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Self-heating analysis of hybrid thin-ply laminates subjected to cyclic mechanical loading

Andrejs Pupurs, Alens Šņepsts

Laboratory of Experimental Mechanics of Materials, Riga Technical University, Riga, Latvia

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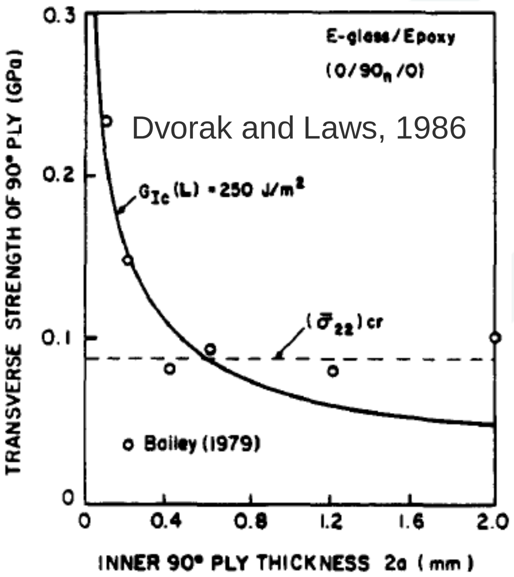
Outline

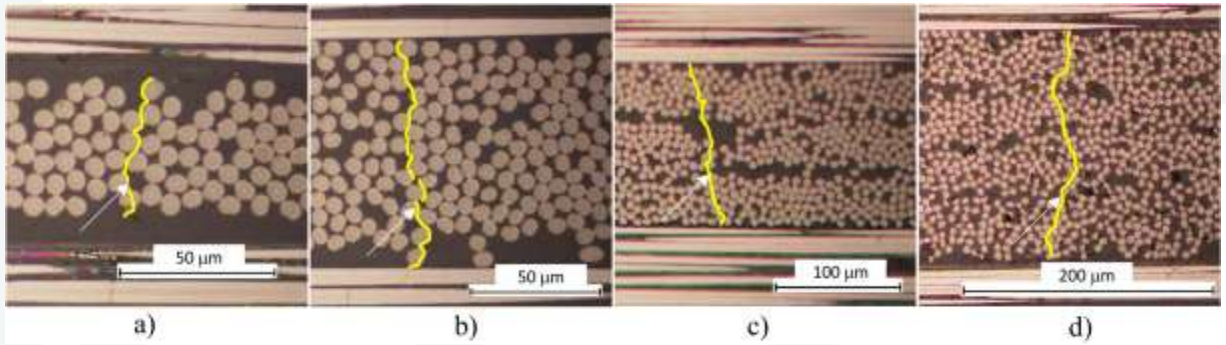
- **Introduction**: hybrid thin-ply laminates
- **Objective** of study
- **Experimental test program** and test set-up
- **Results:** effect of lay-up (ply thickness), maximum strain level, loading frequency, load ratio
- **Conclusions**
- **Future work**

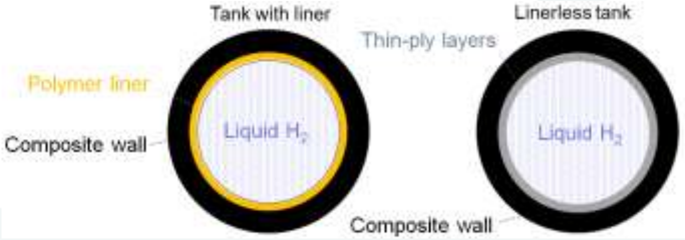
Introduction (1/2)

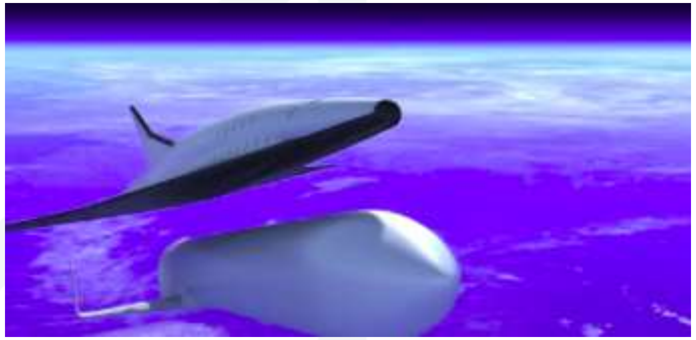
- Thin-ply laminates have been shown to have an increased resistance to micro-damage formation
- Hence they have become attractive in applications where micro-cracking is not permitted, e.g., cryogenic fuel tanks.
- Drawback: brittleness of the ultimate failure



