Determination of Failure Criteria for Spacecraft Structures During Re-Entry

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Introduction

- Spacecraft entering the Earth atmosphere from space encounter large thermal and mechanical loads during re-entry
- Spacecraft not designed to withstand these loads break up during re-entry either by the thermal or the mechanical loads or both
- There are several software tools designed for computing the destruction history of spacecraft. There are two general approaches:
  - Object-oriented approach: Define a very simplified model of the spacecraft and compute the destruction history by using pre-defined triggers, e.g. melting temperature, dynamic pressure, acceleration
  - Spacecraft-oriented approach: Define a very detailed model of the spacecraft and compute the destruction history by examining the destruction process on a local level (local melting, local breaking)

Destruction criteria used in the S/C-oriented code SCARAB

- Melting. The temperature is computed locally for each surface element. If an element reaches melting temperature it is regarded as having no connectivity to neighbor elements. Break-up occurs when a gap is detected, i.e. the integrity analysis detects separate non-connected parts.

  This is a pure thermal destruction criterion.

- Cut-off: The mechanical loads are computed for pre-defined elements, typically joints to appendices (e.g. solar panels), and using simple beam theory. When the computed stress in a joint exceeds the breaking stress the joint is considered as broken and the appendix is considered to become a separated fragment

  This is a thermo-mechanical criterion, since the temperature and the related changes of material properties are considered for the joints.

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Study: Determination of failure criteria for spacecraft structures during re-entry

- Funded by DLR, Contractors: IRS and HTG
- Contract duration: 3 years
- Main goals:
  - Theoretical/Numerical: Examine a generalized thermo-mechanical approach to be used in re-entry codes
  - Experimental: Measure the thermo-mechanical failure for certain test cases in a wind tunnel for representative re-entry conditions
  - Synthesis: Compare numerical predictions with experimental results with the possibility to derive generalized failure criteria
- Implementation:
  - Theoretical/Numerical: Stand-alone implementation of an FE-code with interfaces to SCARAB geometry and material (HTG)
  - Experimental: Measurement of load cases for selected test cases to be compared with the numerical approach (IRS)

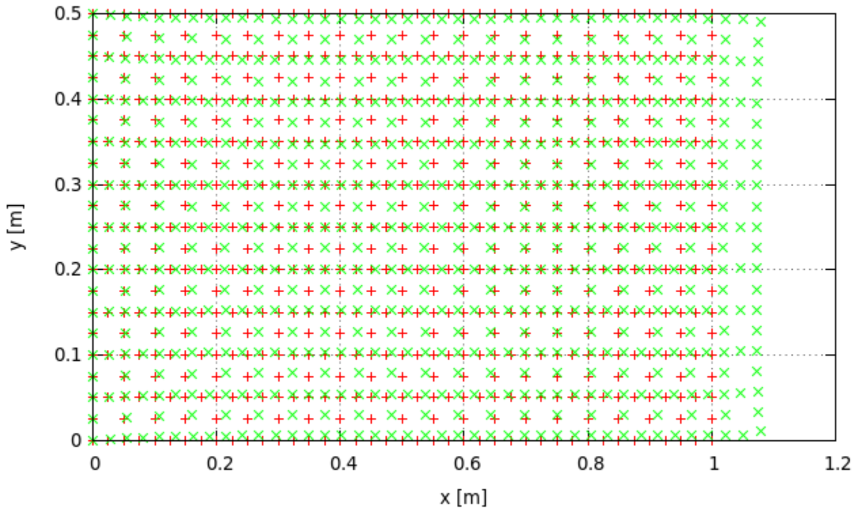
Numerical approach: FE Method, Test geometry and Material data

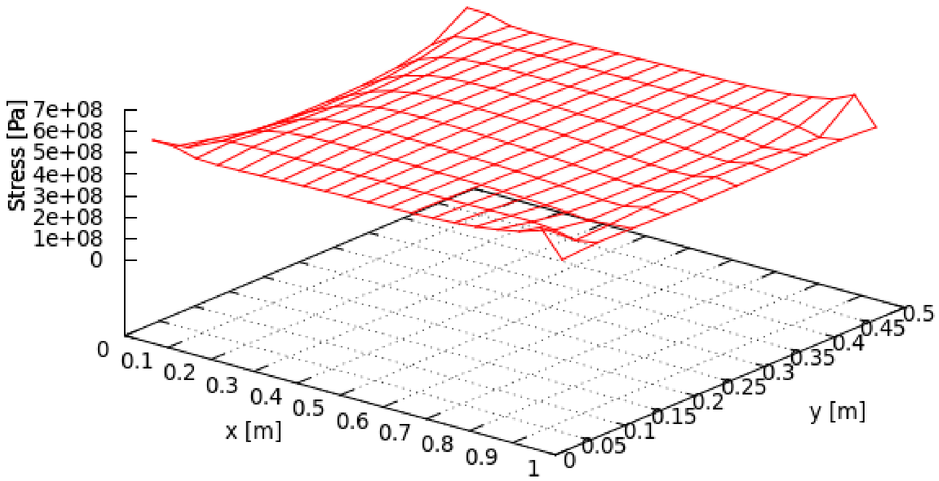
- Finite element method
  - Derived from textbook, no COTS
  - Quadratic form functions for planar loads
  - Bi-cubic form functions for vertical loads
  - Geometry data read from SCARAB geometry files
- Test geometry
  - Plate with rectangular grid
  - Dimensions: 1m x 0.5 m x 0.005 m
  - Grid: X x Y = 20 x 10
- Material data
  - Based on Al properties
  - Material data read from SCARAB database files

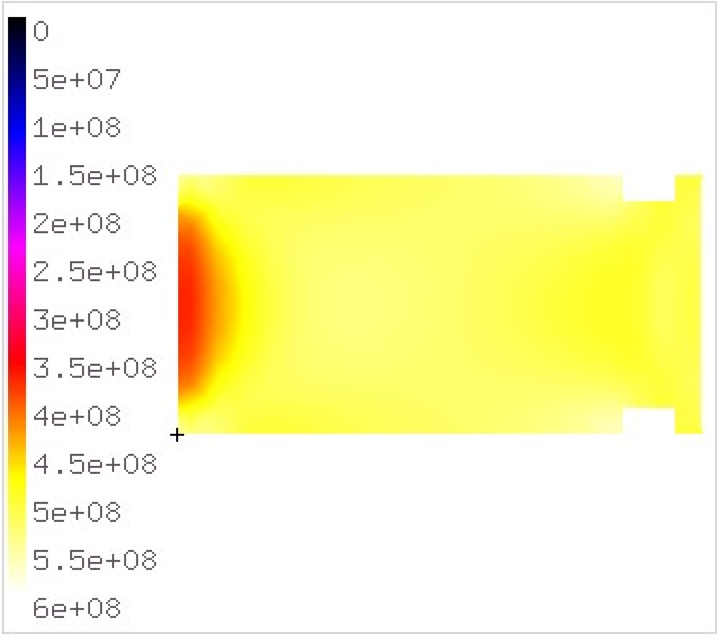
Numerical approach:
Load cases for testing

- Mechanical cases
  - Tensile load (Left side fixed, boundary load on the right side in x-direction)
  - Shear load (Left side fixed, boundary load on the right side in y-direction)
  - Bending load (Left side fixed, uniform pressure load in z-direction)
  - Buckling load (All sides fixed, uniform pressure load in z-direction)
- Thermomechanical cases
  - All mechanical cases with uniform heating
  - All mechanical cases with normal-distributed heating

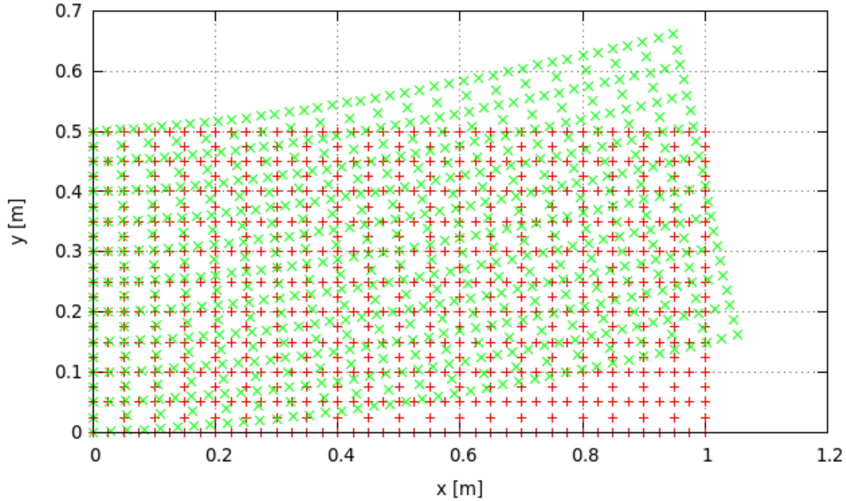
Deformation and stresses at failure for tensile load (300K)

