SAND2019-6180C

Modeling the Decomposition Behavior of Carbon Fiber Epoxy Composites

Sarah Scott[1], Victor Brunini[1], Andrew Kurzawski[1], John Hewson[1], Juan Hidalgo[2], Rory Hadden[3], Stephen Welch[3]

[1] Sandia National Laboratories
[2] School of Civil Engineering, The University of Queensland
[3] School of Engineering, The University of Edinburgh

11th Mediterranean Combustion Symposium

June 16–20, 2019

Outline

Motivation for Studying Fiber Reinforced Polymers in Fires
- These materials are different than traditional engineering materials
- This talk will focus on Carbon Fiber Epoxy Composites

Computational Model
- Description of the computational strategy
- Mechanism creation from TGA for a carbon fiber epoxy composite
- Parameters explored in uncertainty estimation

Model Validation and Uncertainty Estimation
- Comparison of prediction to experiments
- Sensitivity of input parameters to temperature and mass loss predication

Experimental Co-Authors

Juan Hidalgo
- School of Civil Engineering, The University of Queensland

Rory Hadden, Stephen Welch
- School of Engineering, The University of Edinburgh

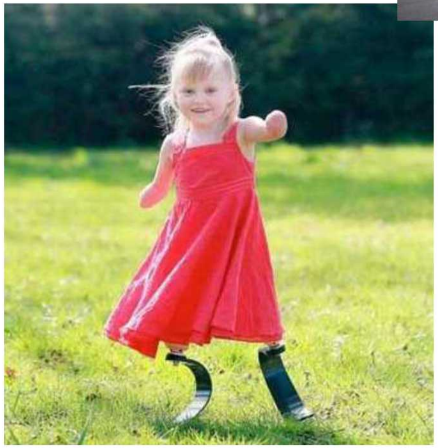
J. P. Hidalgo, R. Hadden, S. Welch, and P. Pironi, "Effect of Thickness on the Ignition Behavior of Carbon Fibre Composite Materials used in High Pressure Vessels," *Eighth Int. Semin. Fire Explos. Hazards*, pp. 353–363, 2016.

J. P. Hidalgo, P. Pironi, R. M. Hadden, and S. Welch, "A framework for evaluating the thermal behaviour of carbon fibre composite materials," *Eur. Symp. Fire Saf. Sci.*, pp. 195–200, 2015.

J. P. Hidalgo, R. Hadden, S. Welch, and P. Pironi, "Experimental Study of the Burning Behavior of a Commercial Carbon Fibre Composite Material used in High Pressure Vessels," in *ECCM17 - 17th European Conference of Composite Materials*, 2016, p. 8.

Motivation for Studying Carbon Fiber Epoxy Composites in Fires

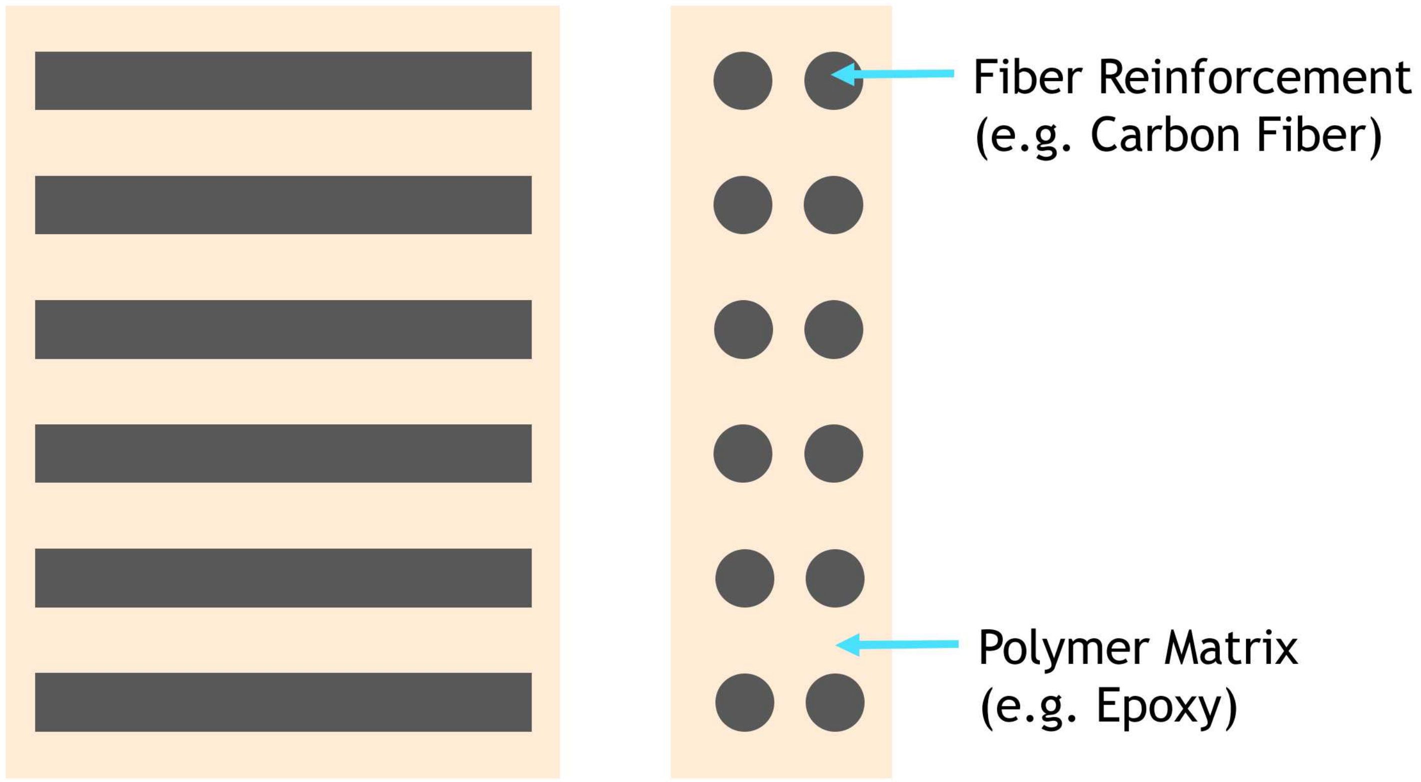
Fiber Reinforced Polymers



An increasing number of engineered systems that require high strength and low weight use fiber reinforce polymers

- Aerospace, automotive, sporting goods, electronics, transportation, prosthetics…

What is a Fiber Reinforced Polymer?



Fibers provide strength and rigidity to the polymer, while the polymer provides structure to the fibers.

Carbon fiber epoxy composites are an example of a fiber reinforced polymer

The Trouble with Fiber Reinforced Polymers

The replacement of metals with fiber reinforced polymers cause concerns in fire environments.

The polymers and fibers can be fuel for the fire, were as traditional building materials are inert.

Objective of this Work

Validate a computational model of pyrolyzing and smoldering carbon fiber epoxy composite using cone calorimeter data.