Dvorak and Laws, 1986



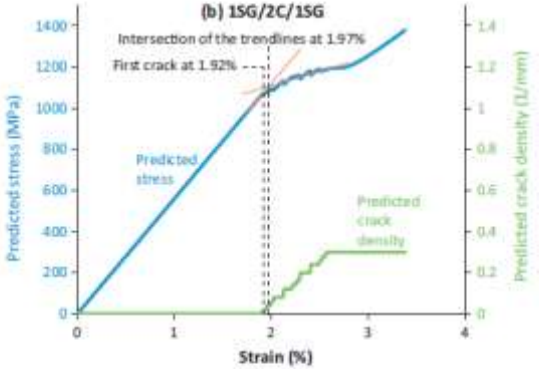




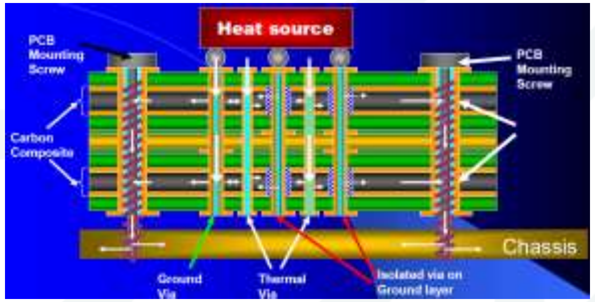
Introduction (2/2)

- Hybridization (e.g., combining carbon and glass fiber layers) has been shown to lead to quasi-ductile behavior and failure (safer structures).
- Characterization and monitoring of damage state is becoming **increasingly challenging.** Techniques such as micro CT, SEM and similar are used.
- Present study proposes **self-heating tests** during cyclic mechanical loading as potential method for monitoring behavior and damage state in hybrid thin-ply laminates.
- Furthermore such study is relevant for cyclic loading applications and even for multifunctional applications of hybrid carbon/glass composites e.g., in flexible electronics.

Wisnom et al, 2016



K.Vasoya, Hunter technology



Objective

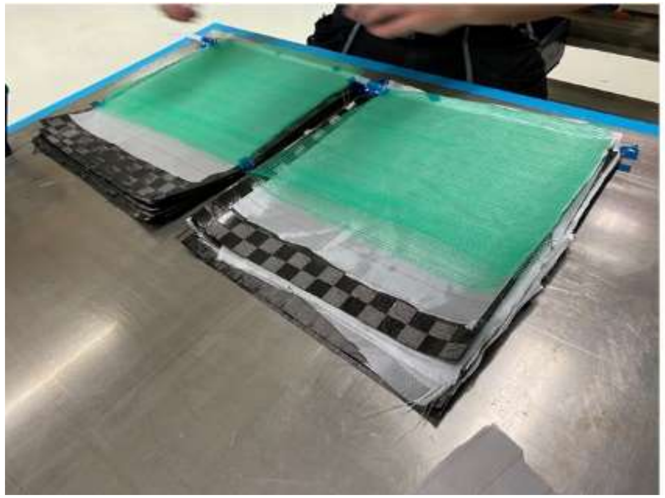
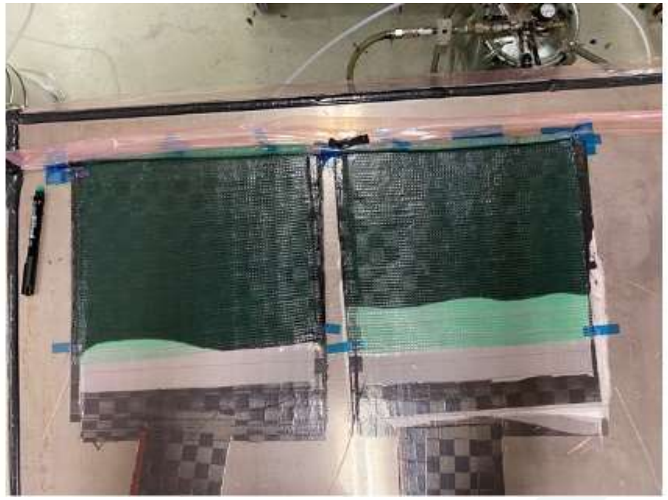
- To analyze self-heating of hybrid thin-ply laminates during cyclic mechanical loading. To evaluate potential of high resolution thermal imaging as a robust methodology for evaluation of behavior and damage state in hybrid thin-ply laminates.

Tasks

- Develop a robust manufacturing method for hybrid thin-ply laminates
- Develop high accuracy thermal imaging test set-up for self-heating analysis
- Perform experimental investigation of parameters affecting self heating behavior, such as lay-up, ply thickness, maximum strain level, loading frequency, loading ratio.

