ESA – 2023 CLEAN SPACE INDUSTRY DAYS

A Direct Approach for Assessing Demise Capability and Modelling Correlation for DRAMA: A Case Study on Composite Materials

Alexandre A. Looten - École Polytechnique Fédérale de Lausanne

October 19 2023

ESTEC - Noordwijk

eSpace EPFL Space Center

LPAC Laboratory for Processing of Advanced Composites

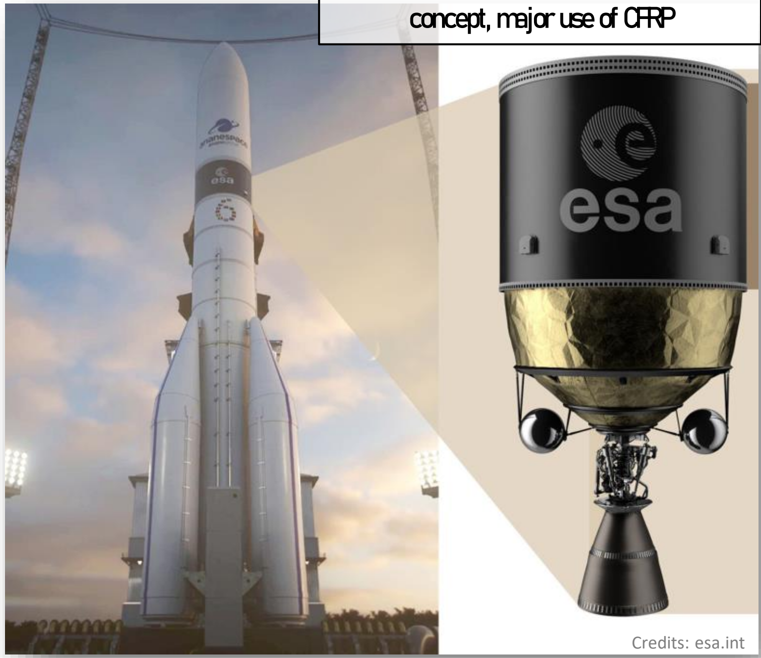
Context

Design for demise with composite systems

The Demisable Composite: An Intensive Quest Toward Zero Ground Casualty Risk

- Rising integration of advanced composites in the space sector
- Multi-level advantages of carbon fiber reinforced polymer – CFRP
  - Highest specific strength on market
  - Tailorable properties
  - High thermal stability
- But End-of-Life management issues
  - High reentry survivability → High Ground Casualty Risk

Ariane 6 ultra-light upper stage Phoebus concept, major use of CFRP



Credits: esa.int

pixabay.com

COPV – Australia, 2021
twitter.com/katiepatrick

CFRP sandwich, SpaceX Crew-1 trunk, Australia, 2022
nzherald.co.nz

isro.gov.in

COPV – Indian PLSV 3rd stage, Australia, 2023
7news.com.au

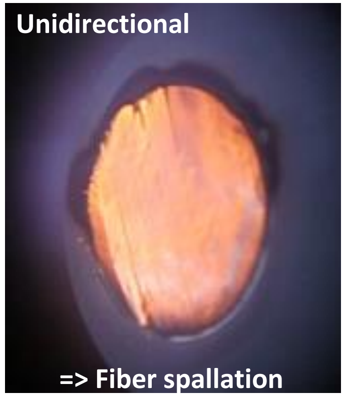
Alexandre A. Looten
EPFL

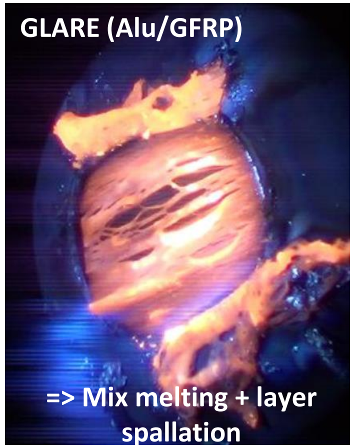
Context

Critical composite elements and mitigation studies

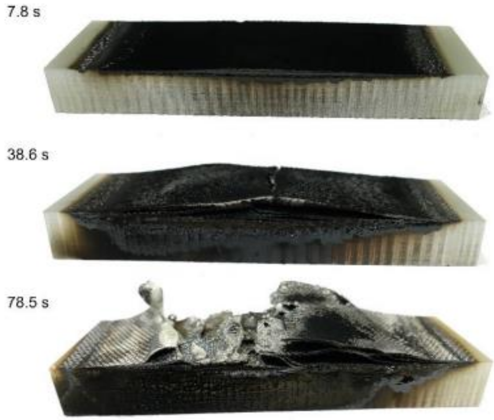
Current FRPs demise performance obstacles :

- Use of continuous critical fibers (CF, glass)
- High variability of demise behaviour linked to large material selection
- Low experimental testing predictions
- Tight and interwoven reinforcement stacking
- Laminate thickness effect





[1]



[2]

Several mitigation approaches underwork :

- Demisable fibers integration (Natural, organic)
- Specific reinforcement placement / Topology optimization
- Specific material combination modelling correlation from experimental testing