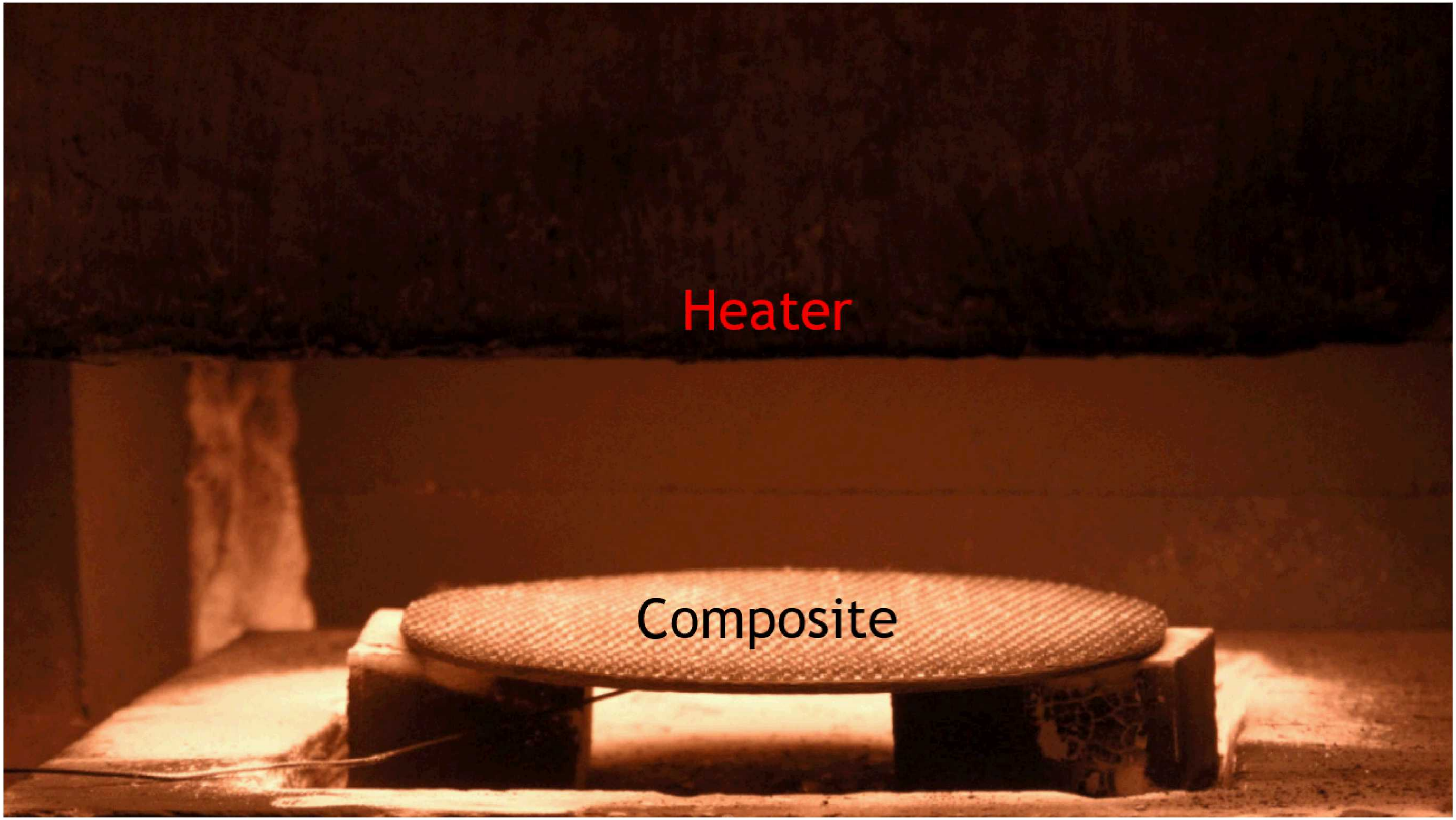
Compare temperature and mass loss data

Evaluate uncertainty and sensitivity of temperature and mass loss to variation of input parameters


Computational Model

Decomposing Carbon Fiber Epoxy Composite

55 minute test compressed into 30 seconds



How are we going to model this?

Governing Equations

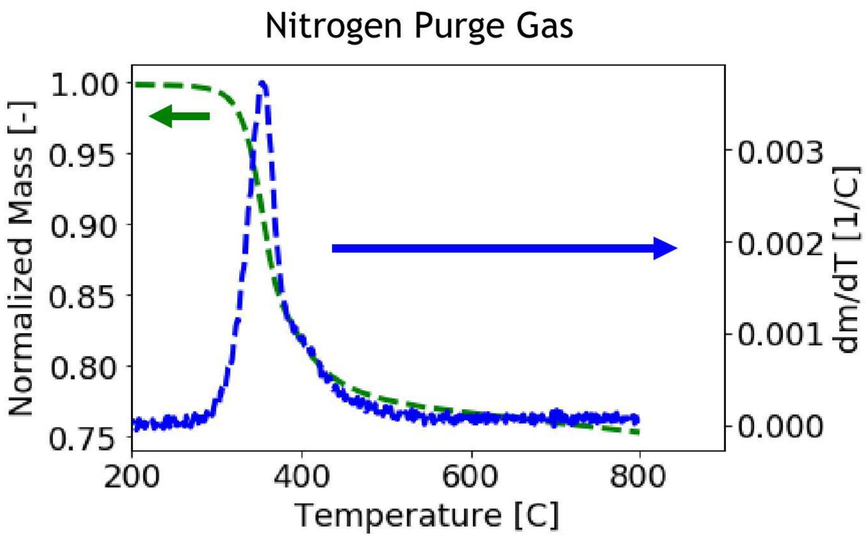
Reaction Parameters

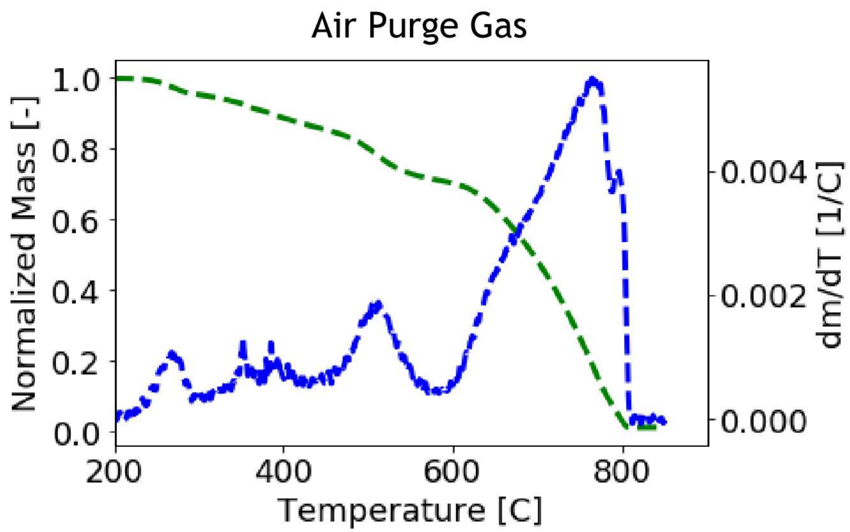
Material Properties

Governing Equations

	Solid Phase		Gas Phase
Continuity	The mass lost in the solid must equal the mass gained in the gas	⟺ Reaction	The flow is governed by the pressure gradient and Darcy's law for flow through a porous medium The source of mass is the reaction
Species Continuity	The mass lost in the solid must equal the mass gained in the gas for each species	⟺ Reaction	The flow of each species is governed by the pressure, velocity, and diffusivity The source of mass in each species is the reaction
Enthalpy	Energy moves through the system through conduction Sources are convection and the reaction	⟺ Convection	Energy moves through the flow and diffusion Sources are convection and the reaction