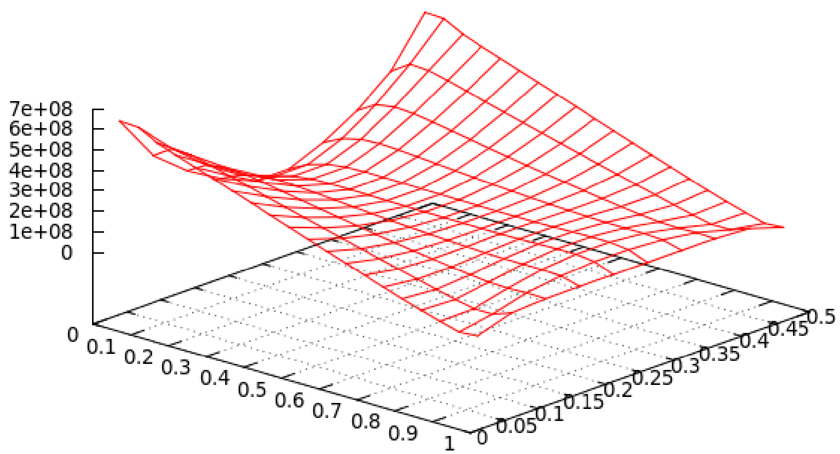


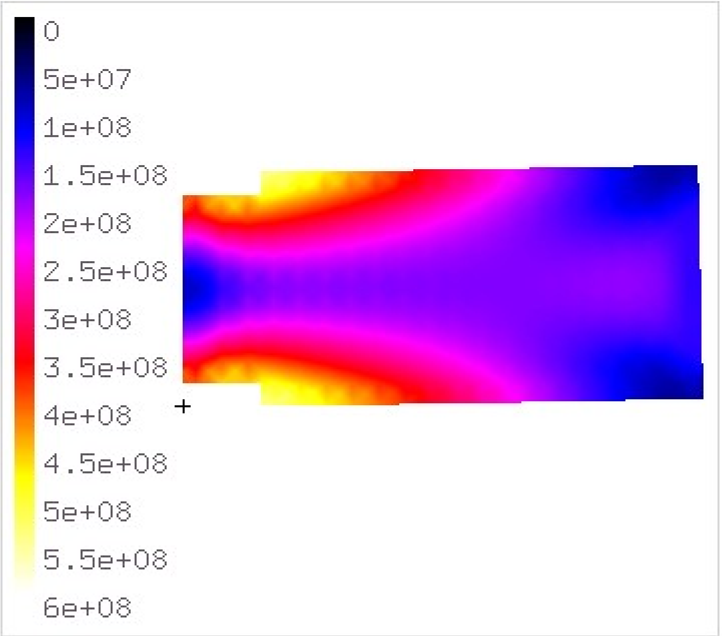




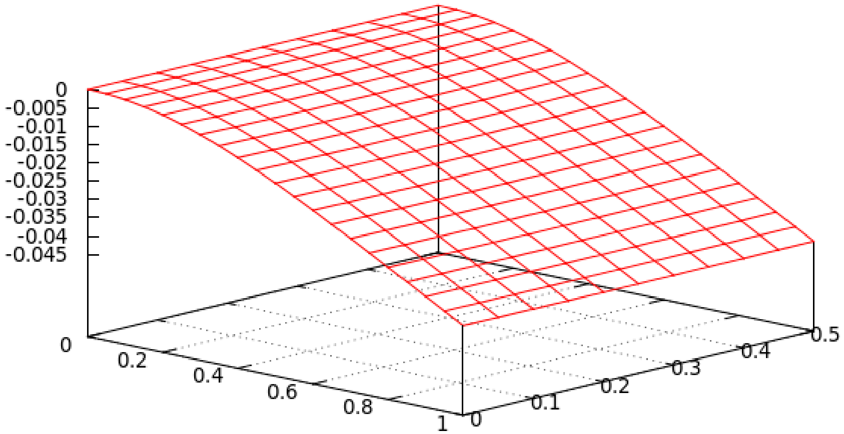
Deformation and stresses at failure for shear load (300K)

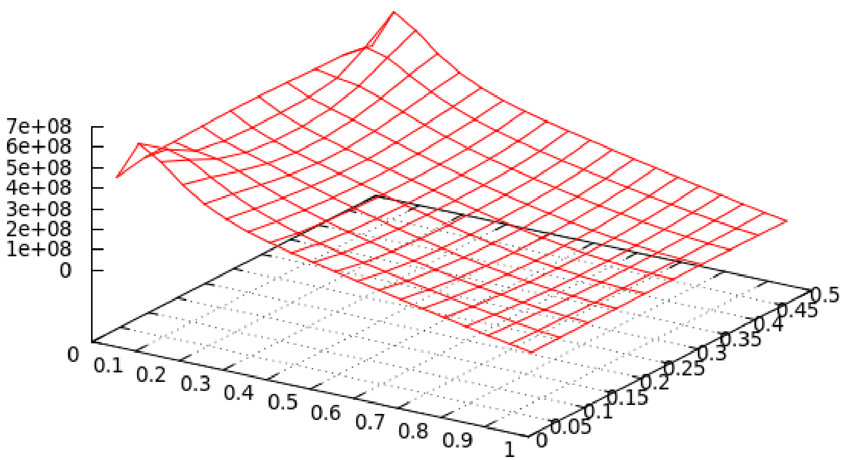


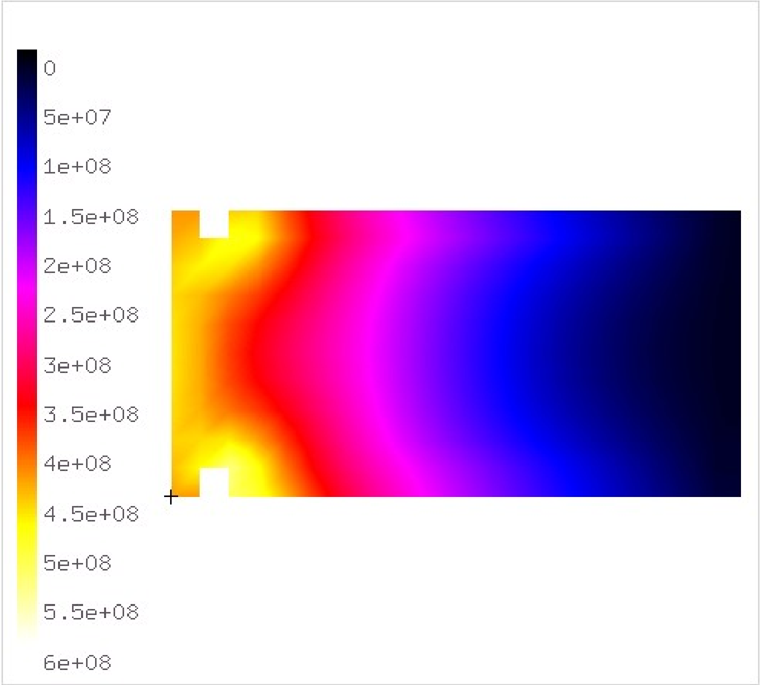




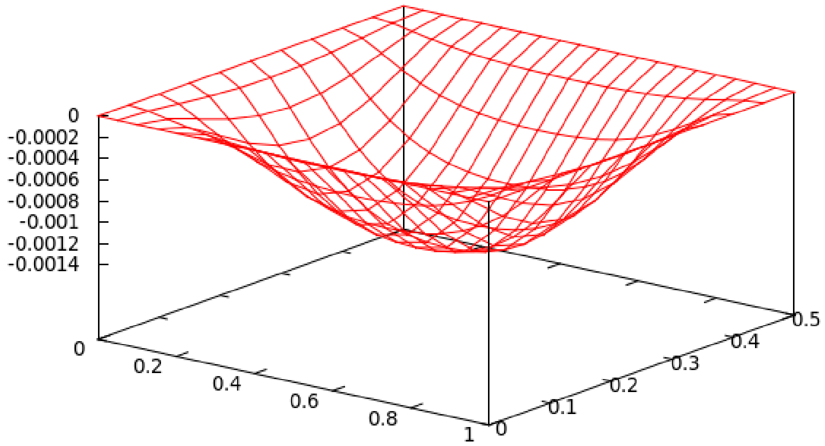
Deformation and stresses at failure for bending load (300K)

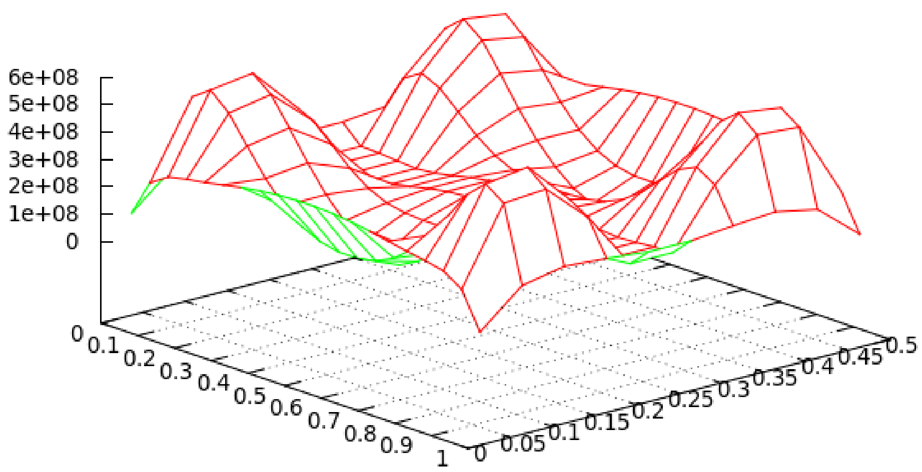


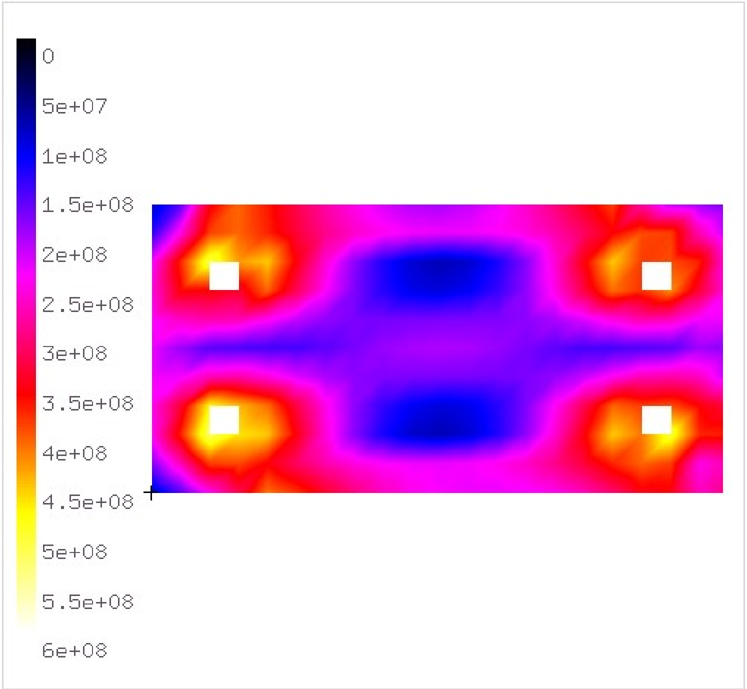




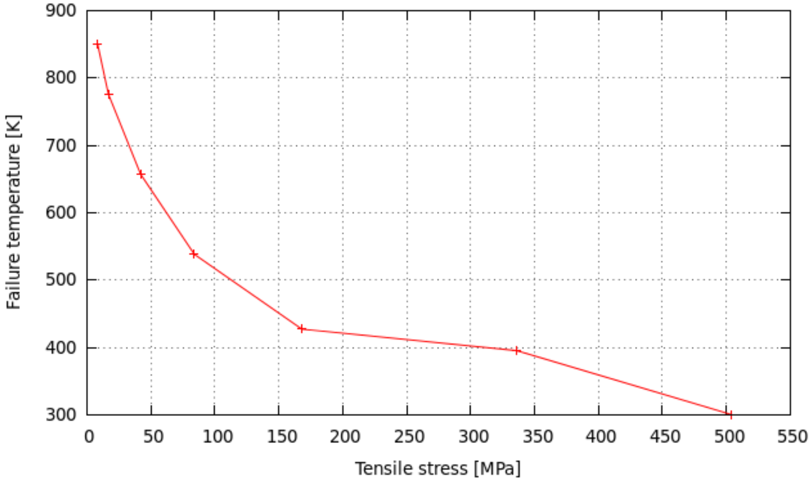
Deformation and stresses at failure for buckling load (300K)