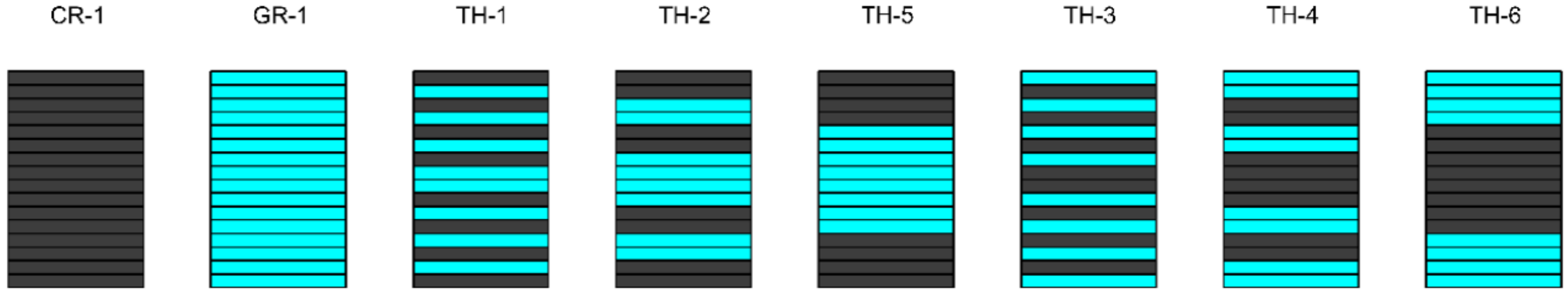
Manufacturing of hybrid thin-ply laminates

- Dry fabric lay-up and vacuum infusion, in collaboration with RISE SICOMP, Piteå, Sweden
- Carbon fiber (CF) fabrics, 100g/m^2, from Oxeon Textreme (Sweden), glass fiber (GF) fabrics, 80 g/m^2, from Interglas (Germany).
- Epoxy resin LY1564 from Huntsman (USA) with XB 3404-1 hardener was used as the matrix
- Cured at 80°C for 8 hours.

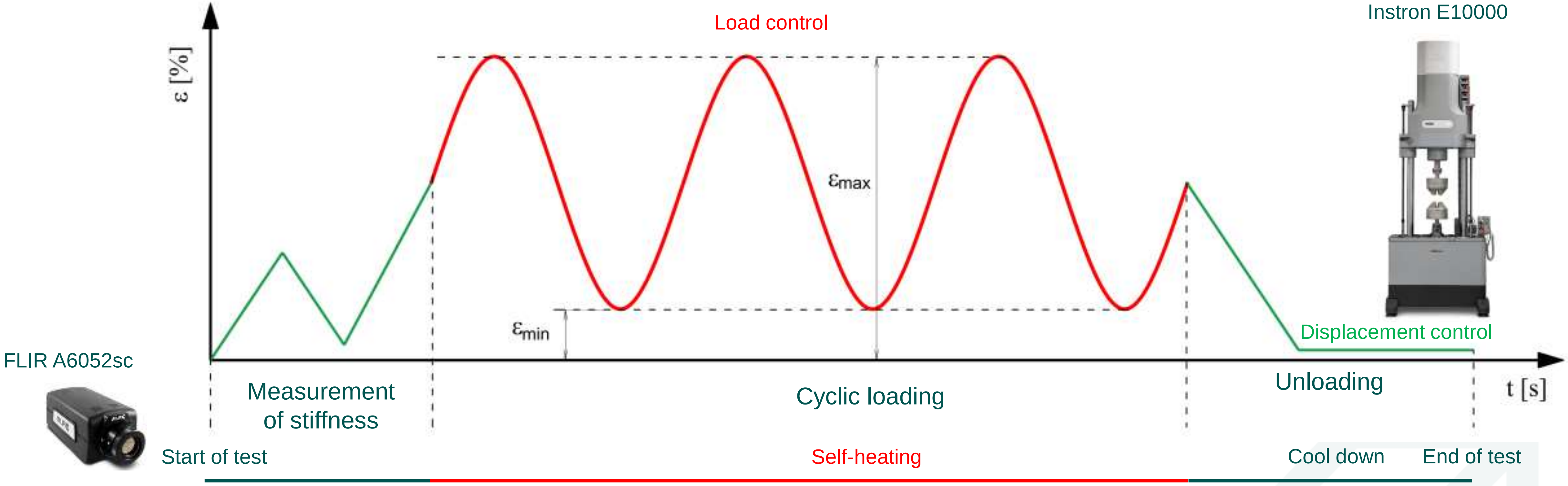

Laminate lay-ups

- Reference laminates: CR-1 (carbon/epoxy) and GR-1 (glass/epoxy)
- 6 different hybrid laminates with different layer thicknesses: TH-1, TH-2, TH-3, TH-4, TH-5, TH-6
- All hybrid laminates contain 8 layers of carbon/epoxy and 8 layers of glass/epoxy



Nr.	Lay-up	Notation	Thickness [mm]
1	$[CF]_{16}$	CR-1	1.92
2	$[GF]_{16}$	GR-1	1.61
3	$[CF/GF]_{4S}$	TH-1	1.70
4	$[CF_2/GF_2]_{2s}$	TH-2	1.71
5	$[GF/CF]_{4s}$	TH-3	1.73
6	$[GF_2/CF_2]_{2s}$	TH-4	1.74
7	$[CF_4/GF_4]_s$	TH-5	1.72
8	$[GF_4/CF_4]_s$	TH-6	1.70