Pyrolysis and Smoldering Mechanism



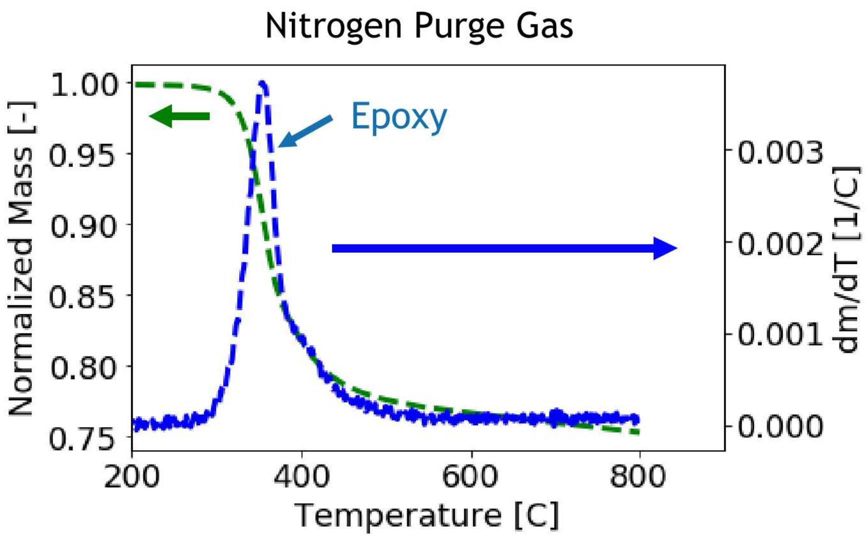


TGA conducted at 5 C/min

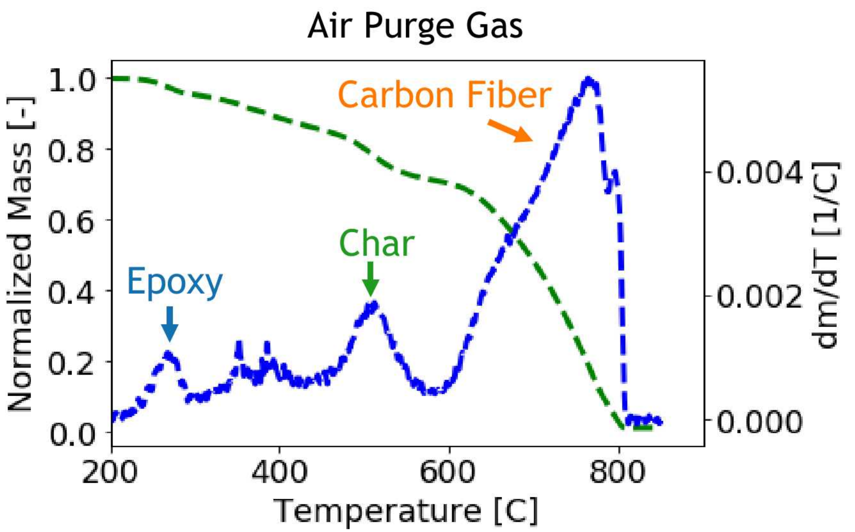
Nitrogen and air purge gas

Temperature and mass recorded

Pyrolysis and Smoldering Mechanism



$$Epoxy \rightarrow Char + fuel$$

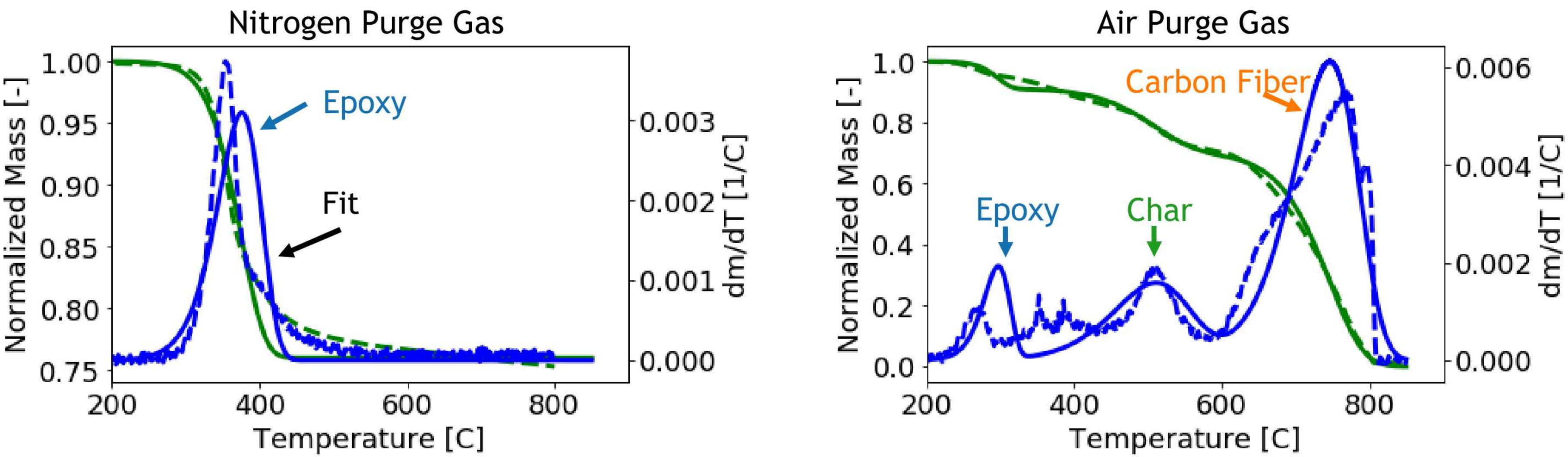


$$Epoxy + O_2 \rightarrow Char + fuel$$

$$Char + O_2 \rightarrow Residue + gas$$

$$Carbon\ Fiber + O_2 \rightarrow Residue + gas$$

Pyrolysis and Smoldering Mechanism



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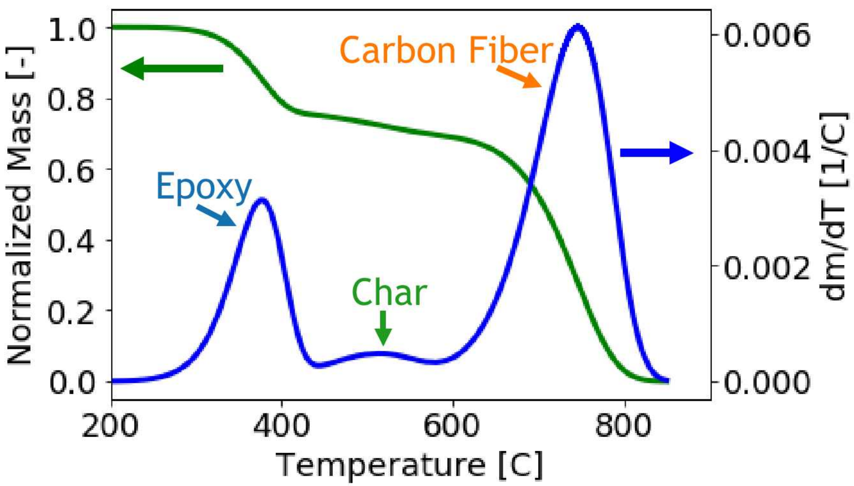
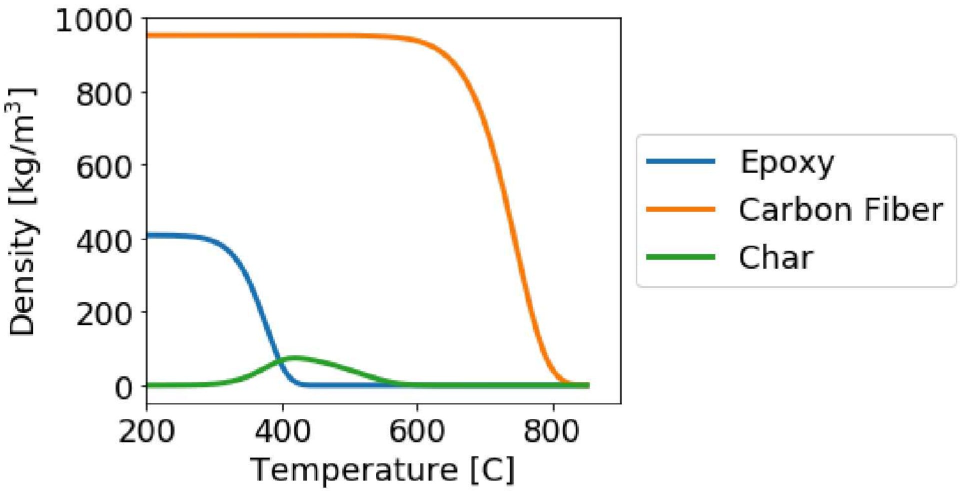
Pyrolysis and Smoldering Mechanism





$$Epoxy \rightarrow Char + fuel$$

$$\sout{Epoxy + O_2 \rightarrow Char + fuel}$$

$$Char + O_2 \rightarrow Residue + gas$$

$$Carbon\ Fiber + O_2 \rightarrow Residue + gas$$

Material Properties

Each Composite Phase

(Epoxy, Char, Carbon Fiber)

- Conductivity
- Specific Heat
- Density
- Permeability
- Radiative Conductivity
- Emissivity

Each Gas Phase

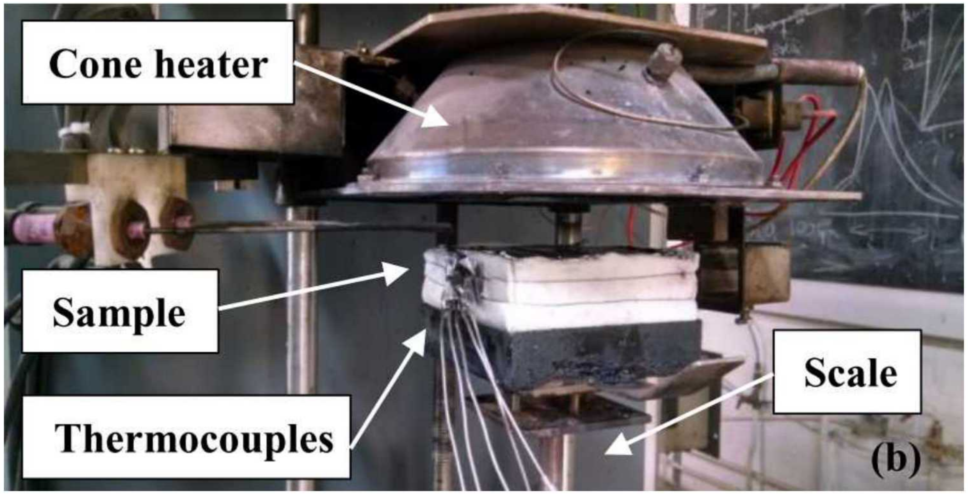
(CH_4, CO, CO_2 O_2, N_2)