Alexandre A. Looten

EPFL

space.com

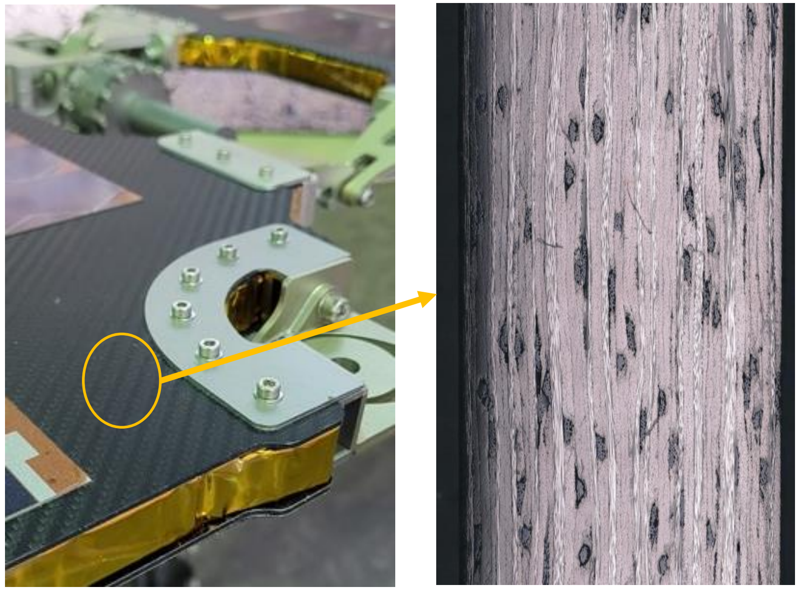
[1] Pagan A , IRS Stuttgart (2017), *Experimental Investigation of Material Demisability in Uncontrolled Earth Re-entries*

[2] Greene BR and Ostrom C.L., NASA (2021), *Pyrolysis rate and yield strength reduction in carbon fiber and glass fiber composites under reentry heating conditions*

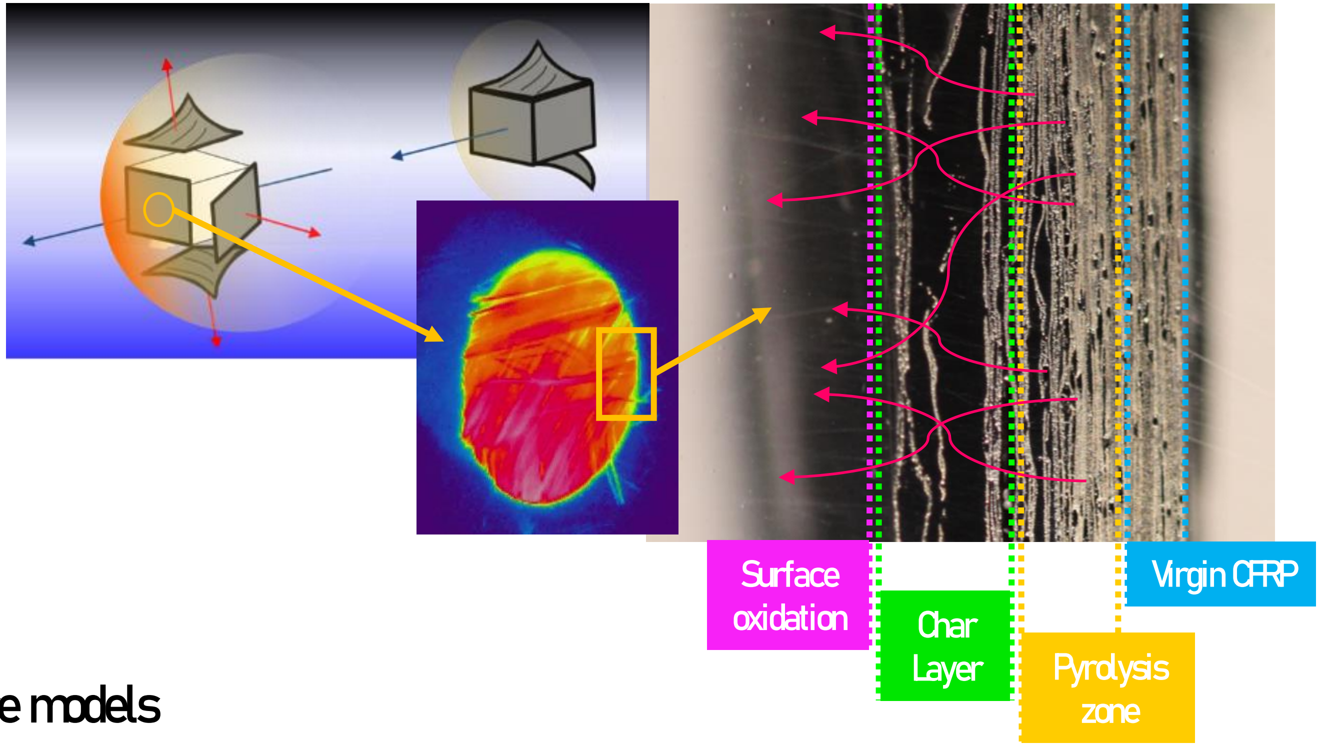
Demise models

Material-level modelling

Fiber-reinforced composite demise process



-> Synergic reactions between the matrix and fibers



DRAMA SARA-tool

2 material types built-in demise models

Metal-like

- Melting temperature
- Specific melting heat
- Oxide formation heat

CFRPs-like

- Char dynamic + oxidation
- Pyrolysis reaction
- Pyrolysis gases formation + interaction + convective blockage

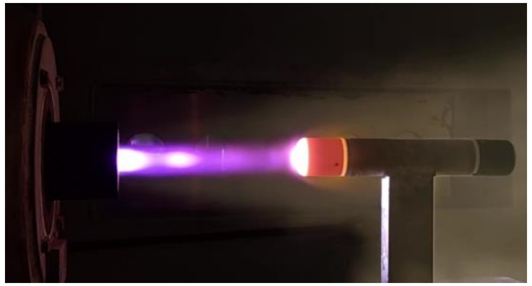
- CFRPs material parameters require 11 specific parameters
- High uncertainties by using built-in CFRP parameters (fiber and matrix types ?)