Cyclic mechanical loading test set-up



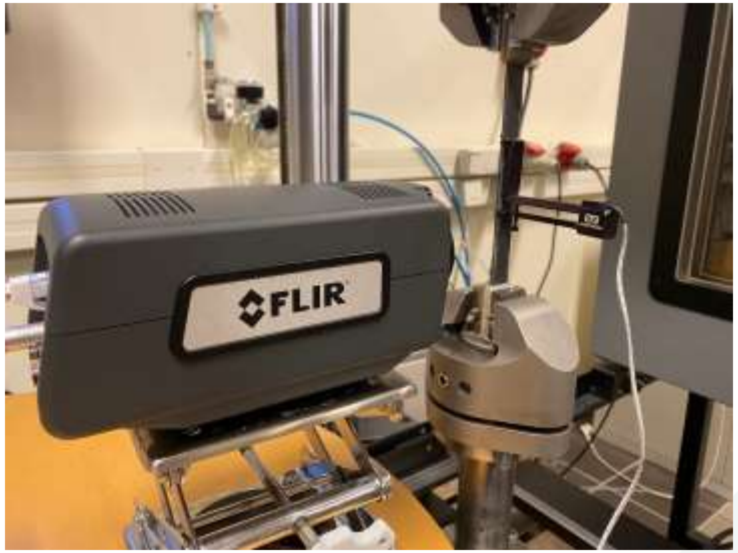
Thermal image acquisition frequency: 5Hz
Total test time: ~960s

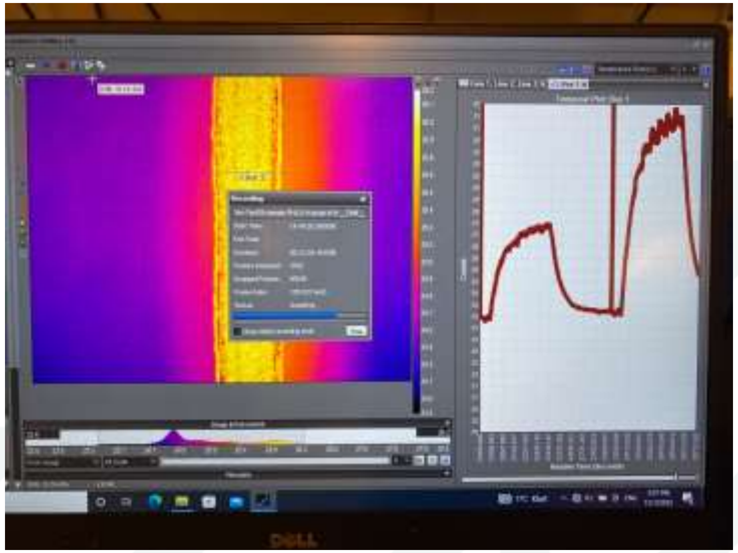
Parametric study:
$\varepsilon_{max} = 0.4 - 0.8\%$
$f = 20, 25, 30Hz$
$R = \varepsilon_{min}/\varepsilon_{max} = 0.1, 0.3, 0.5$

Cyclic loading time t [s]	Frequency f [Hz]	Number of cycles N [-]
500	20	10000
500	25	12500
500	30	15000

Experimental testing: self-heating

- Specimens subjected to cyclic mechanical loading, 20 – 30 Hz frequency
- Instron E10000 dynamic testing machine, load capacity ±10 kN.
- Tension-tension cyclic loading regime, load ratio R=0.1 – 0.5, frequency 20Hz-30Hz. Maximum tensile strain levels: 0.4% - 0.8%.
- Self-heating and temperature distribution measured with FLIR A6752 high performance MWIR thermal imaging camera, resolution 640x512, FLIR 1x microscope lens, f/2.5, 3-5μm.
- Tests started at room temperature. Cooling of specimen down to room temperature was also recorded.

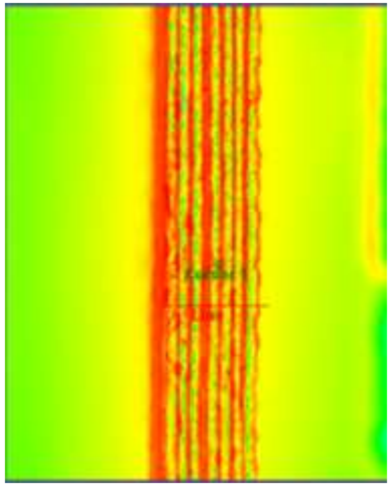




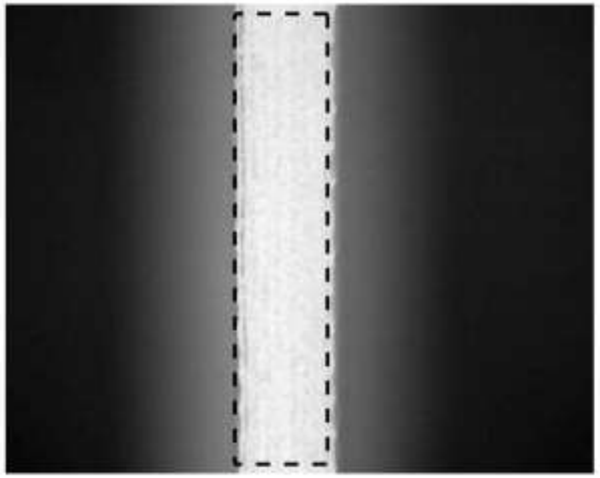
Thermal image processing

- Specimen surface was spray painted black to remove effects of surface emissivity.
- Grayscale image and each-pixel-temperature files were exported from FLIR thermal imaging software and processed in Matlab.
- Image was loaded in matrix of size n-x m-pixels, consisting of 8-bit values of each pixel. Specimen location in each frame was found based on contrast change