- Specific Heat
- Molecular Weight
- Mass Diffusivity

Properties are a function of temperature, reaction, or both

Properties come from measurement, literature, and calibration

29 mm Sample – 30 kW/m²



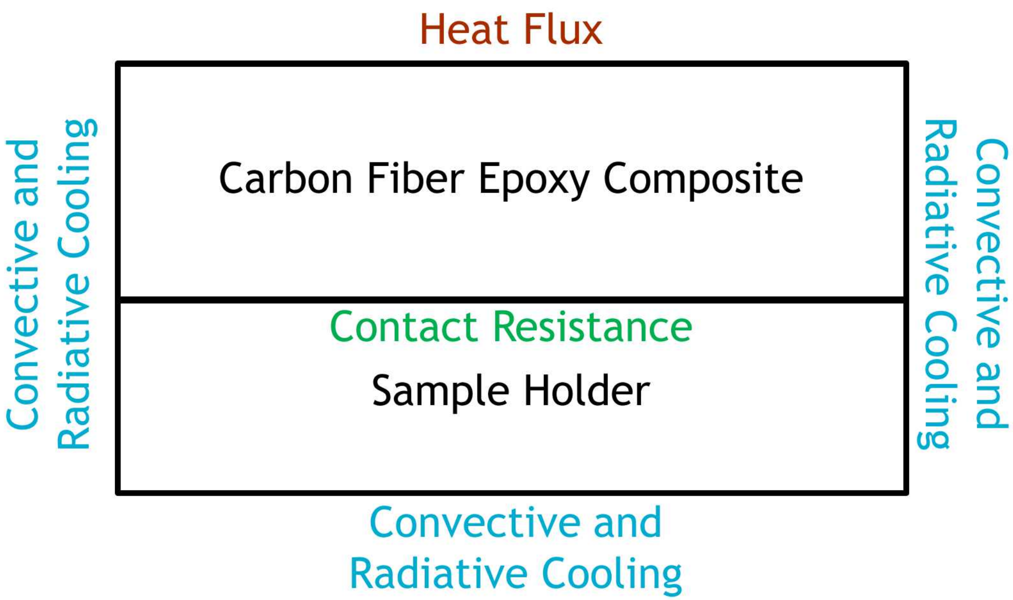
Sample dimensions: 100 x 100 x 29 mm

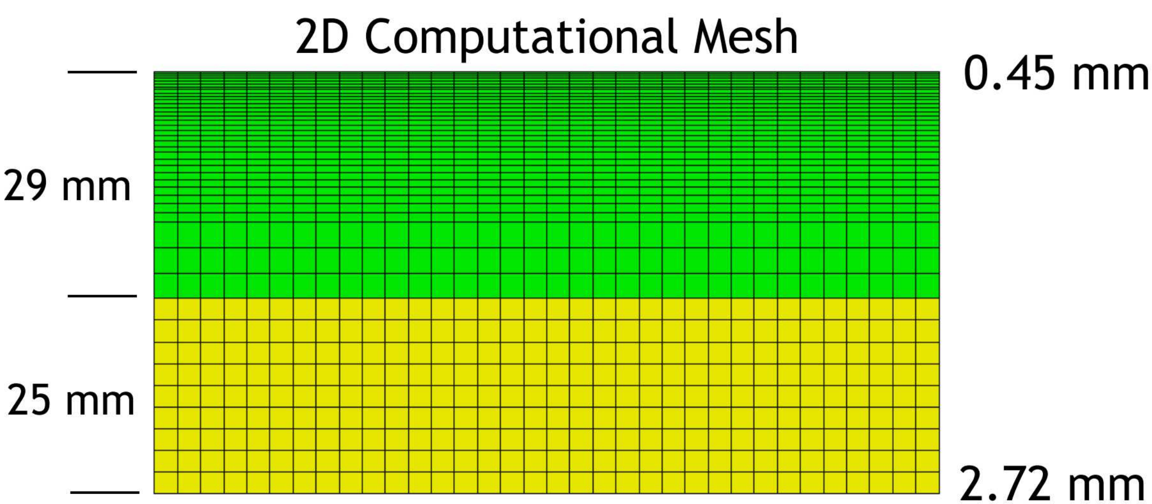
Sample holder material: Aluminum

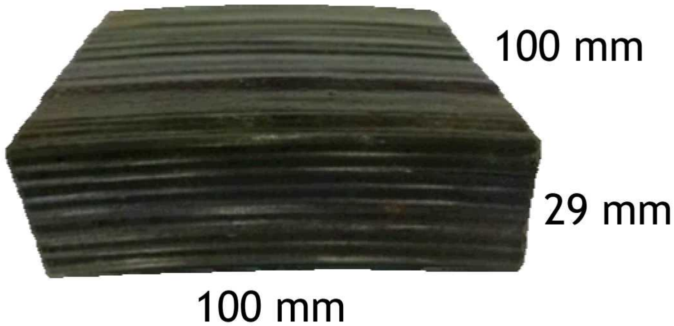
Heat flux: 30 kW/m^2

Temperature and mass loss recorded

Translating the Experiment into a Model

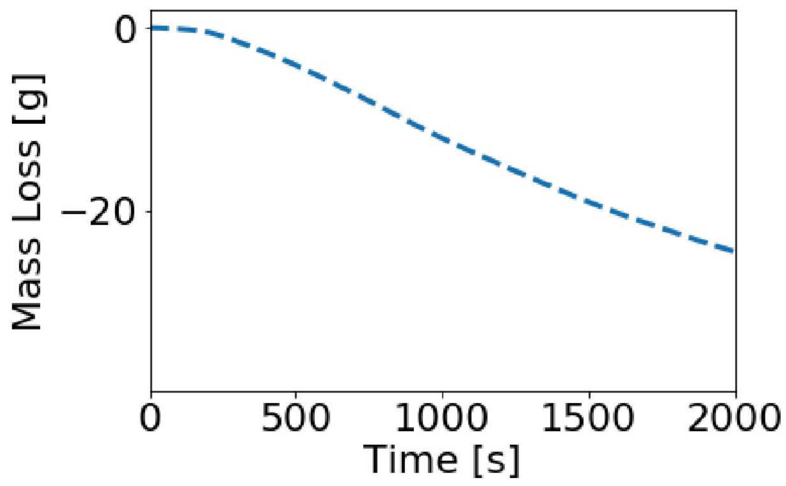


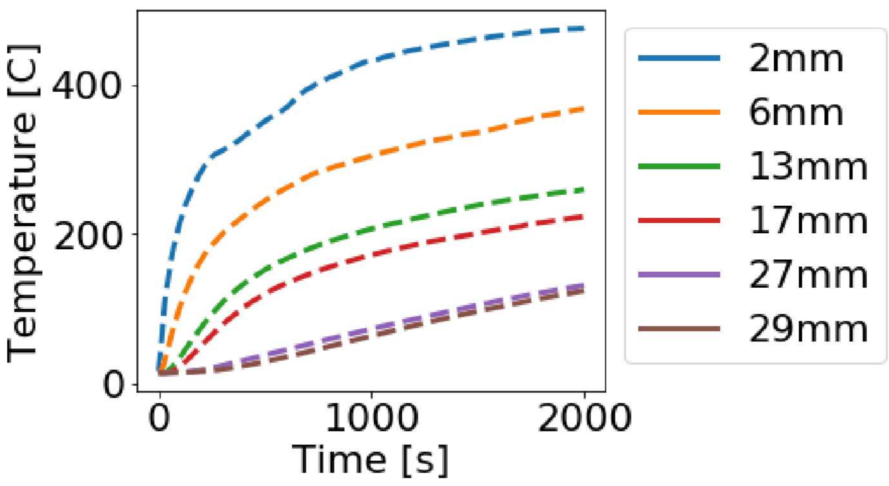





Model Validation, Uncertainty, and Sensitivity

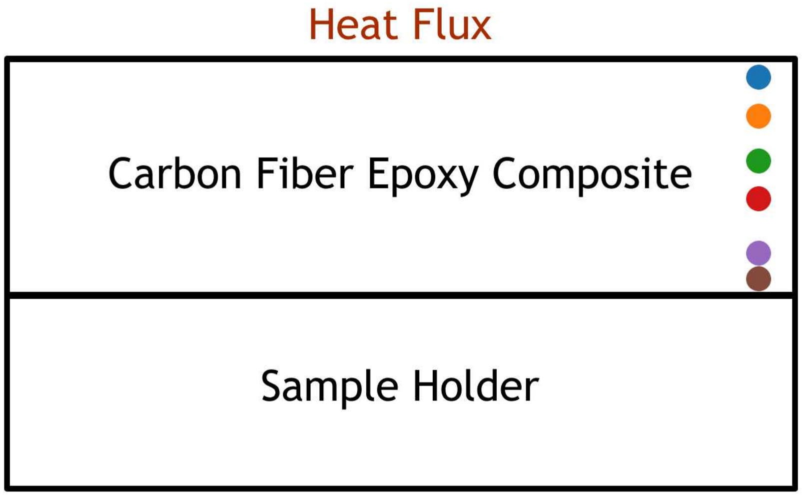
29 mm “Thick” Sample – 30 kW/m²





20 g (5%) of the sample are lost over the half hour test

200 C temperature gradient over the sample



