer based solutions compared to standard Glass-phenolic ones. The geopolymer honeycomb core did not cause pillow effect as observed in the previous tests with organic sandwiches cores, and the part has retained very good structural integrity after the test,
- The use of aramid, e.g. In molding C with the hybrid carbon/aramid fabric led to extra improvements, not only with respect to the impact resistance compared to 'carbon only' composite solutions, but also with respect to the weight of the glass-phenolic and the basic geopolymer composite solutions.

For potential application in the aircraft structure, some specific problems that have not been dealt with yet remain to be solved:

- To ensure the uniform quality of the composite material it is necessary to introduce mechanized manufacturing of the semi-product, so-called 'wetpreg'. Accurate machine dosing and distribution of geopolymer resin in the fiber reinforcement is the important factor to achieve low specific weight and uniform mechanical properties, which are critical parameters of the FRGC material,
- The methods of suitable surface treatment of geopolymer moldings should also be studied. Specific issues relating to durability of standard coating systems on geopolymer surface may arise,
- In the ideal case, to get response from practical operation, one or more parts should be deployed in the real service whilst monitoring its operational characteristics during long-term exploitation. But before FRGC structure is applied in the serial airplane production, a range of administrative and regulation questions should also arise concerning the certification process.

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Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

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