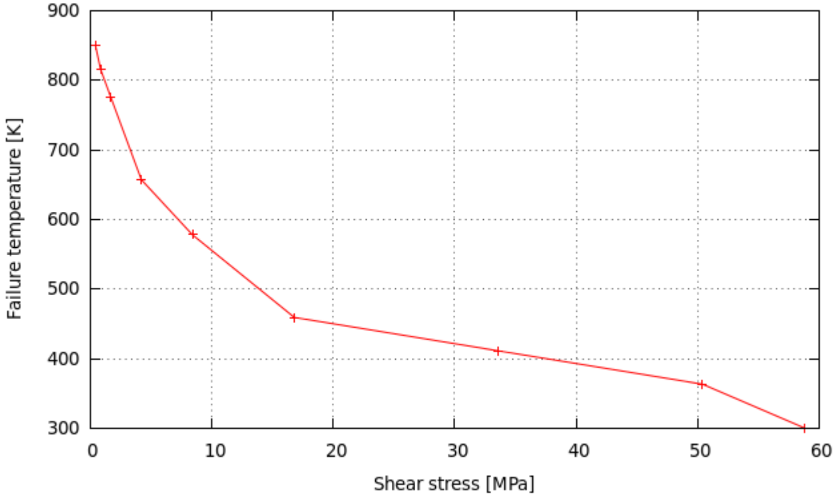


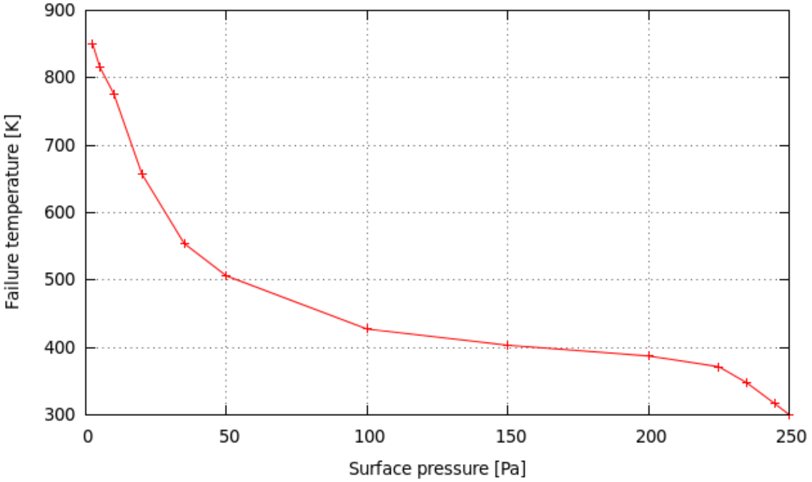




Failure temperature at mechanical load for uniform heating







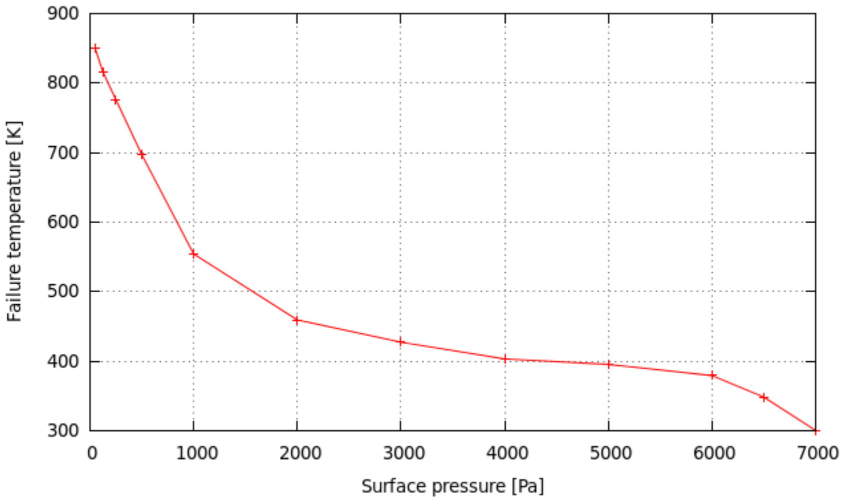
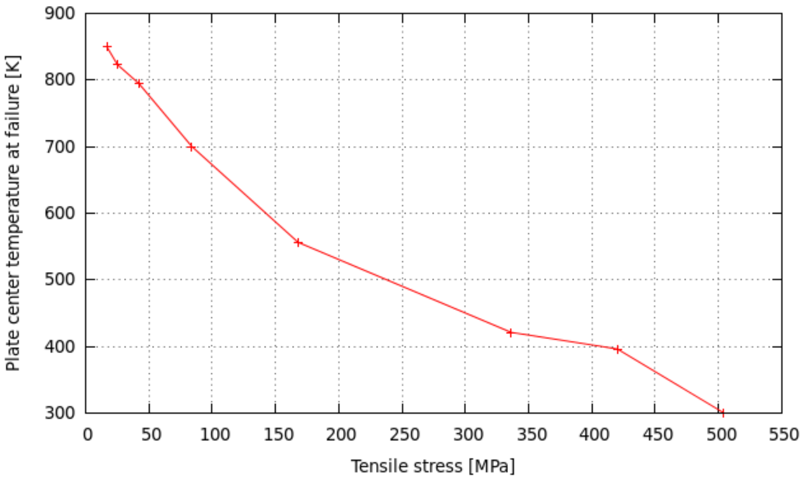
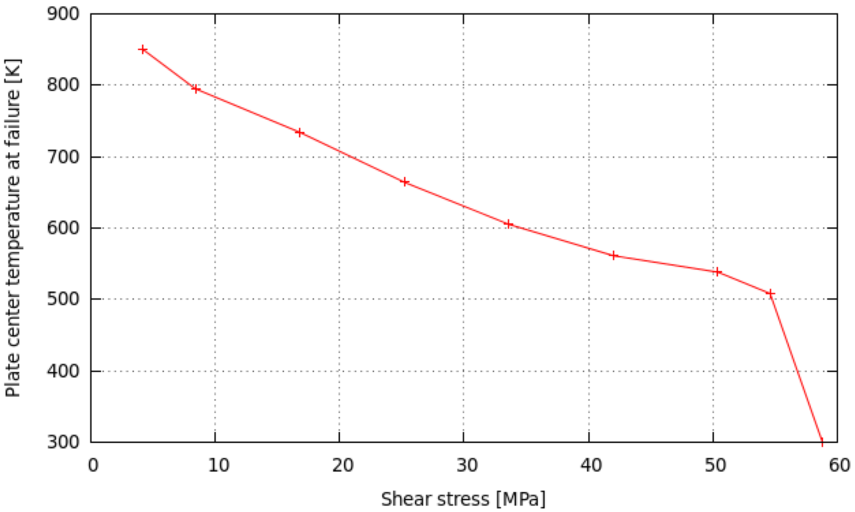
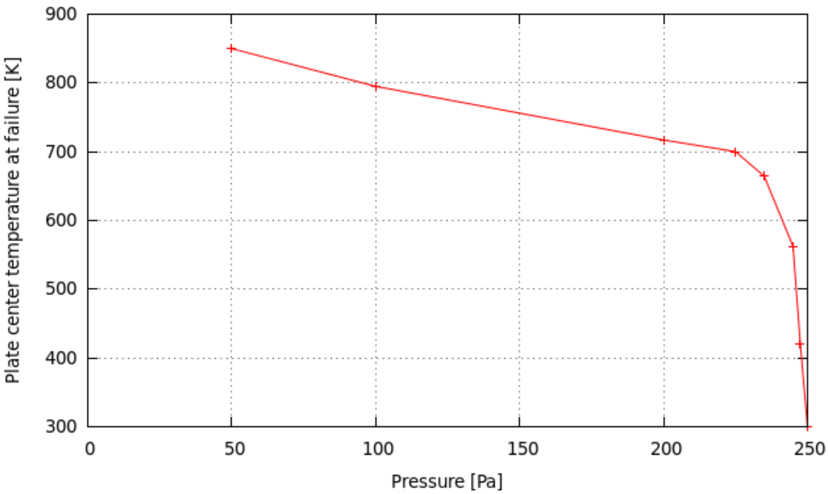
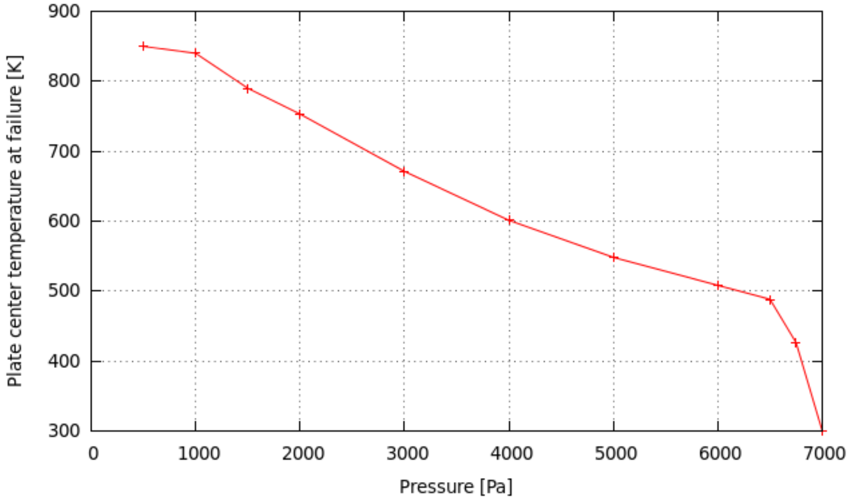