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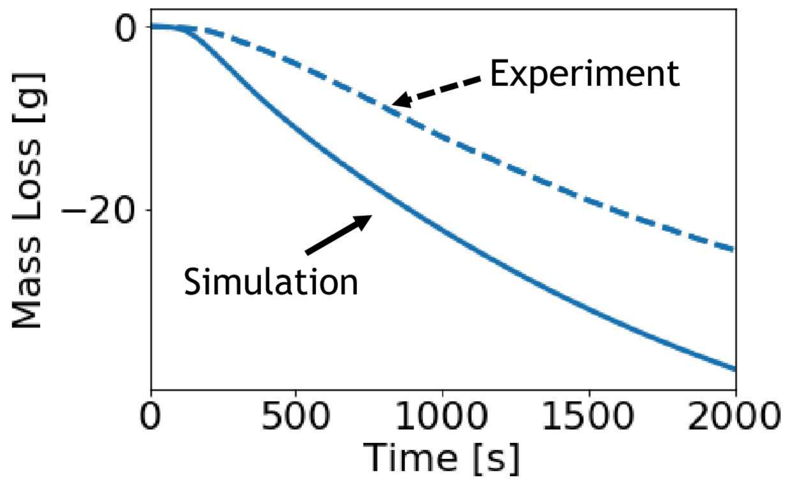
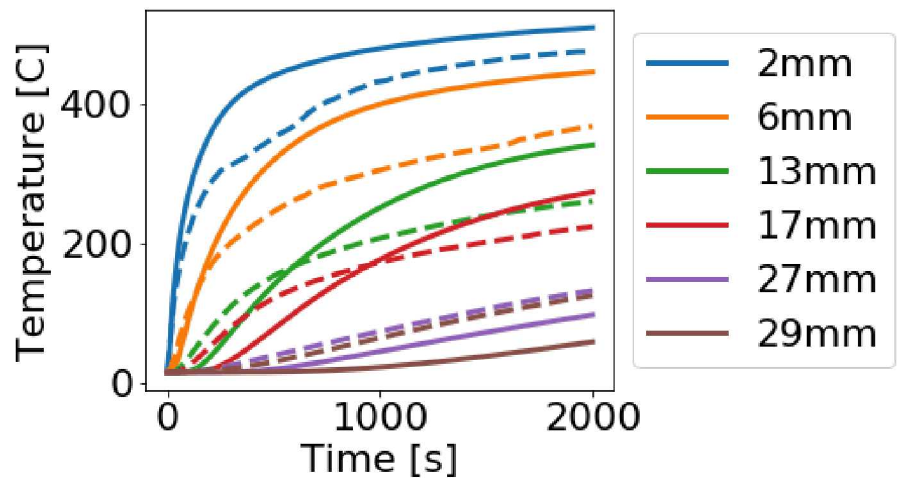
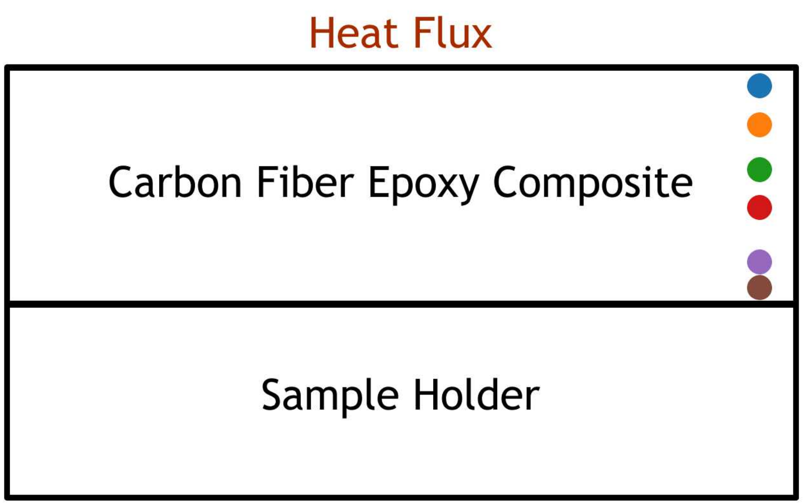




Mass loss: good qualitative agreement

Temperature: Over predicting in the middle of the sample



Model Parameters for Uncertainty Evaluation

27 Parameters

Each Composite Phase:

- Conductivity (k)
- Volumetric Heat Capacity (ρc_p)
- Permeability (K)
- Radiative Conductivity (k_e)
- Emissivity (ϵ)
- Initial Carbon Fiber $(\%CF)$

Each Reaction:

- Pre-Exponential Factor (A)
- Activation Energy (E_a)
- Stoichiometric coefficient (ν)
- Heat Release (H)

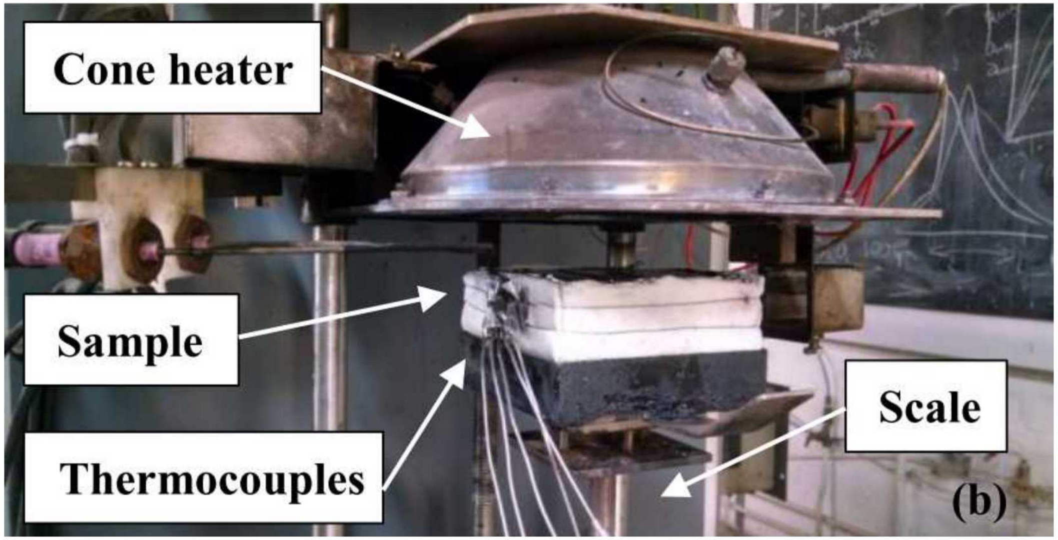
Each Holder Material:

- Conductivity (k)
- Volumetric Heat Capacity (ρc_p)
- Emissivity (ϵ)

Boundary Conditions:

- Heat Flux (q)
- Convective Heat Transfer (h_{cv})
- Contact Resistance (R_c)