Direct approach

Experiment-to-model method

DRAMA demise model equations

CFRP material model



Experimental data

TGA, DMA, MDSC, Static reentry chamber, PWT

MATLAB

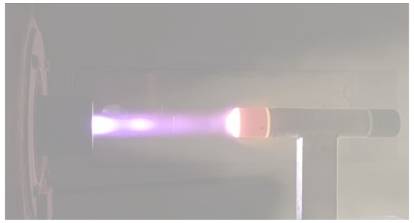
Data and model fitting process

New material parameters

DRAMA-CFRP model

SARA reentry tool composite material model

DRAMA demise model equations
CFRP material model



Experimental data
TGA, DMA, MDSC, Static reentry chamber, PWT

MATLAB®
Data and model fitting process

New material parameters

- DRAMA CFRP-model based on 1D ablation model [3]

Heat balance terms

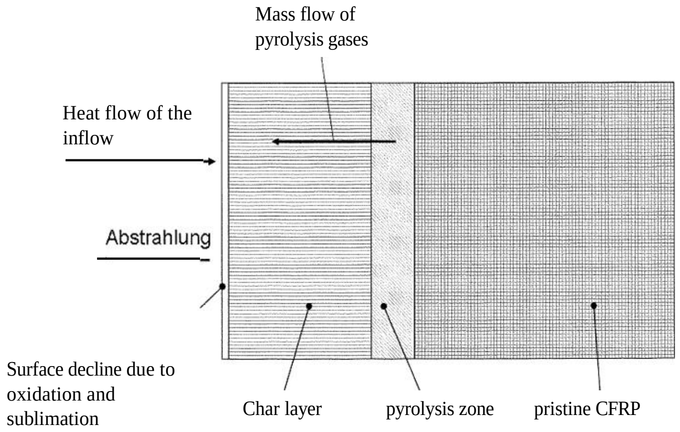
Heating:
1. Plasma inflow
2. Surface oxidation

Cooling:
3. Material heat dissipation
4. Pyrolysis reaction
5. Surface reradiation
6. Pyrolysis gas blowing factor
7. Pyrolysis gas flow through char

Mass loss terms

A. Matrix pyrolysis
B. Spallation – Pyrolysis gas char blowing
C. Char/fiber oxidation

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + h_{pyr}\frac{\partial \rho}{\partial t} + \dot{m}_g c_{p,g}\frac{\partial T}{\partial x}$$

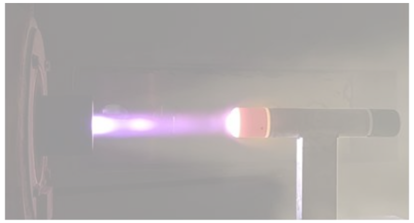


[3] Kuch M, Thesis, TU Braunschweig (2011), *Entwicklung eines Modells für die ablative Zerstörung von Kohlefaser-Epoxy Komposites beim Wiedereintritt*

Blackbox reverse engineering

DRAMA demise model equations

CFRP material model



Experimental data

TGA, DMA, MDSC, Static reentry chamber, PWT

MATLAB

Data and model fitting process

New material parameters

A. First iteration

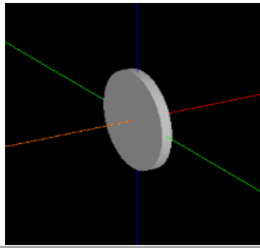
- Pyrolysis reaction with 3 terms $F = \sum_{i=1}^{3} A_i e^{\frac{-E_i}{RT}}$
- Char reaction = 2 (based on M.Kuch thesis [3])