Plate center temperature at failure for normal-distributed heating

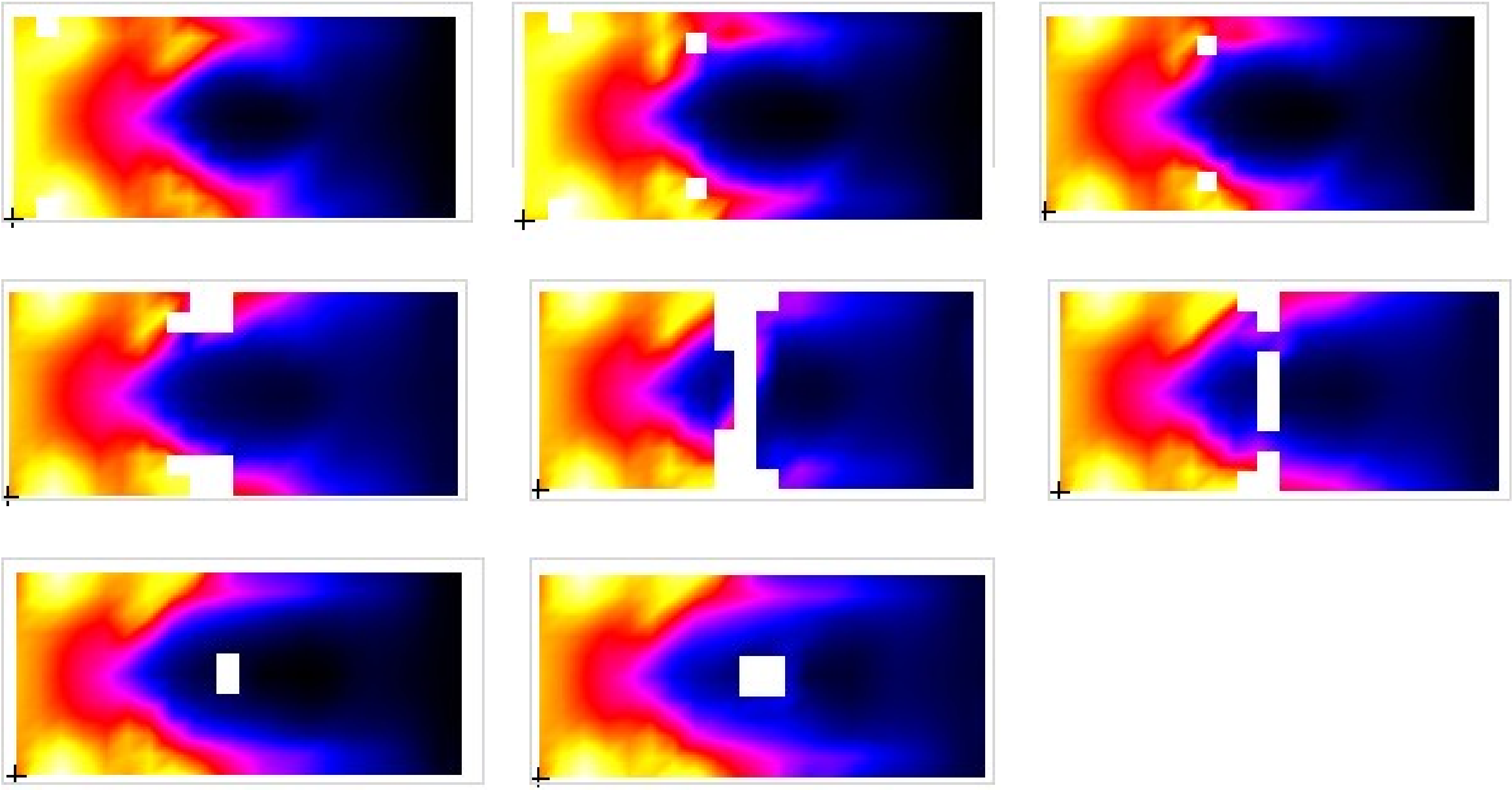






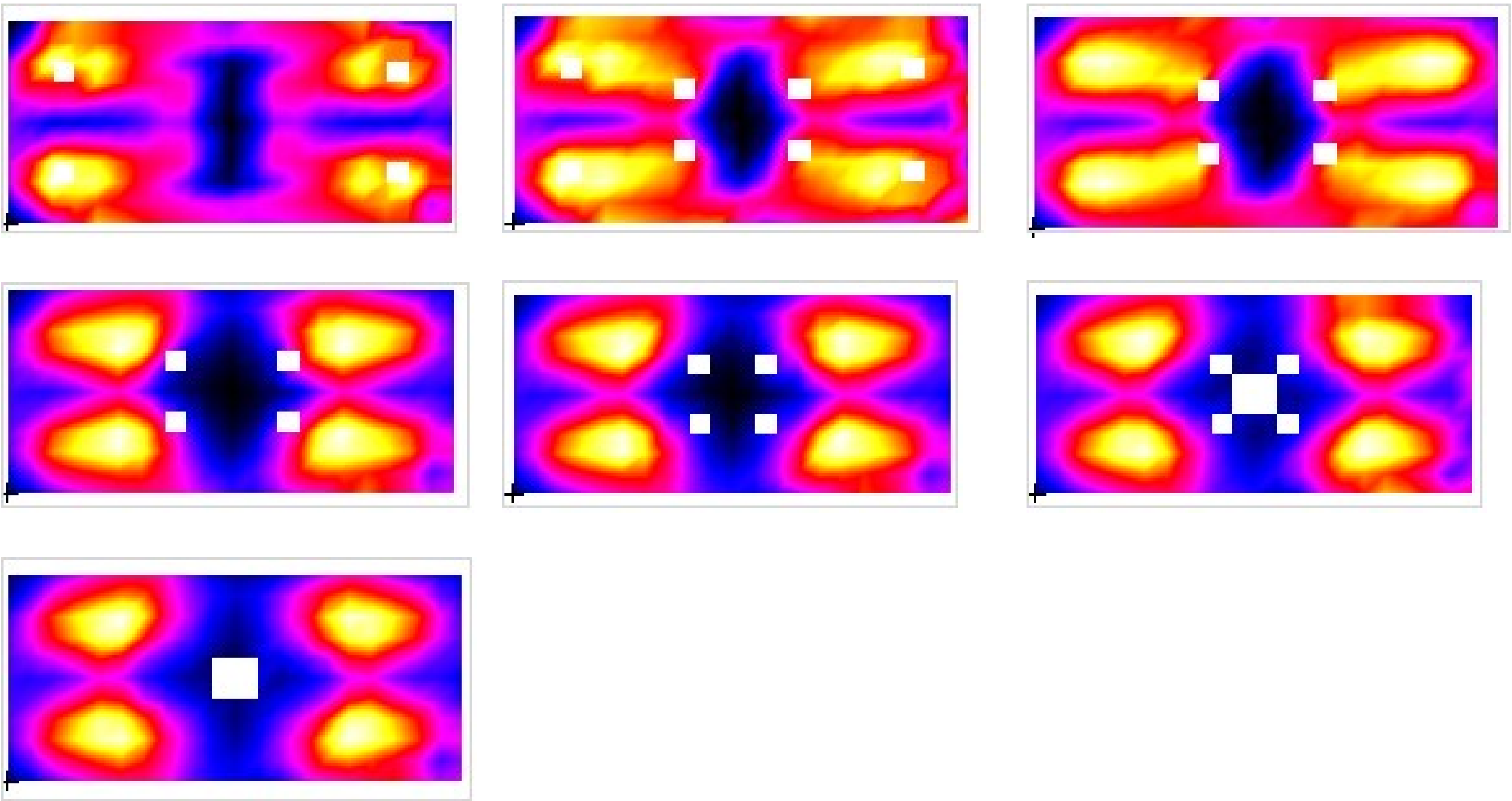


Relative stress distribution at failure on a left-side fixed plate



Failure temperature increases from 300 K (upper left) to melting temperature (lower right)

Relative stress distribution at failure on an all-sided fixed plate

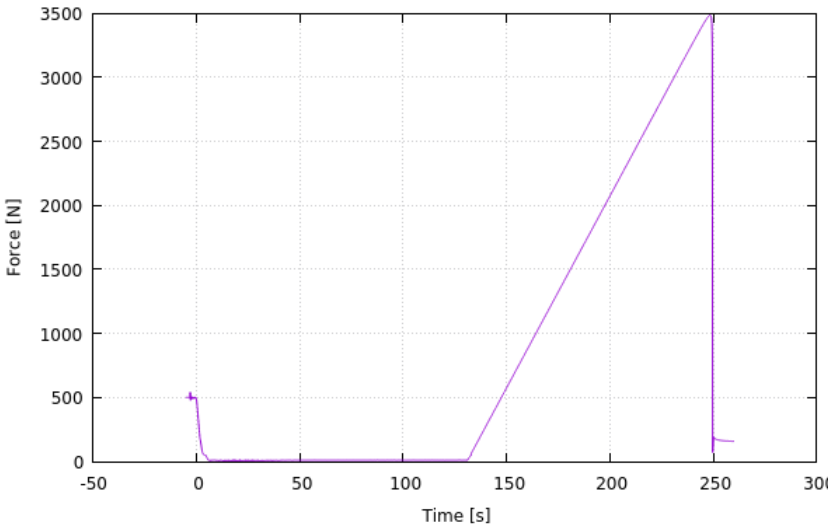


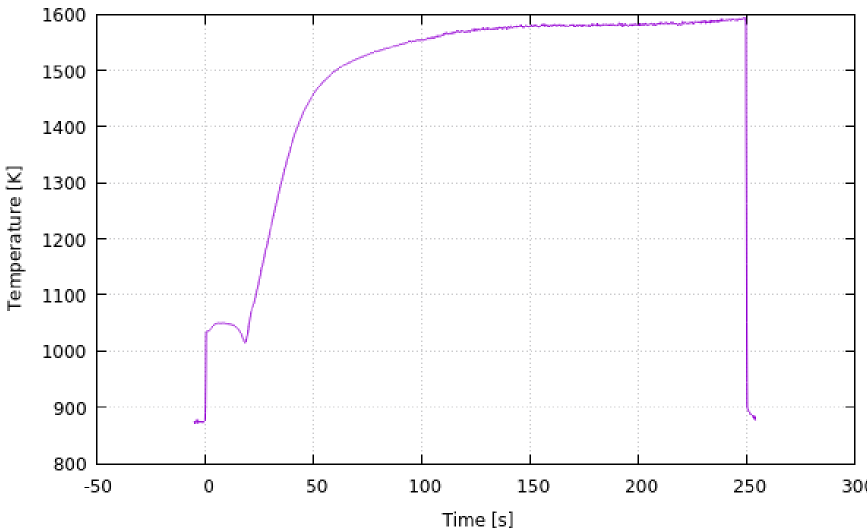
Failure temperature increases from 300 K (upper left) to melting temperature (lower right)

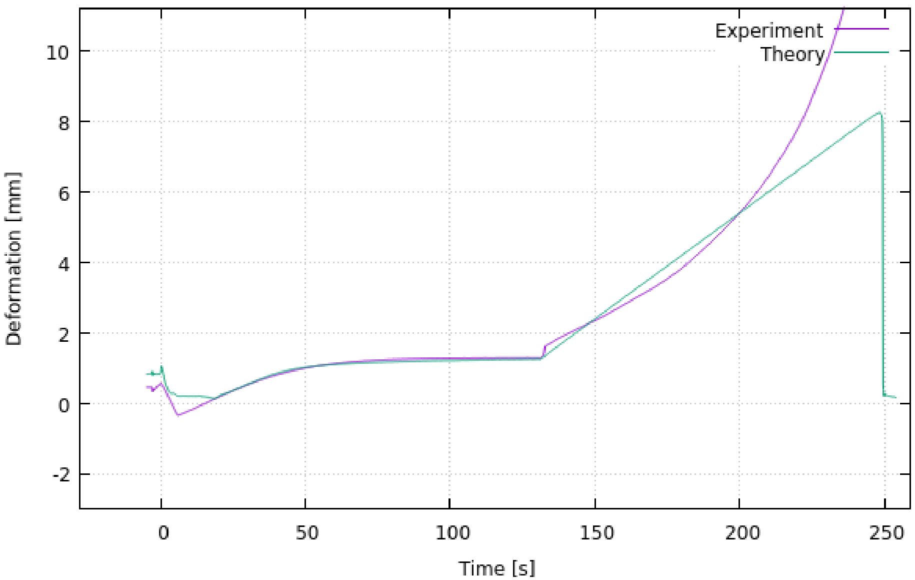
Comparison with Experiments

- Experiments performed at IRS Stuttgart PWT
- Probe: Slab with dimensions 80x20x5 mm
- Load type: Tensile, variable force, constant heat flux
- Materials:
  - Steel
  - Aluminium
  - Titanium
- Free-stream conditions (heat flux and corresponding flight altitude according to Cygnus entry trajectory)
  - 845 kW/m^2, 65 km
  - 499 kW/m^2, 75 km
  - 121 kW/m^2, 90 km