Experiment



Sample dimensions: 100 x 100 x 29 mm

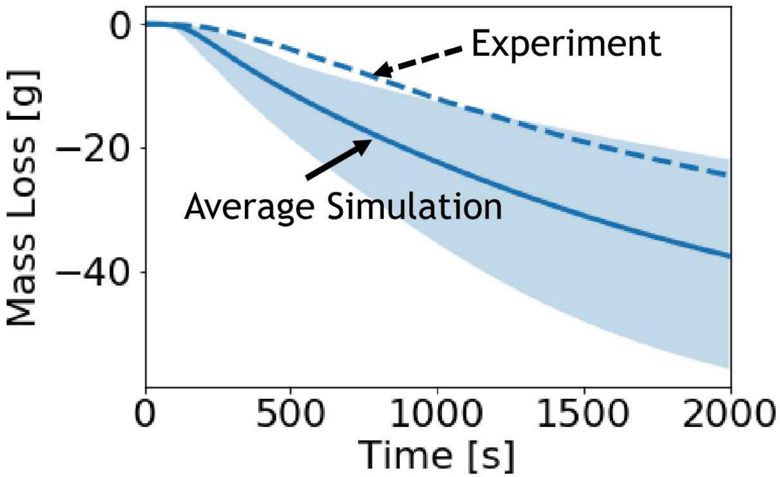
Sample holder material: Aluminum

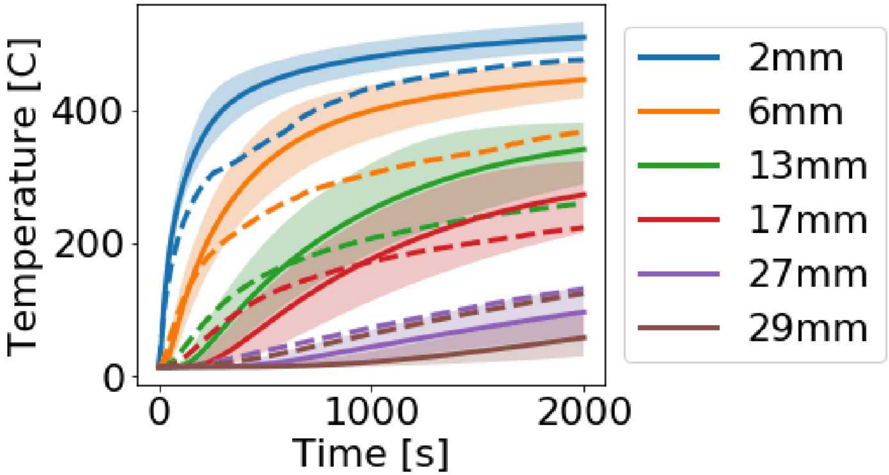
Heat flux: 30 kW/m^2

Temperature and mass loss recorded

Flaming Ignition: No

29 mm Thick Sample – 30 kW/m²





270 simulation in the ensemble

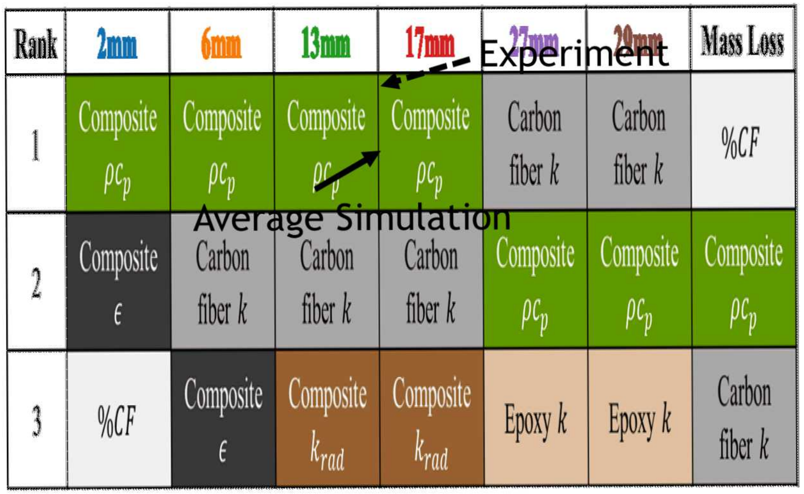
Average Simulation presented with min/max bounds

TC locations measured from top of the sample

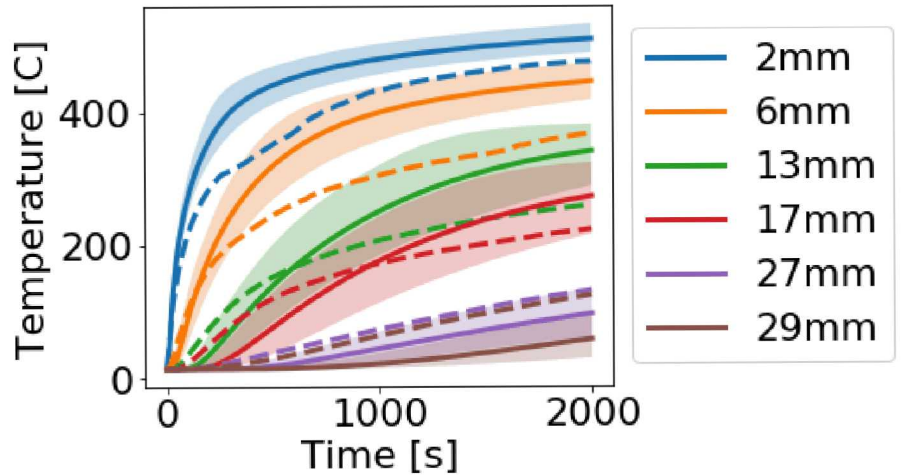
Mass loss: good qualitative agreement

Temperature: Over predicting in the middle of the sample

29 mm Thick Sample – 30 kW/m²



Rank	2mm	6mm	13mm	17mm	27mm	29mm	Mass Loss
1	Composite ρc_p	Composite ρc_p	Composite ρc_p	Composite ρc_p	Carbon fiber k	Carbon fiber k	$\%CF$
2	Composite ϵ	Carbon fiber k	Carbon fiber k	Carbon fiber k	Composite ρc_p	Composite ρc_p	Composite ρc_p
3	$\%CF$	Composite ϵ	Composite k_{rad}	Composite k_{rad}	Epoxy k	Epoxy k	Carbon fiber k



Rank	2mm	6mm	13mm	17mm	27mm	29mm	Mass Loss
1	Composite ρc_p	Composite ρc_p	Composite ρc_p	Composite ρc_p	Carbon fiber k	Carbon fiber k	$\%CF$
2	Composite ϵ	Carbon fiber k	Carbon fiber k	Carbon fiber k	Composite ρc_p	Composite ρc_p	Composite ρc_p
3	$\%CF$	Composite ϵ	Composite k_{rad}	Composite k_{rad}	Epoxy k	Epoxy k	Carbon fiber k

Summary and Future Work

Summary

Computational Model

- 2D FEM Model, smoldering and pyrolysis, gas and condensed phase
- Mechanism created from TGA using both nitrogen and air data

Model Validation and Uncertainty Estimation

- 27 input parameters varied to improve understanding of uncertainty
- Mass loss showed good qualitative agreement
- Ratio of carbon fiber to epoxy, followed by volumetric heat capacity and conductivity were most important the mass loss prediction
- Temperature over predicted in the middle of the sample
- Volumetric heat capacity and conductivity were most important to the temperature prediction

Future Work

Improve material characterization, particularly conductivity, specific heat, and ratio of carbon fiber to epoxy

- Anisotropic properties

Model gas phase combustion to increase the range of experiments that can be compared to

Couple solid phase model to gas phase model


Questions?