B. Second iteration

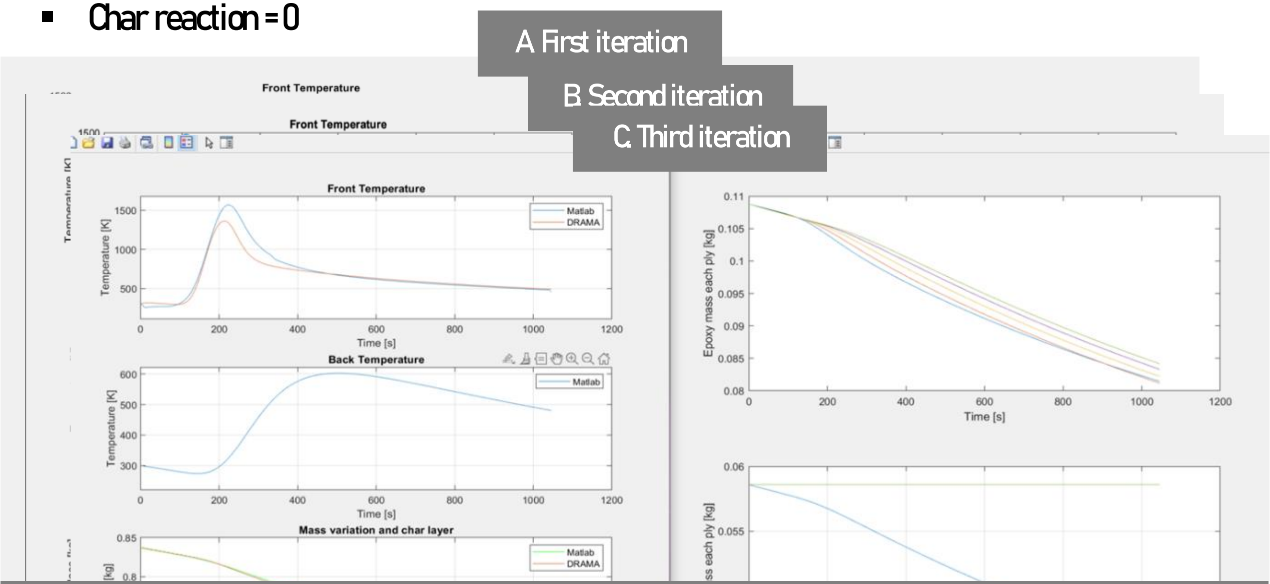
- Pyrolysis reaction with 1 term $F = A_1\, e^{\frac{-E_1}{R\,T}}$
- Char reaction = 2

C. Third iteration

- Pyrolysis reaction with 1 term
- Char reaction = 0



Implementation of DRAMA
Aerothermal history in Matlab code



- **DRAMA model uses only single term Arrhenius pyrolysis reaction | Ea and A**
- **Clear understanding of the displayed parameters of DRAMA UI**

Experimental data

Specific composite material demise parameters

TESTING METHODS

- Thermogravimetry analysis – TGA
- Thermal conductivity analysis – LFA, Hot disc
- Modulated differential scanning calorimetry – MDSC
- Emissivity measurement facility – EMF
- Static reentry chamber | Mechanical loosening and demise onsets
- Plasma wind tunnel – PWT | Reentry conditions highest fidelity

Pyrolysis reaction | E_a, n, T_{onset}, $mass\ loss\ rate$

Thermal conductivity as fct of T | $\lambda_{cond}(T)$

Matrix specific heat as fct of T | $c_p(T)$

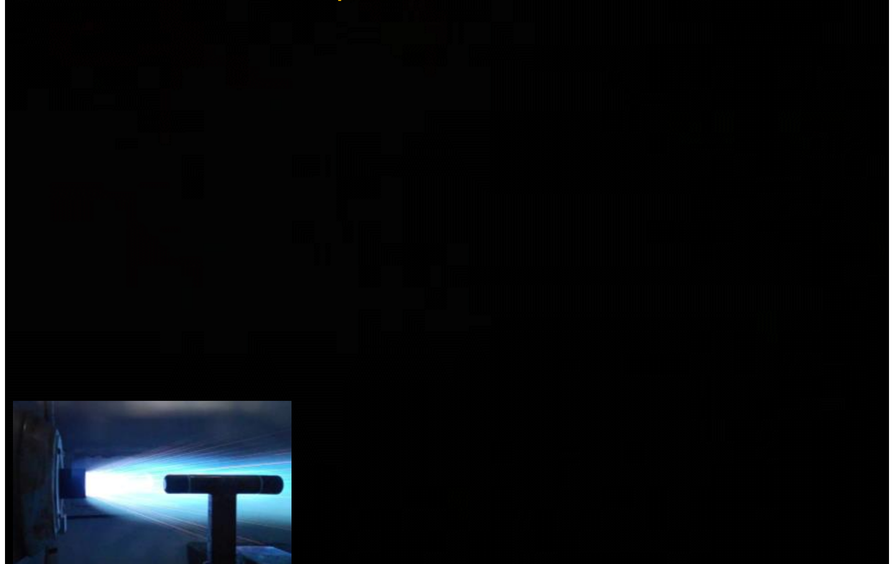
Emissivity as fct of T | $\varepsilon(T)$

Demise behaviour | T_{onset}

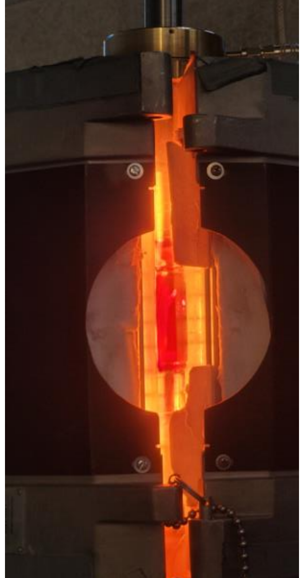
Demise behaviour and fitting data | Front and Back $T_{surface}$, $mass\ loss$, $ablation\ heat$