A316, h=65 km, q=845kW/m^2



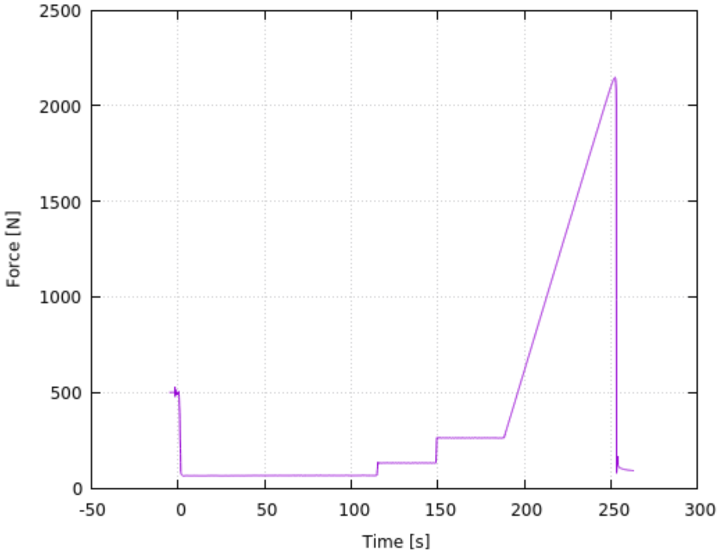


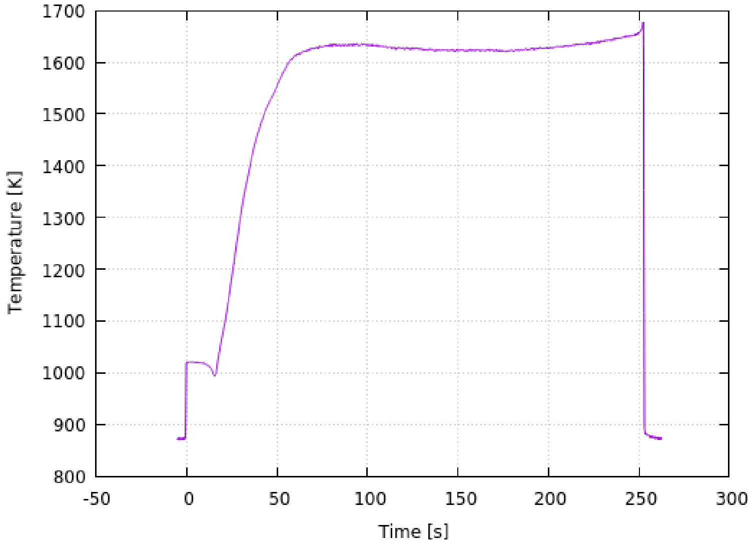


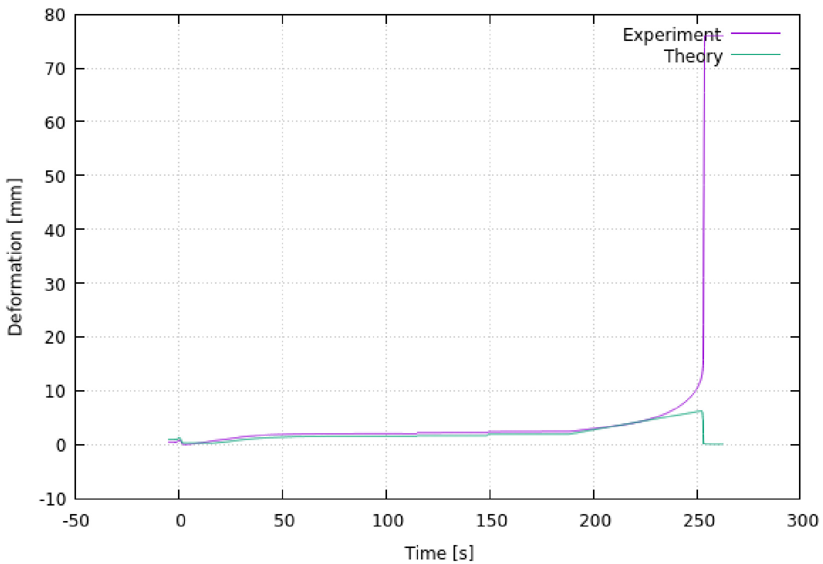
No-load temperature behavior well reproduced