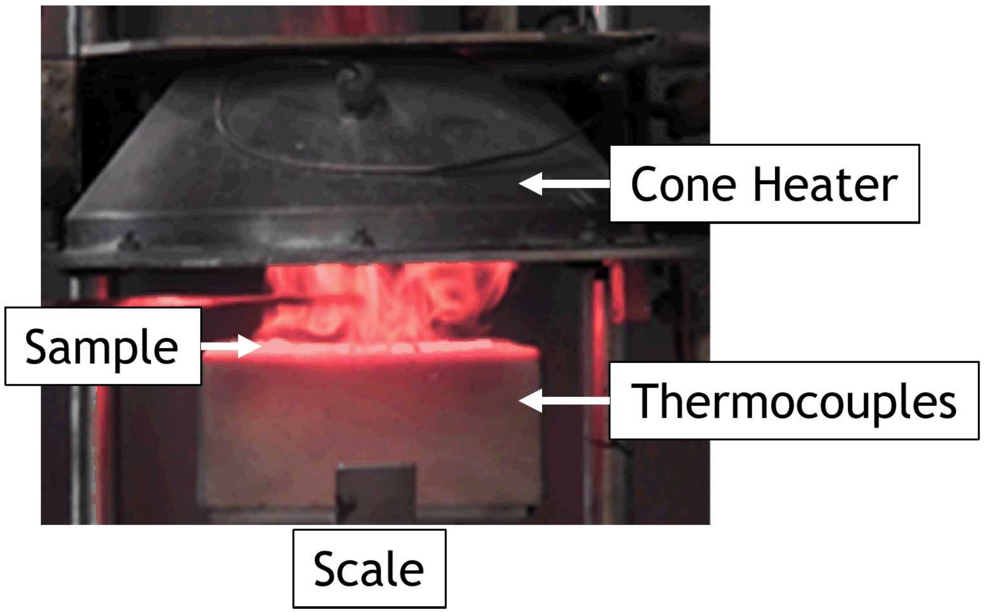
Model Parameters

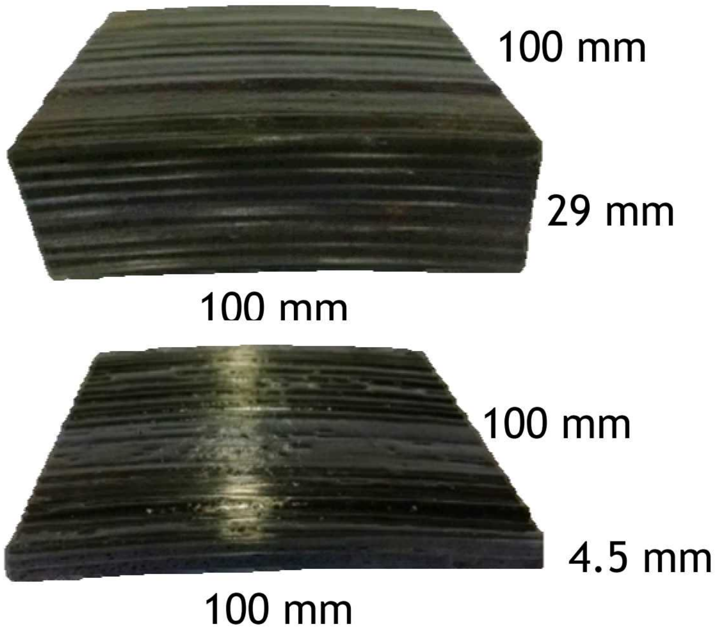
Parameter	Value / Correlation	Uncertainty	Units
Conductivity (k)			W/(mK)
Epoxy	0.145	±35%	
Carbon Fiber	$0.335\ln(T) - 1.8257$	±35%	
Char	0.029	±70%	
Residue	0.00725	±70%	
Density (ρ)			kg/m^3
Epoxy	408	±20%	
Carbon Fiber	952	±20%	
Char	650	±20%	
Residue	2000	±20%	
Specific Heat (c_p)			J/(kgK)
Epoxy	866	±20%	
Carbon Fiber	$4.0997\ \mathrm{T} - 369.12$	±20%	
Char	936	±20%	
Residue	866	±20%	
Permeability (K)			m^2
Epoxy	2.42e-15	-90% +900%	
Carbon Fiber	2.42e-14	-90% +900%	
Char	2.83e-12	-90% +900%	
Residue	2.42e-11	-90% +900%	
Radiative Conductivity (k_e)	$16/(3 * 5000)\sigma T^3$	-60% +400%	W/(mK)
Emissivity (ϵ)	0.91	-10% + 8%	-
Initial Carbon Fiber ($\%CF$)	70	±10%	%

Model Parameters

	A		**E_a**		**ν**		**H**	
	[1/s]		*[J/kmol]*		[-]		*[kJ/kg]*	
Reaction 1a	3.33 e6	±10%	1.13 e8	±0%	0.2	±20%	0	±10 [kJ/kg]
Reaction 1b	1.33 e11	-	1.47 e8	-	0.7	-	0	-
Reaction 2	1895	±10%	9.15 e7	±0%	.0001	±0%	12730	±20%
Reaction 3	9.48 e6	±10%	1.90 e8	±0%	.0001	±0%	24770	±20%

Experiments





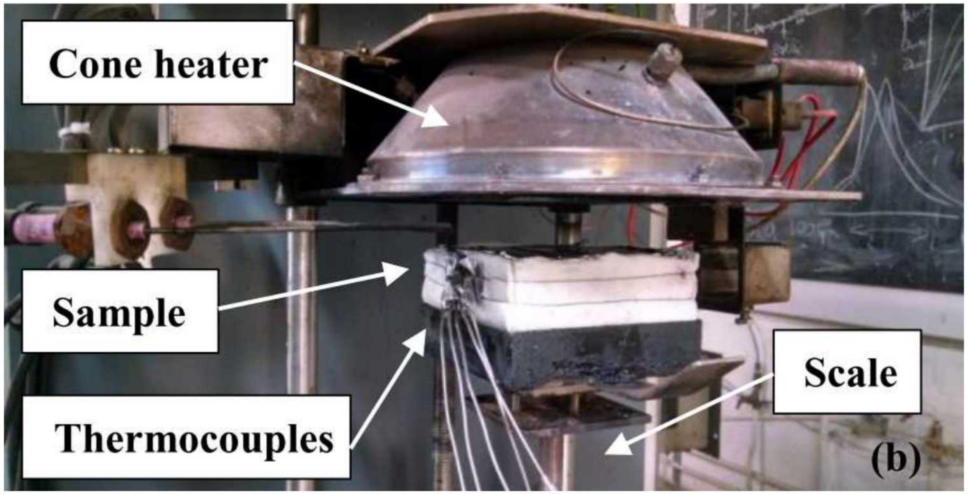
Two sample thicknesses: 4.5 mm and 29 mm

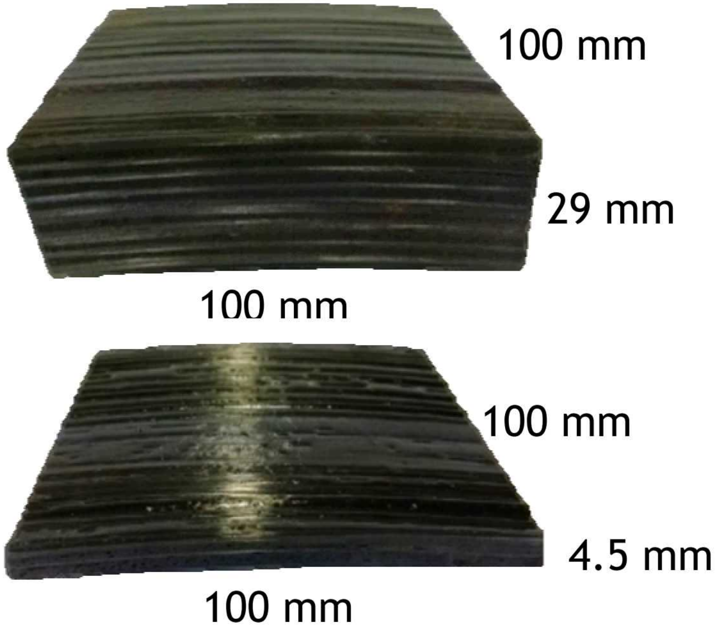
Two sample holder materials: Aluminum and Ceramic

Two heat fluxes: 30 kW/m^2 and 80 kW/m^2

Temperature and mass loss recorded

Experiments





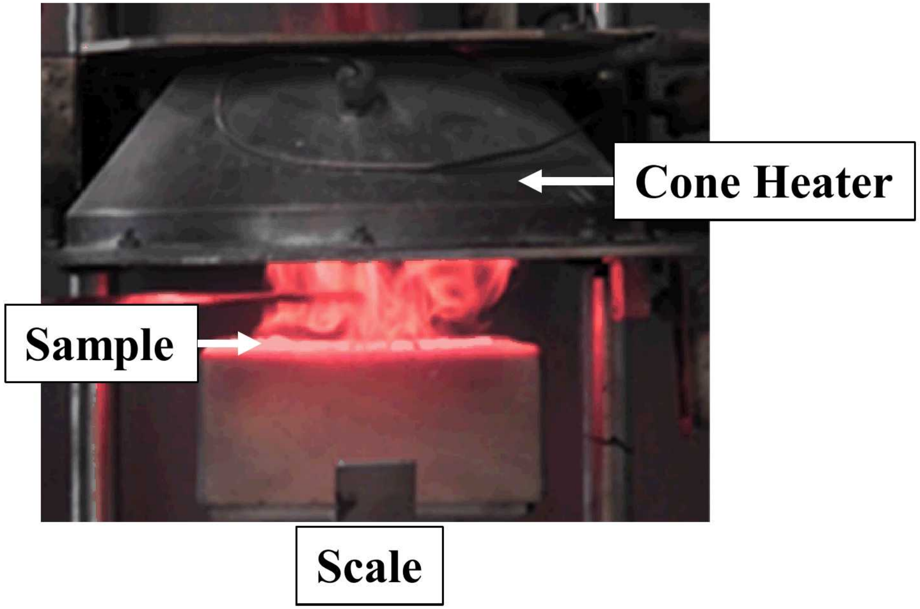
Two sample thicknesses: 4.5 mm and 29 mm