IRS PWK-4 wind plasma facility - CFRP

Heat flux – 520 kW/m² | Ambient pressure 41 Pa



EPFL - Self-developed static reentry chamber

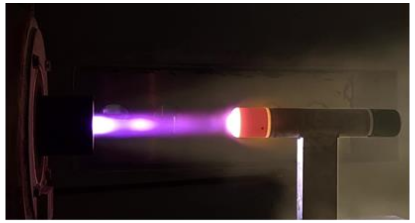


Data and model fitting process

DRAMA-CFRP model

SARA reentry tool composite material model

DRAMA demise model equations
CFRP material model

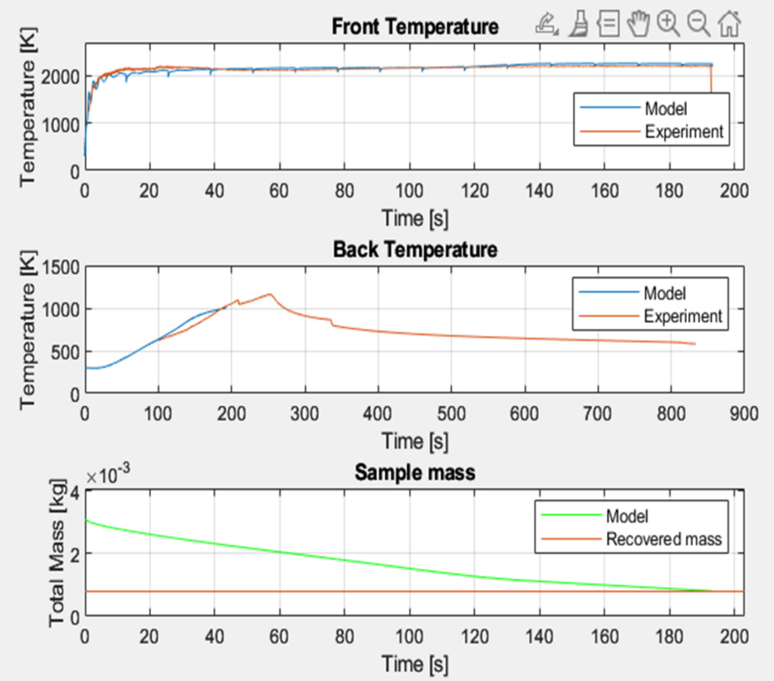


Experimental data
TGA, DMA, MDSC, Static reentry chamber, PWT

MATLAB
Data and model fitting process

New material parameters

- Parametric fitting method
  I. Integration of 11 model-specific material parameters from experimental testing
     - Test campaigns
     - Literature
     - Extrapolation models
  II. Iterative fitting analysis with 3 tuning parameters:
     - Char reaction rate
     - Gas blocking factor
     - Thermal conductivity



CF/epoxy sample under high heat flux conditions (PWT experimental data)

Adequate fitting results

NEW MATERIAL PARAMETERS

Alexandre A. Looten

EPFL

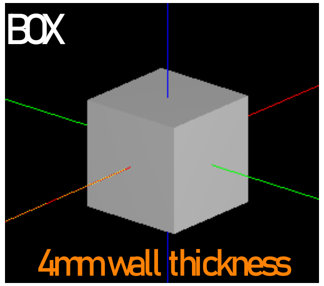
Results

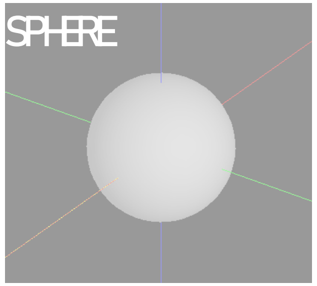
Direct-experimental vs Built-in CFRP parameters

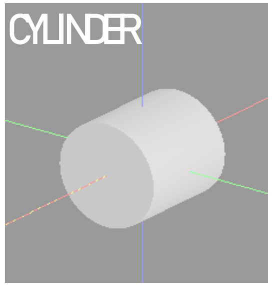
- Object geometry MonteCarlo sensitivity analysis