Load behavior well reproduced within validity limits

Material=A316, h=75 km, q=499kW/m^2

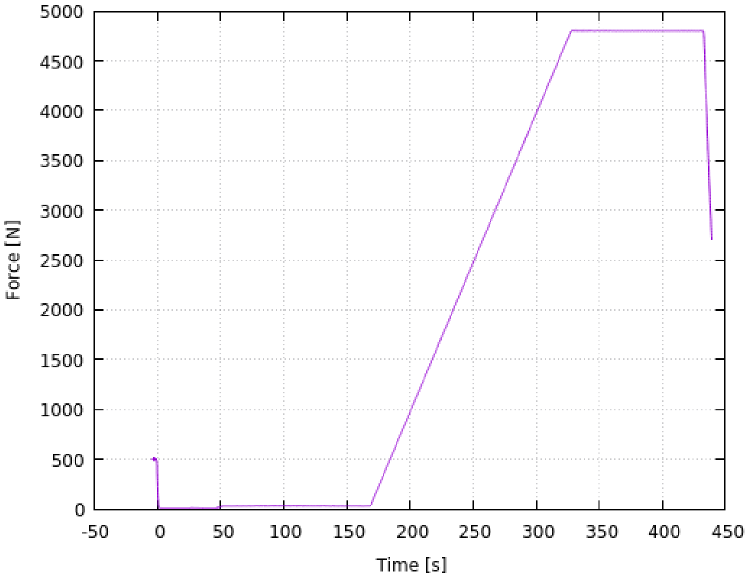


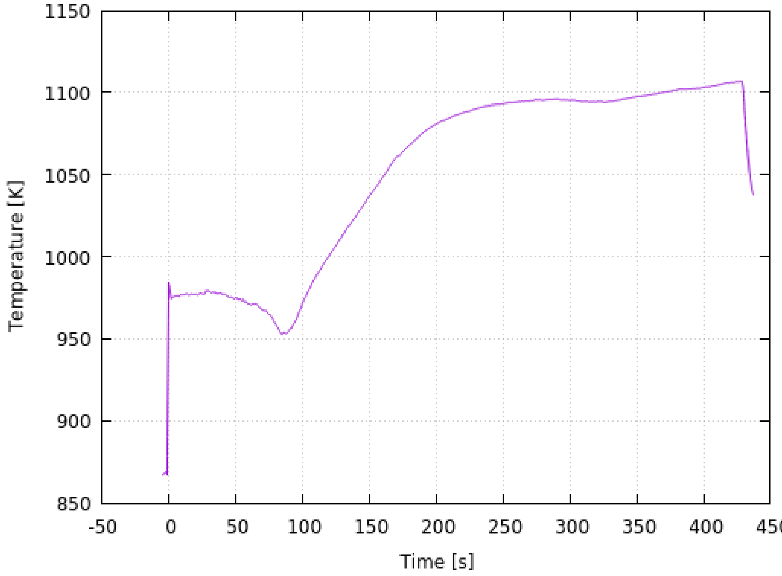


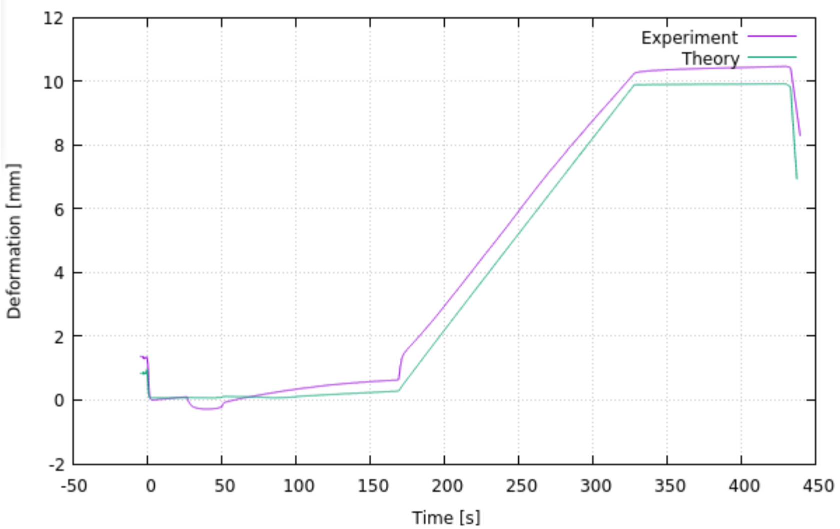


Load behavior well reproduced within validity limits

Material=A316, h=90 km, q=121kW/m^2

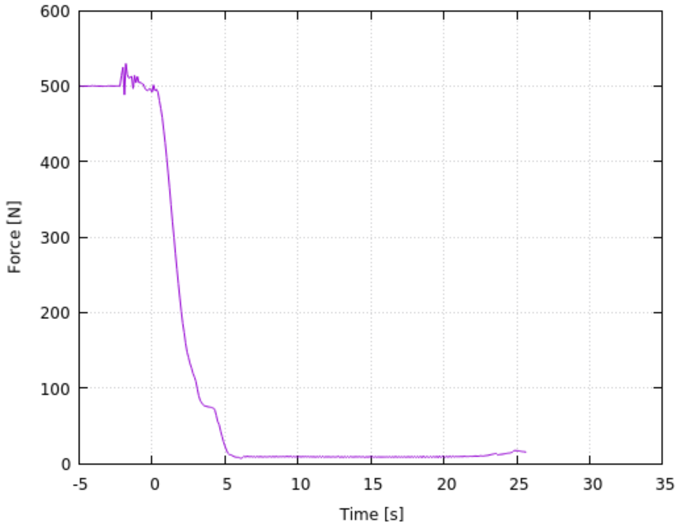


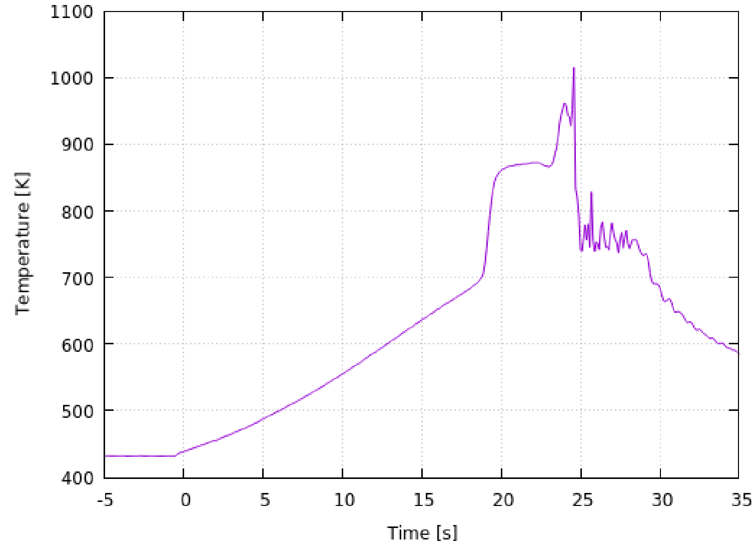


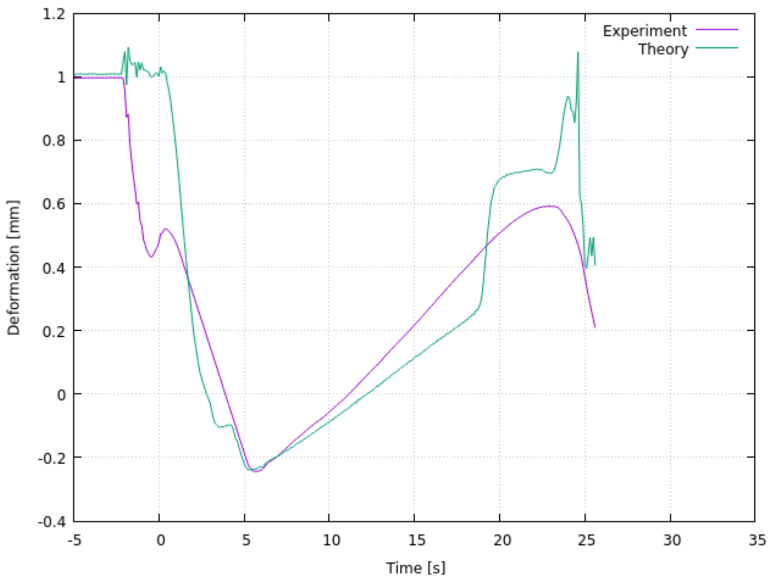


No-load and load behavior well reproduced (no destruction)

Material=AA6060, h=65 km, q=865kW/m^2

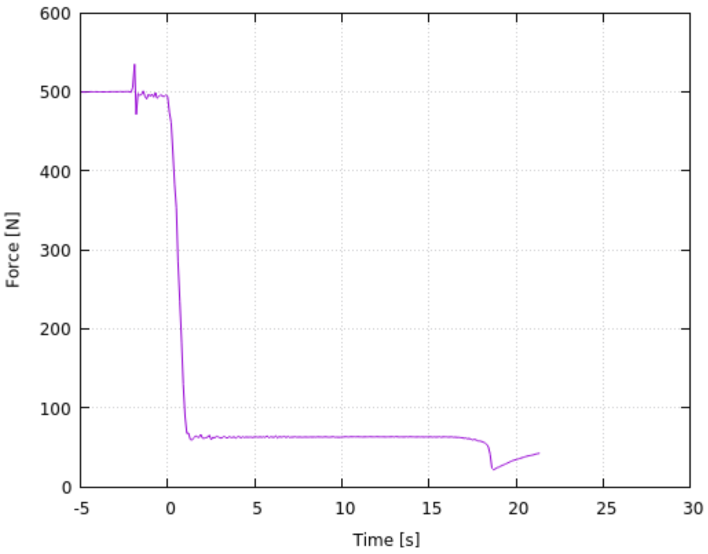


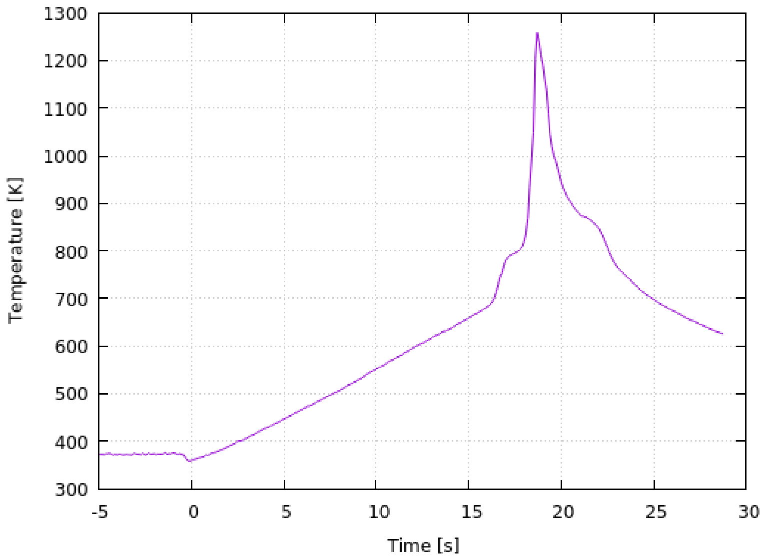


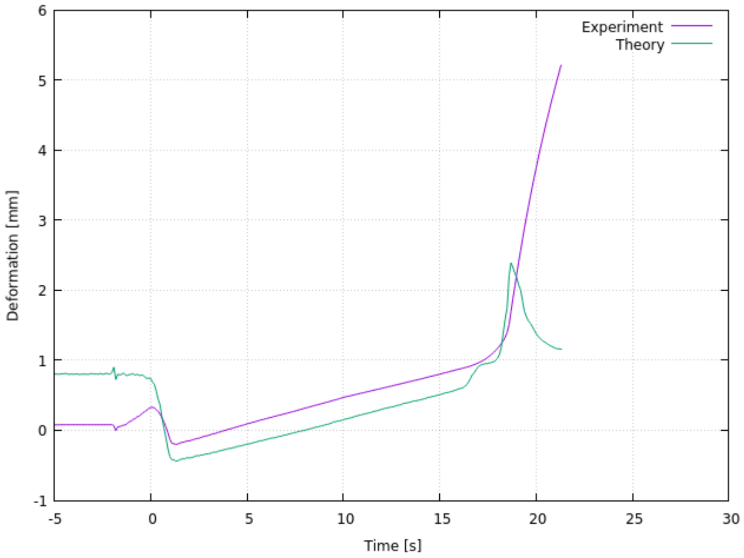


Initial load and no-load temperature (expansion) behavior well reproduced

Material=AA6060, h=75 km, q=499kW/m^2



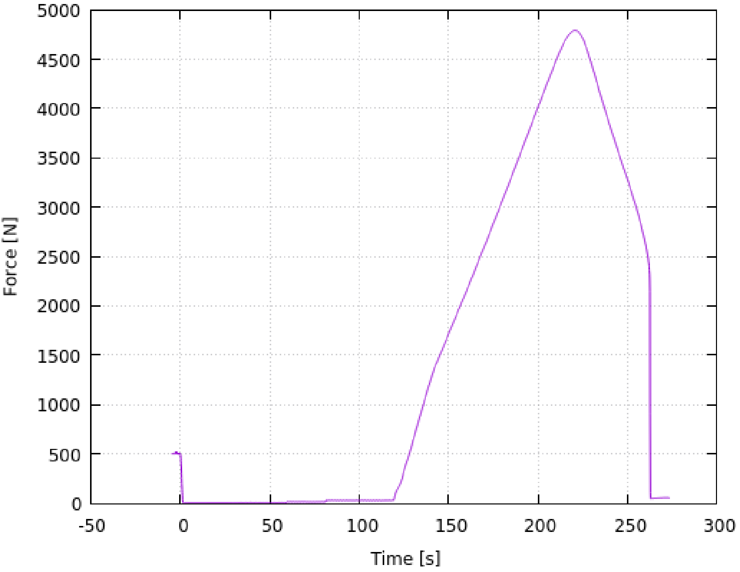


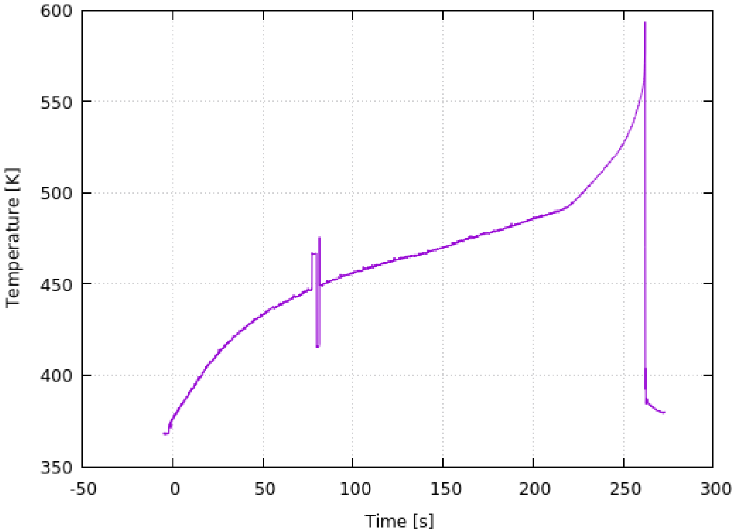


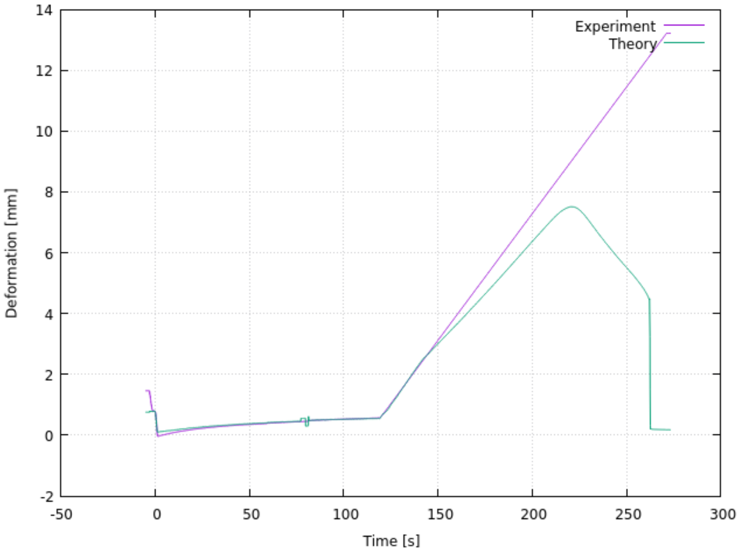
Comparison reveals offset problems (Zero deformation at finite load)