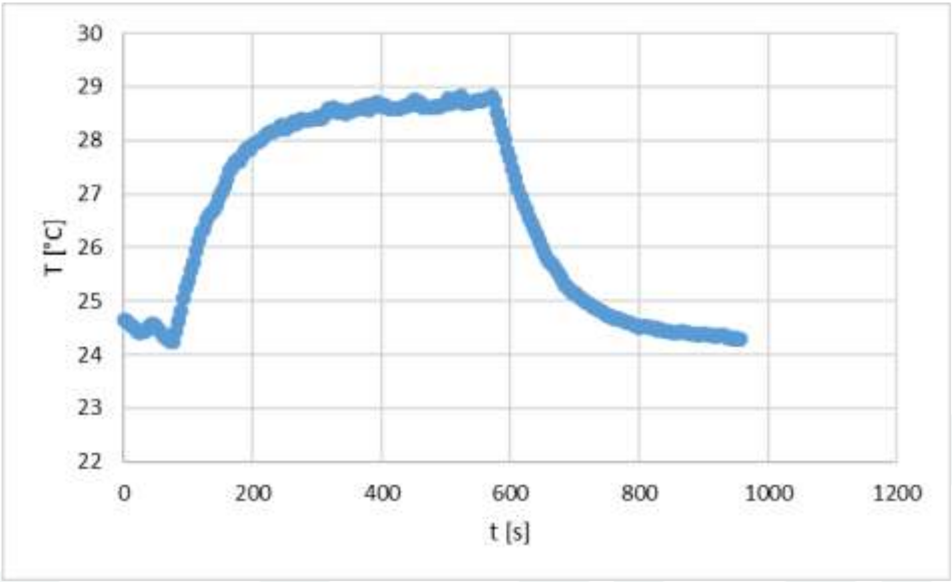
Original thermal image



Processed 8-bit image

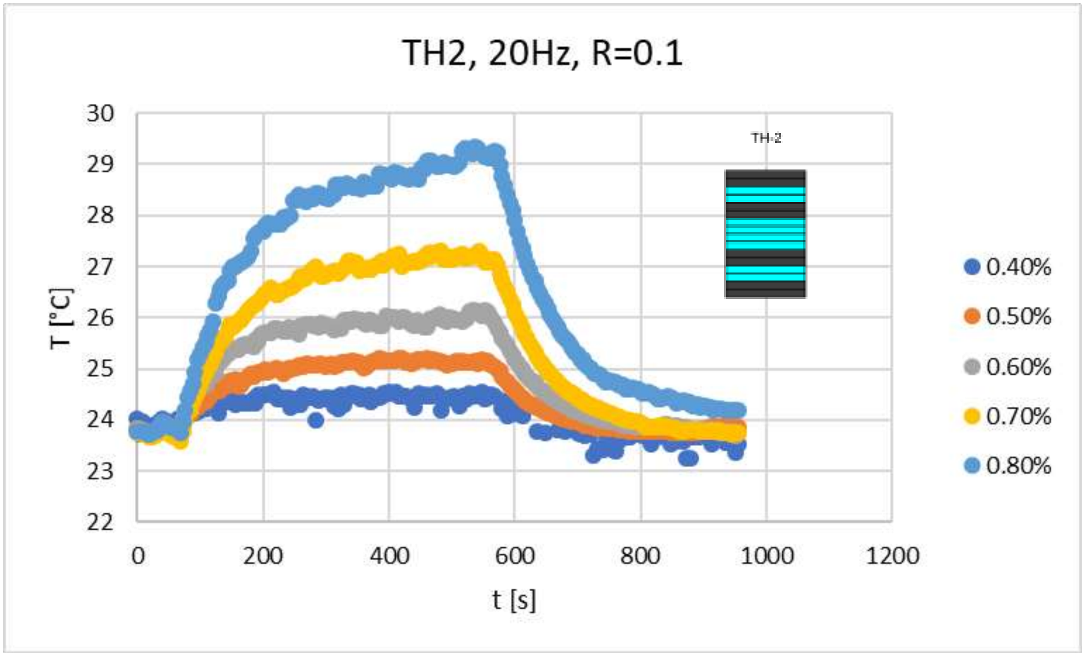


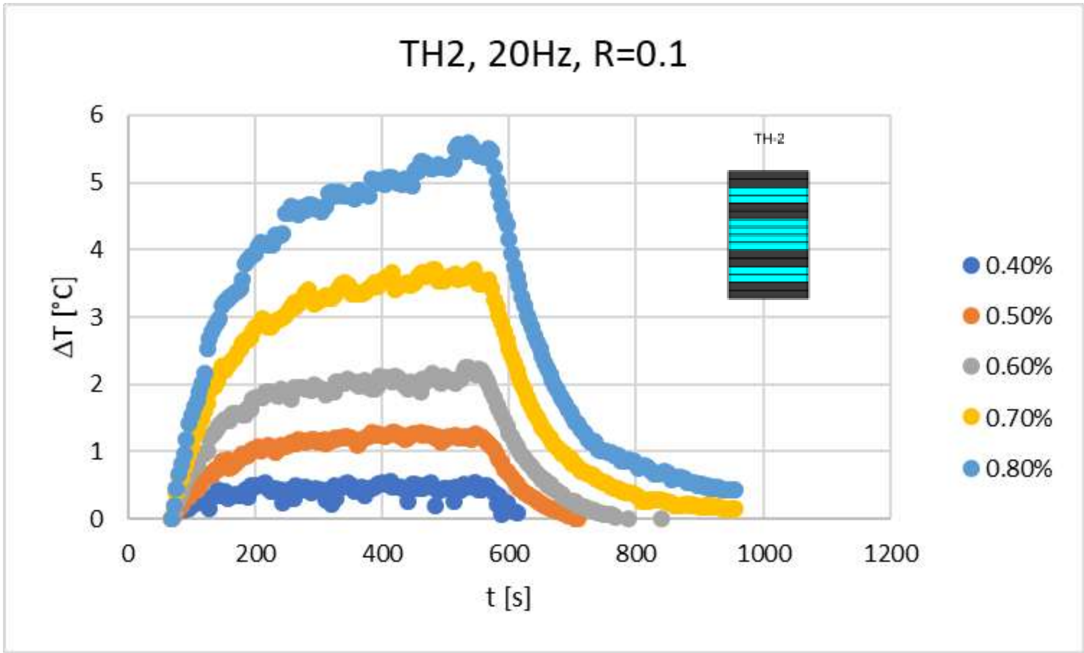
Average temperature vs time



Results: self-heating of laminates

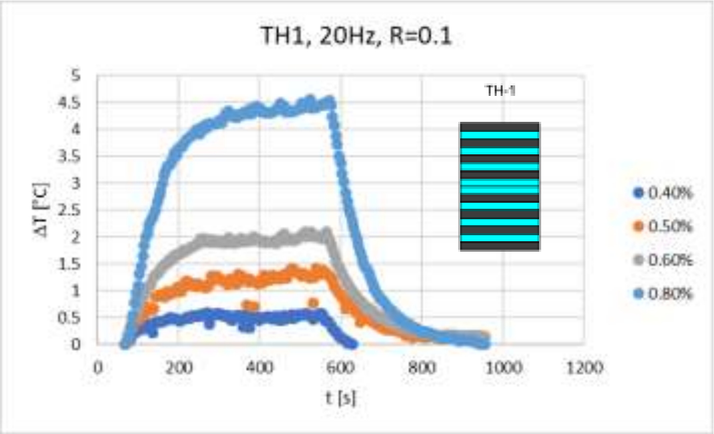
- Typical data: Self-heating effect in hybrid thin-ply laminates