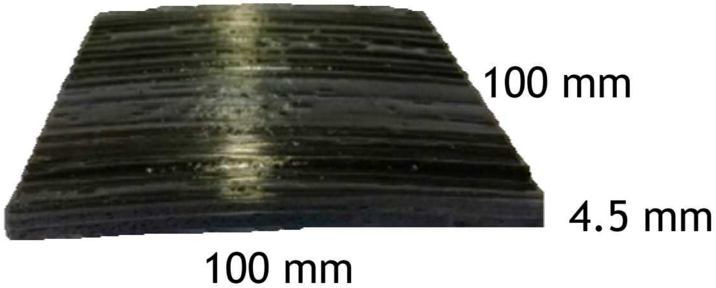
Two sample holder materials: Aluminum and Ceramic

Heat flux: 30 kW/m^2

Temperature and mass loss recorded

"Thin" Sample





Sample thicknesses: 4.5 mm

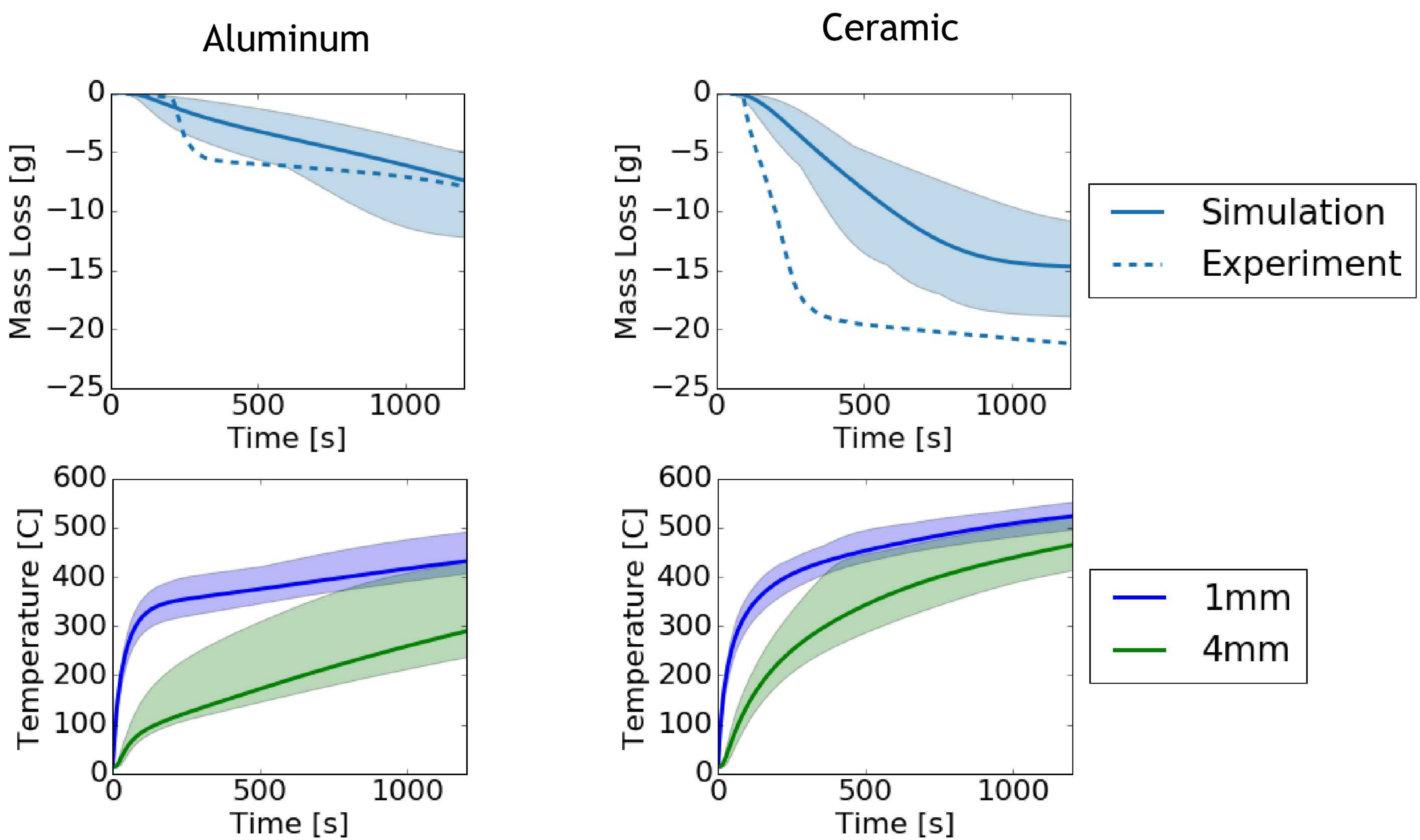
Two sample holder materials: Aluminum and Ceramic

Heat flux: 30 kW/m^2

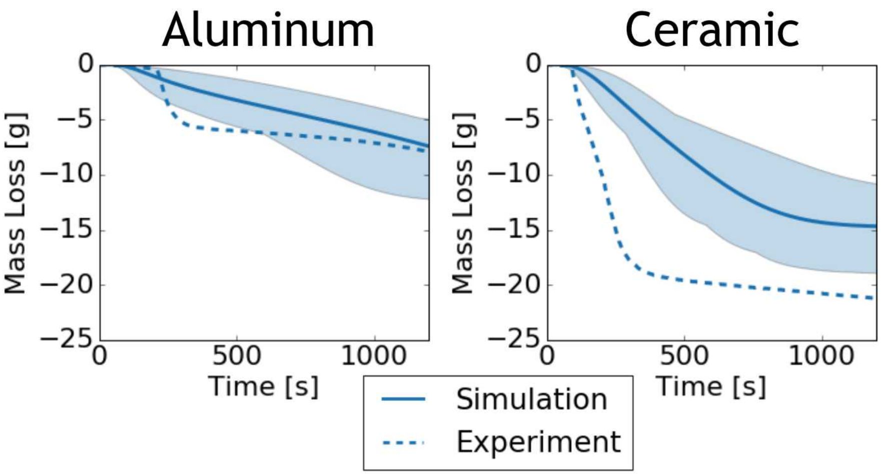
Mass loss recorded

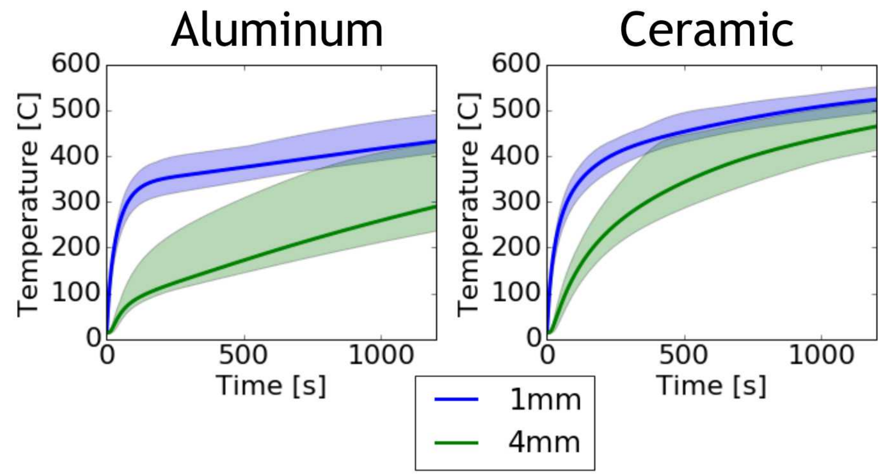
Flaming Ignition: Yes

4.5 mm "Thin" Sample – 30 kW/m²



4.5 mm "Thin" Sample – 30 kW/m^2





	1mm	2mm	3mm	4mm	Mass Loss
Aluminum	Carbon fiber k	R_c	R_c	Carbon fiber k	$\%CF$
	Composite ϵ	Carbon fiber k	Carbon fiber k	R_c	Carbon fiber k
	R_c	Aluminum ρc_p	Aluminum ρc_p	Aluminum ρc_p	R_c
Ceramic	Composite ϵ	Composite ρc_p	Carbon fiber k	Carbon fiber k	$\%CF$
	Composite ρc_p	Carbon fiber k	Composite ρc_p	Composite ρc_p	R_c
	Carbon fiber k	Composite ϵ	Composite ϵ	Ceramic ρc_p	ν