Theory reproduces thermal dependence at finite load

Material=AA6060, h=90 km, q=121kW/m^2



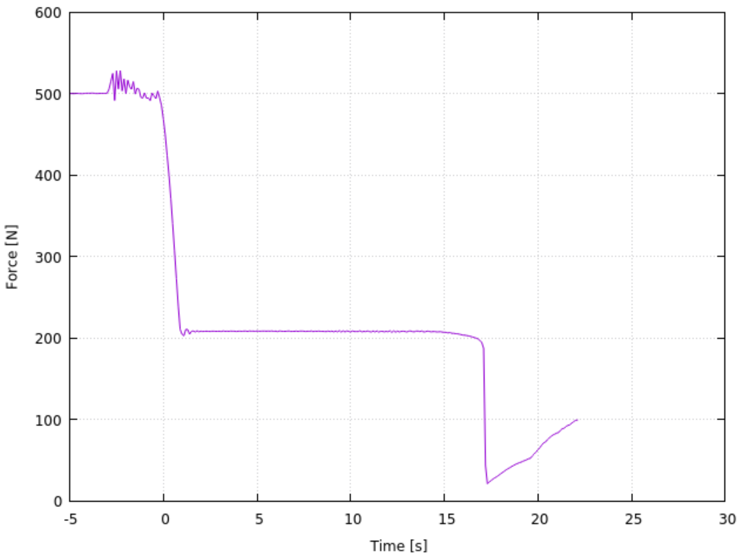


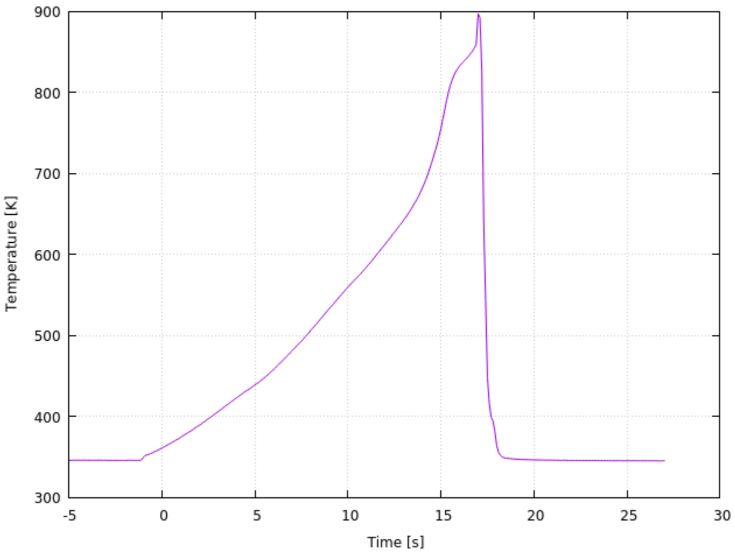


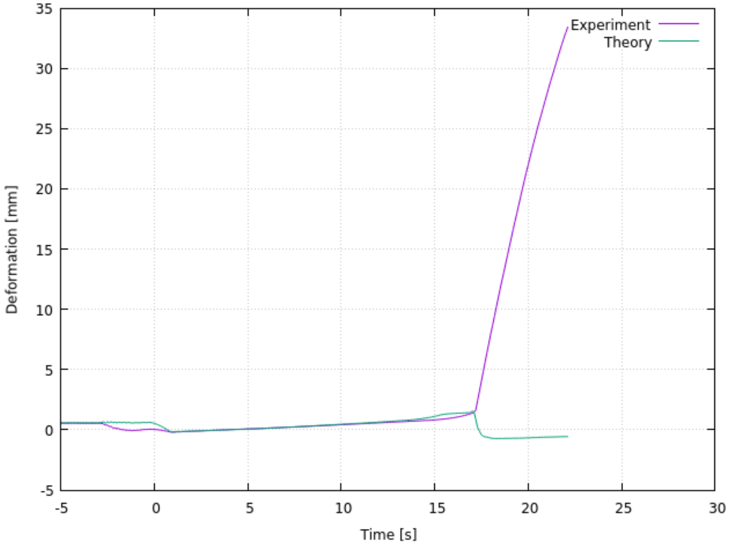
No-load temperature behavior well reproduced