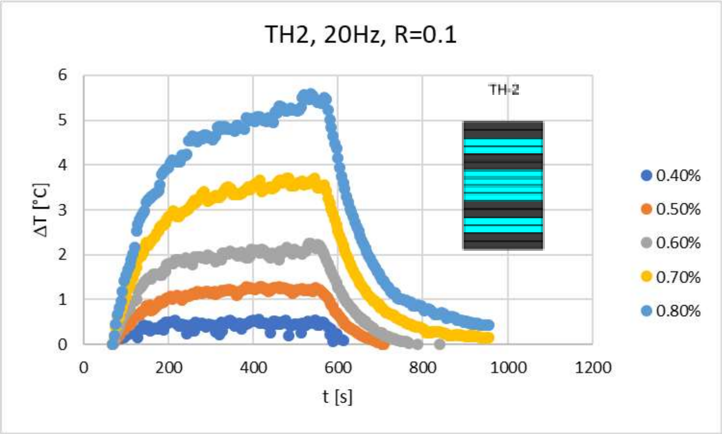


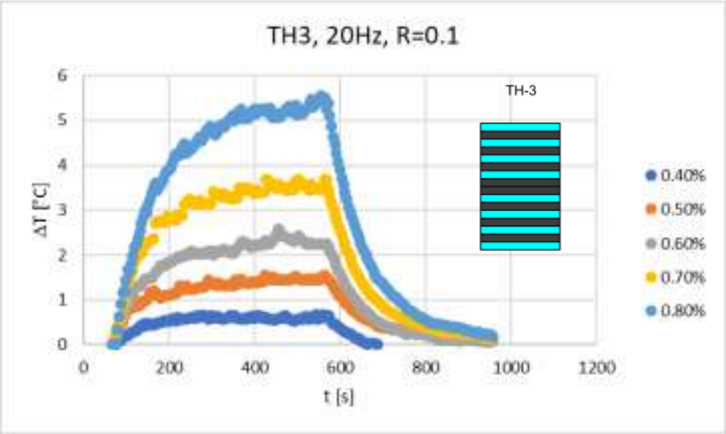


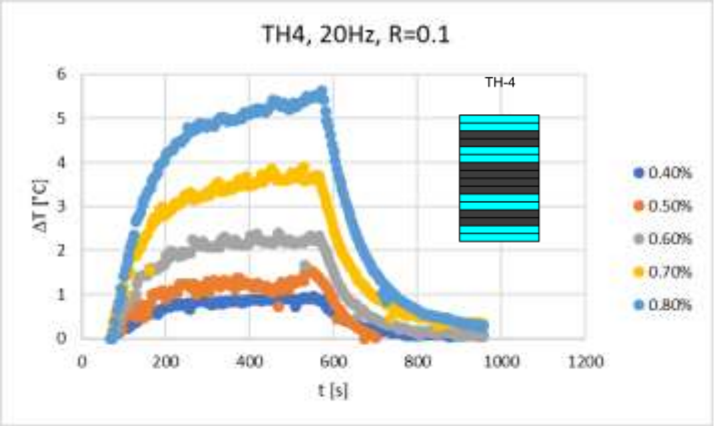
Results: self-heating of laminates

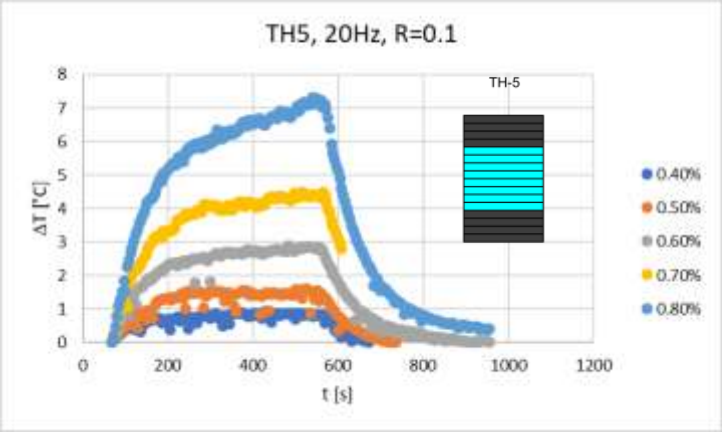
- Typical data: Self-heating effect in hybrid thin-ply laminates, 20Hz, R=0.1