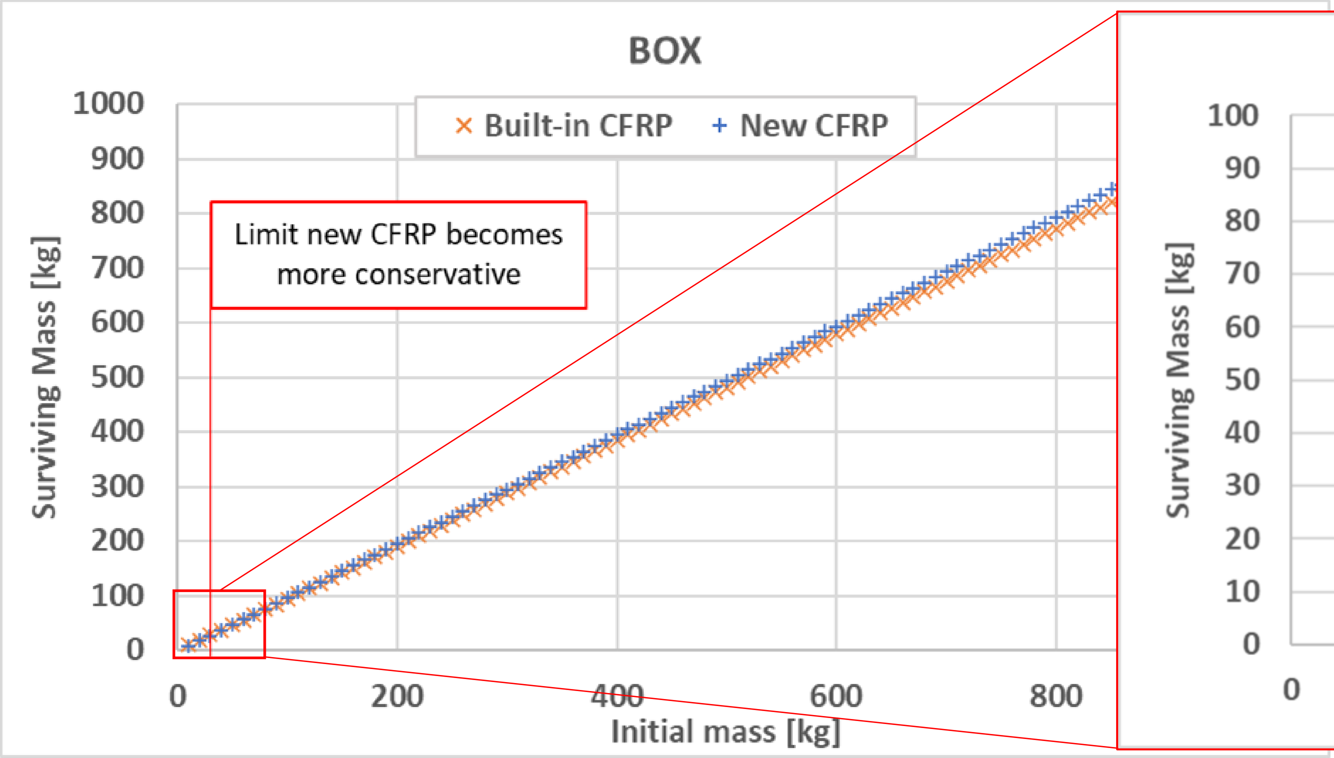
Sensitivity parameter = Initial object mass (wall thickness)
Comparative Index = Surviving mass

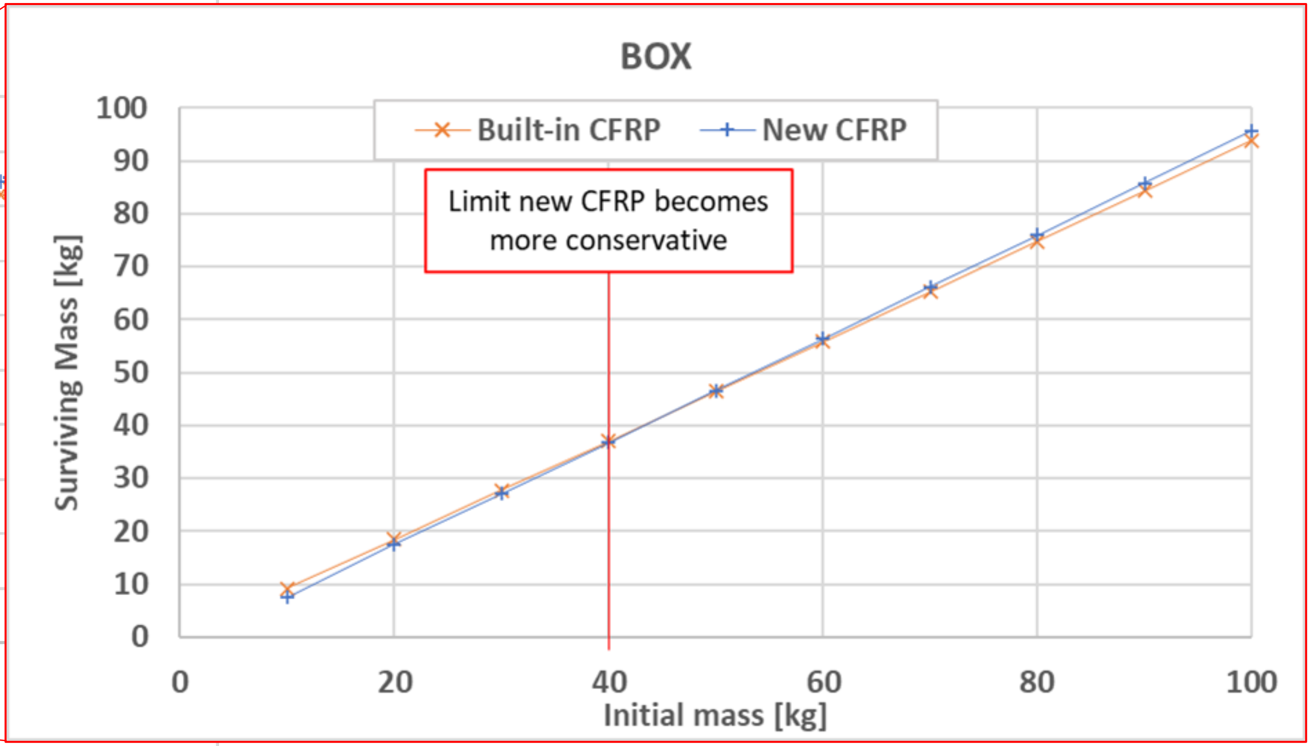
New CFRP more conservative upon:











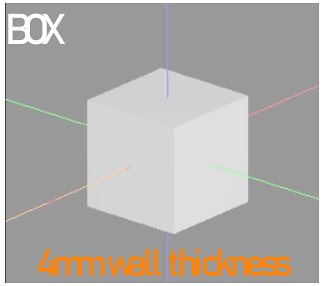
Exp2model CFRP material more conservative upon 40kg ⇔ 4mm wall thickness