Load behavior well reproduced within validity limits

Material=AA7075, h=65 km, q=865kW/m^2

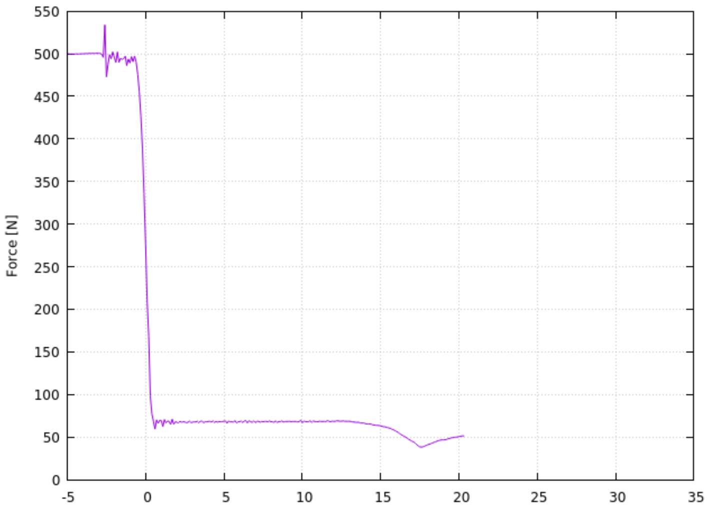


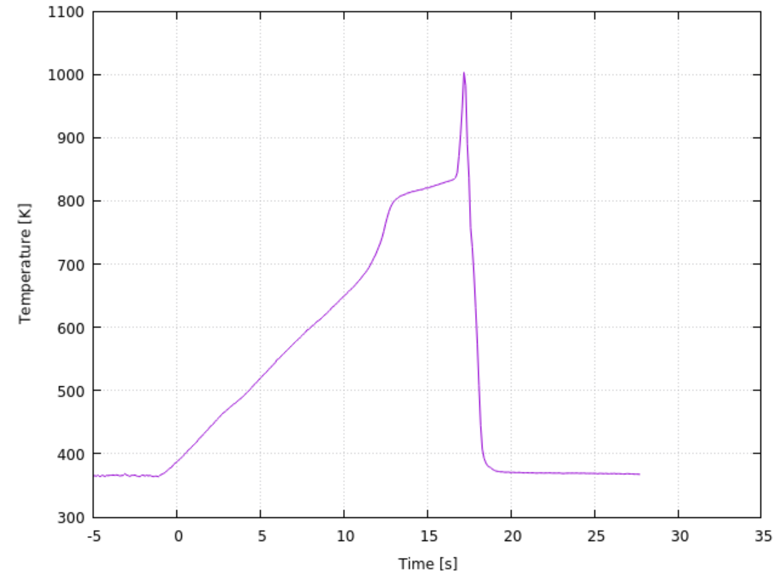


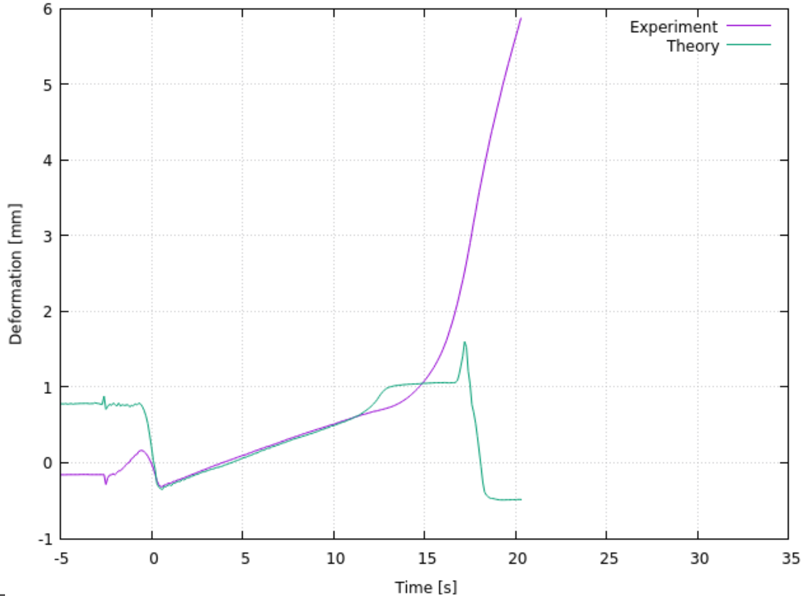


Load behavior well reproduced within validity limits

Material=AA7075, h=75 km, q=499kW/m^2



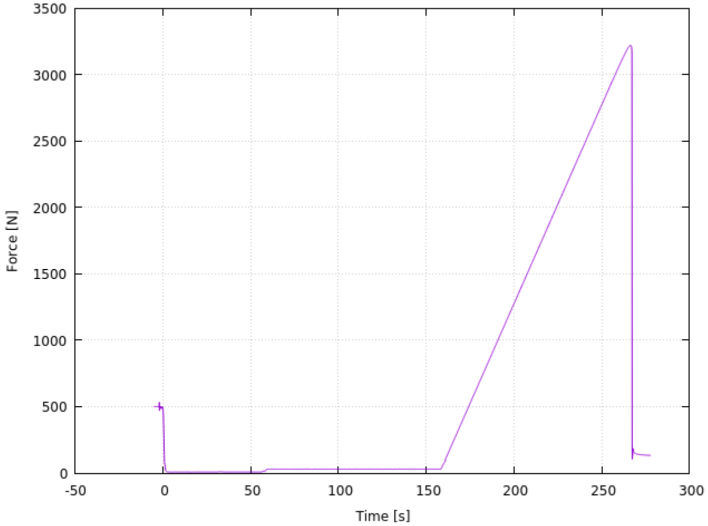


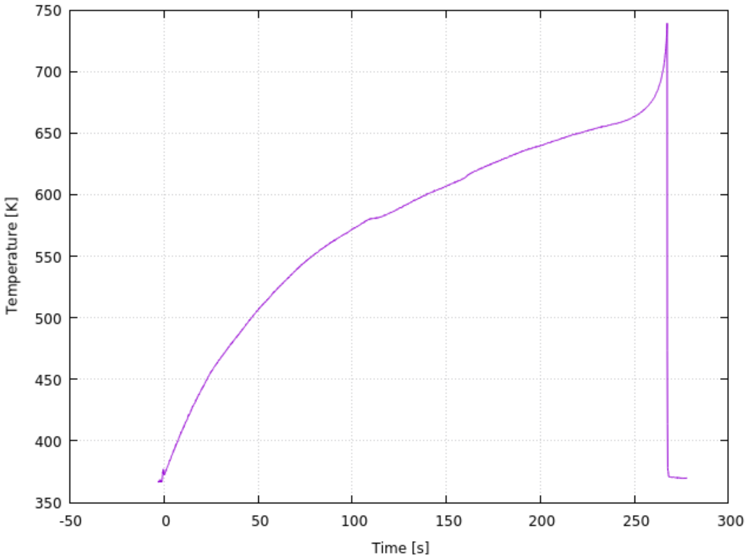


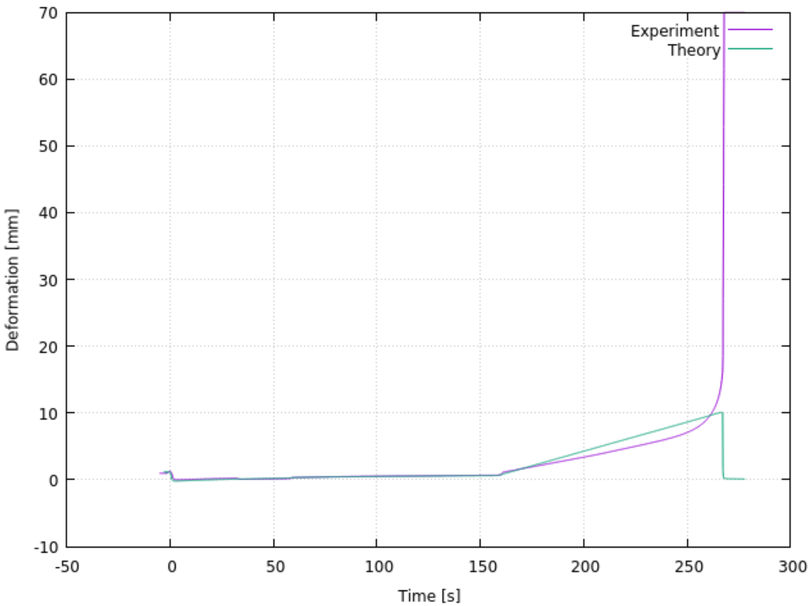
Comparison reveals offset problems
(Zero deformation at finite load)

Theory reproduces thermal dependence
at finite load

AA7075, h=90 km, q=121kW/m^2

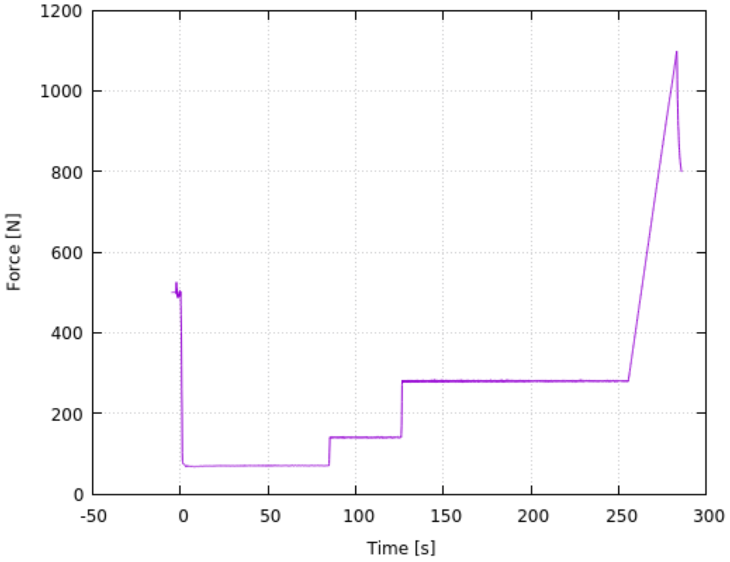


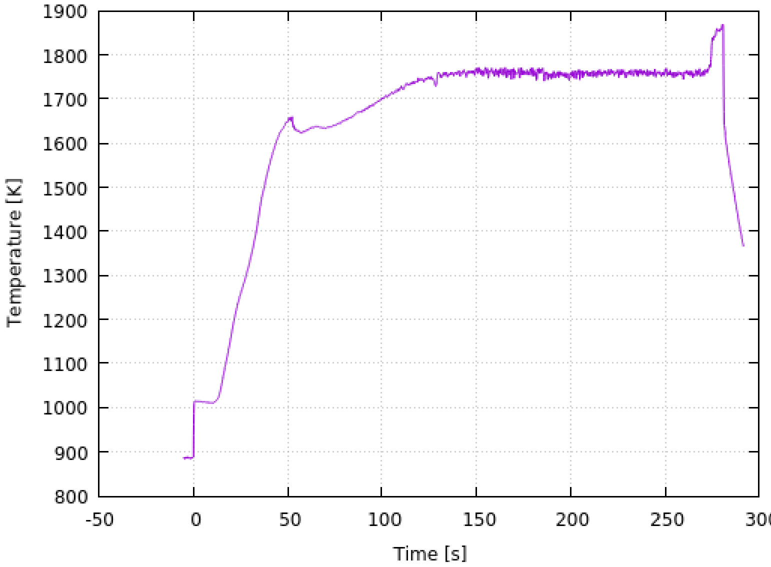


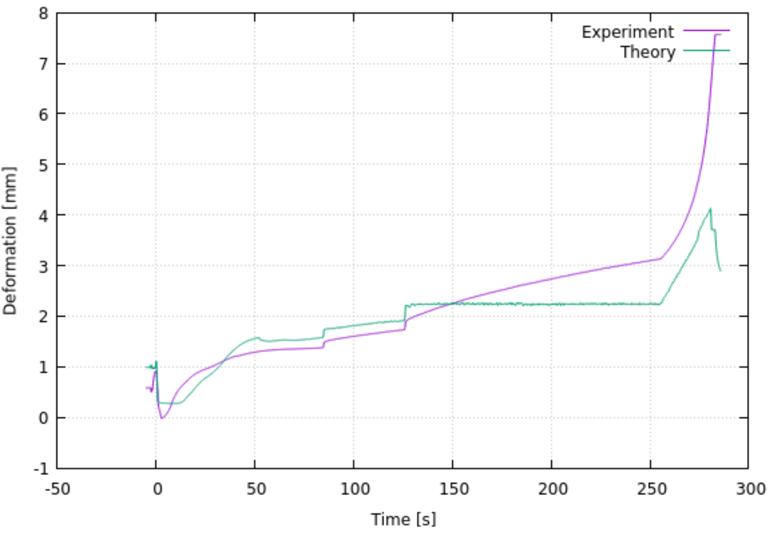


Load behavior well reproduced within validity limits

Material=Ti, h=75 km, q=499kW/m^2

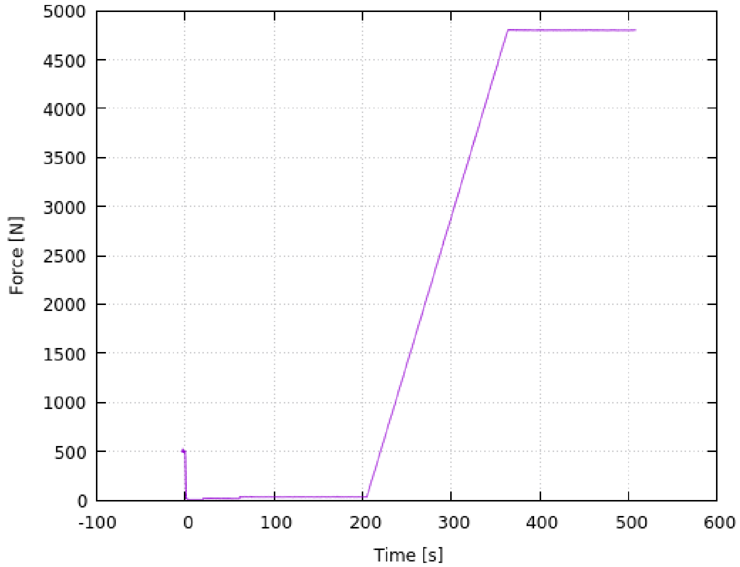


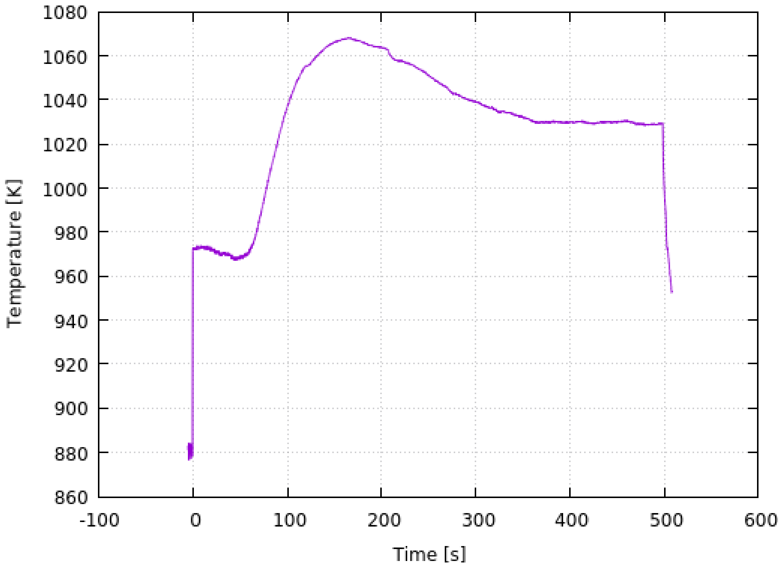


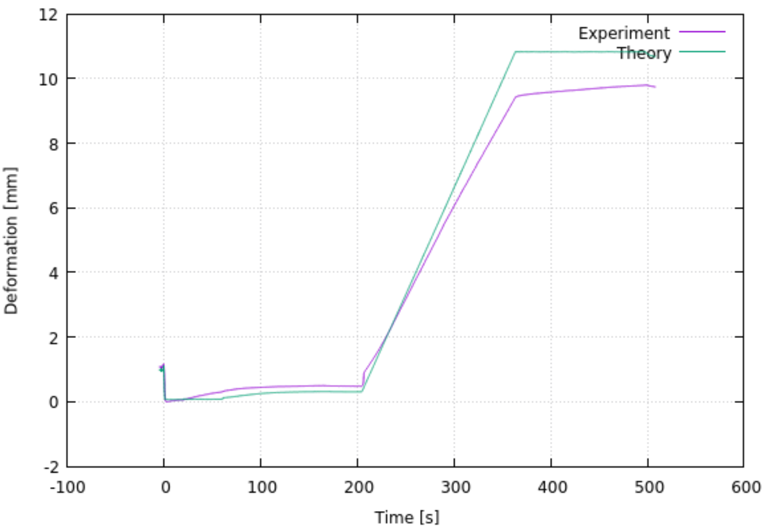


Load behavior well reproduced within validity limits

Material=Ti, h=90 km, q=121kW/m^2







Load behavior well reproduced within validity limits (no destruction)

Conclusions

- A finite element based method has been implemented to pave the way for an overall thermo-mechanical analysis to be used in spacecraft-oriented codes for the analysis of destructive re-entries
- First numerical test case results show that there is a strong interaction between mechanical and thermal loads to be considered
- Extension to more complex geometries is in progress
- The method was validated with wind tunnel tests at IRS Stuttgart
- The findings could also be used to derive simplified destruction criteria for simple object-oriented codes