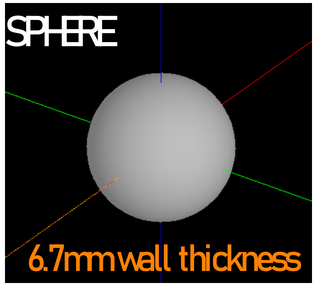
Direct-experimental vs Built-in CFRP parameters

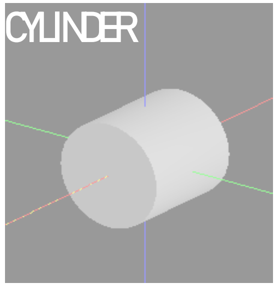
- Object geometry MonteCarlo sensitivity analysis

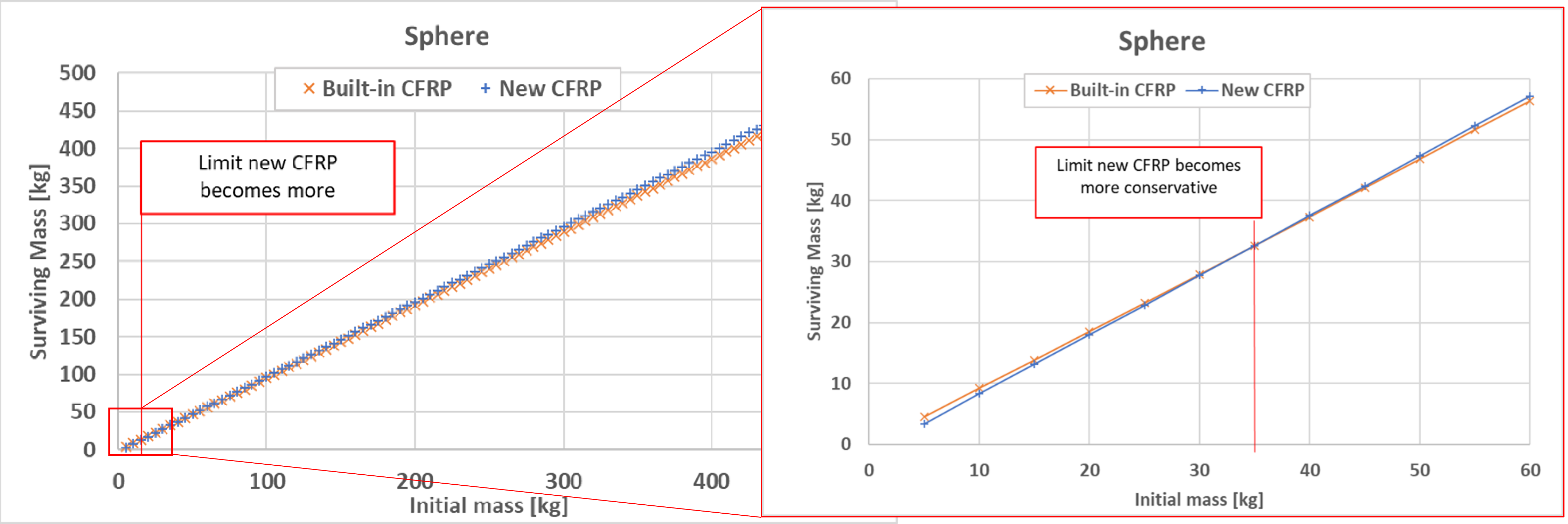
Sensitivity parameter = Initial object mass (wall thickness)
Comparative Index = Surviving mass

New CFRP more conservative upon:









Exp2model CFRP material more conservative upon 35kg ⇔ 6.7mm wall thickness

Alexandre A. Looten

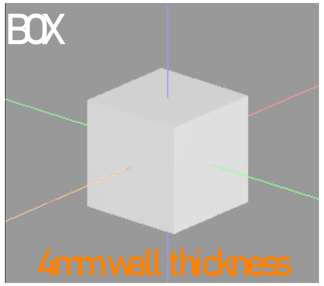
EPFL

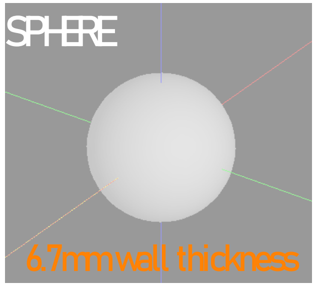
Direct-experimental vs Built-in CFRP parameters

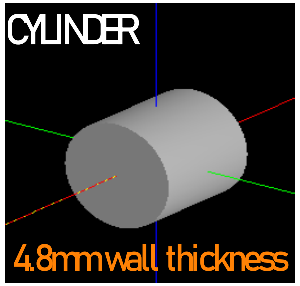
- Object geometry MonteCarlo sensitivity analysis

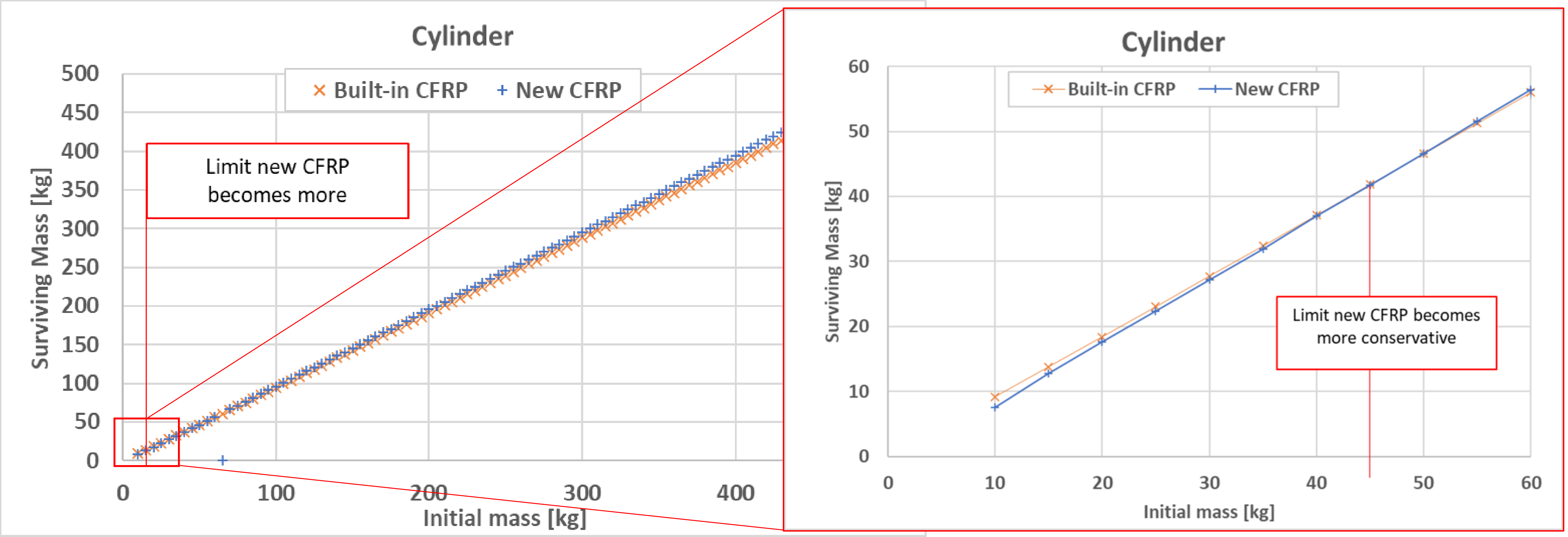
Sensitivity parameter = Initial object mass (wall thickness)
Comparative Index = Surviving mass

New CFRP more conservative upon:









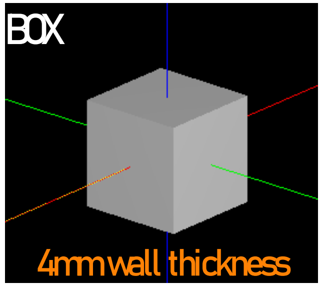
Exp2model CFRP material more conservative upon 45kg ⇔ 4.8mm wall thickness

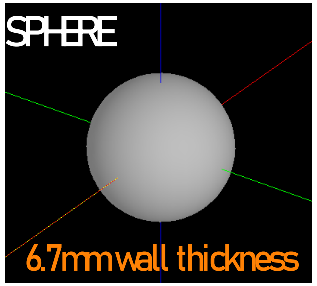
Direct-experimental vs Built-in CFRP parameters

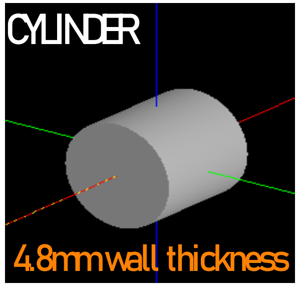
- Object geometry MonteCarlo sensitivity analysis

Sensitivity parameter = Initial object mass (wall thickness)
Comparative Index = Surviving mass

New CFRP more conservative upon:







For monolithic-wall shallow objects:

- Clear influence of object shape and wall thickness on demise results trends

New-CFRP parameters = slower demise with round and thick walls compared to build-in CFRP versions

Conclusion

- Demonstration of a direct experiment-to-model method for DRAMA tool
  ⇒ Integration of novel composite-like materials

- Dedicated material integration in DRAMA
  ⇒ Improved demise prediction accuracy
  ⇒ Reduction of reentry casualty risk critical uncertainties

- Research-level method ⇒ Requires intensive lab and data assembly steps

- Working points:
  - ❑ DRAMA material database from previous PWT test campaigns
  - ❑ Method simplification – Derived the material demise parameters from more simple experimental testing methods
  - ❑ Integration of a dimensional factor in DRAMA demise model to take into account thickness effect on demise behaviour

space.com / image credit: Michael Carroll

Acknowledgments

This work is supported by EPFL and ESA through an NPI (OSIP) program #4000129740/20/NL/MH/hm

esa EPFL

Thanks to:

- EPFL-LPAC and ESA-Clean Space teams
- Project partners

Adam Pagan
IRS

James Beck
Belstead

Ralf Usigner & Alessando Netti
beyond gravity

Albert Vodermayer
ico ɔɘt

Régis Voillat
Bcomp®

Lionel Metrailler
clearspace today

Tank you for your attention !

Any questions ?

Alexandre Looten

Ph.D. Student at Swiss Federal Institute of Technology in Lausanne – EPFL

alexandre.looten@epfl.ch

Annexes

DRAMA-SARA

Metal vs CFRP material parameters UI