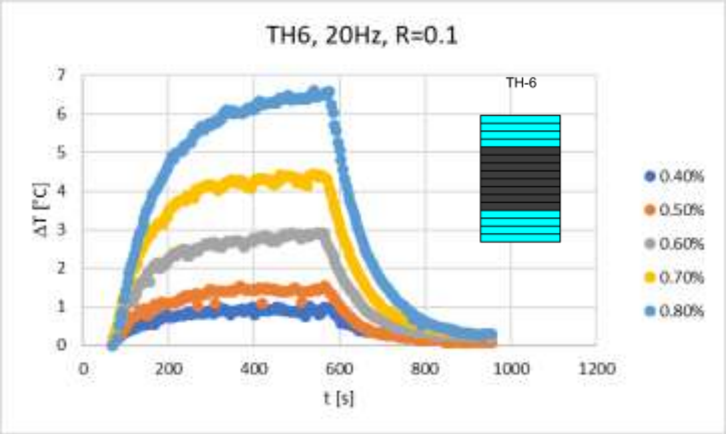






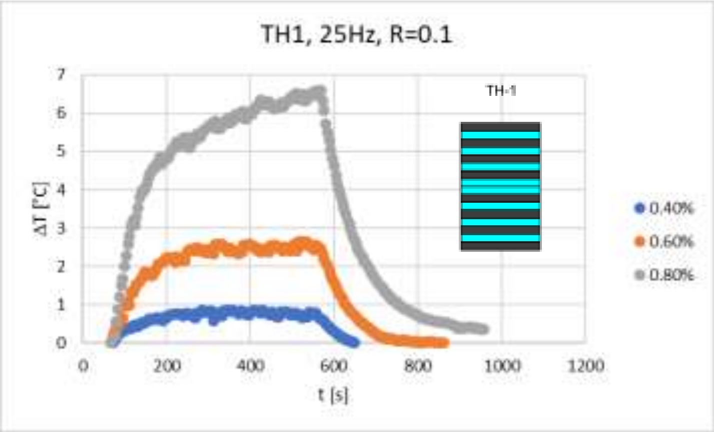


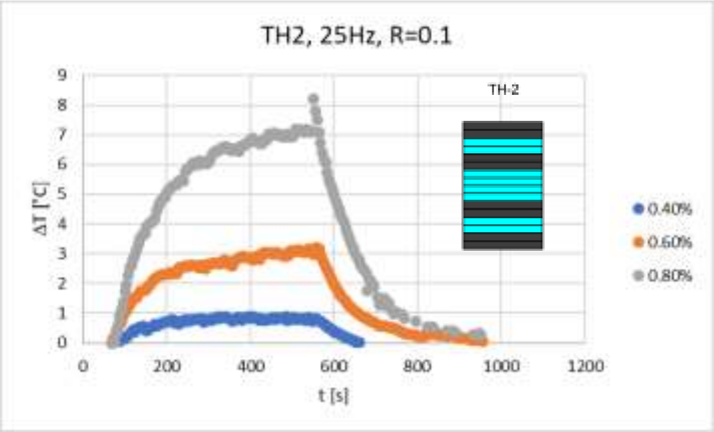


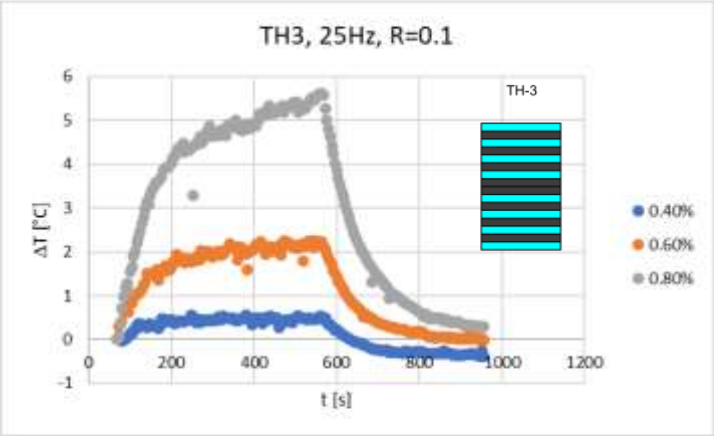


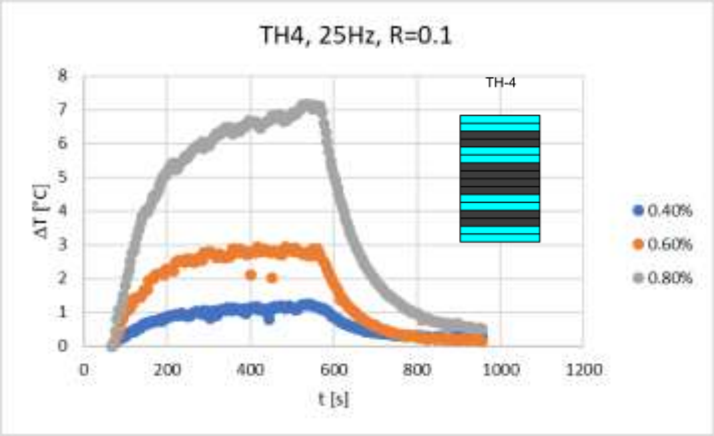
Results: self-heating of laminates

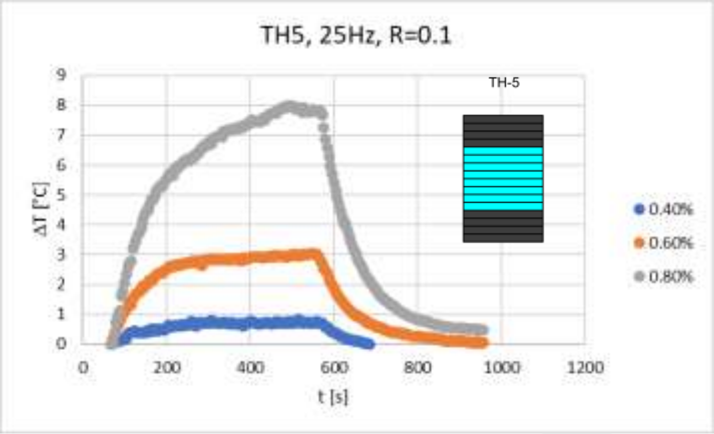
- Typical data: Self-heating effect in hybrid thin-ply laminates, 25Hz, R=0.1

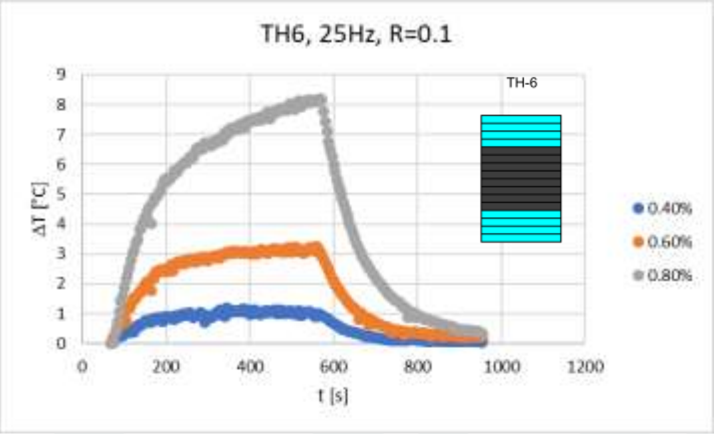






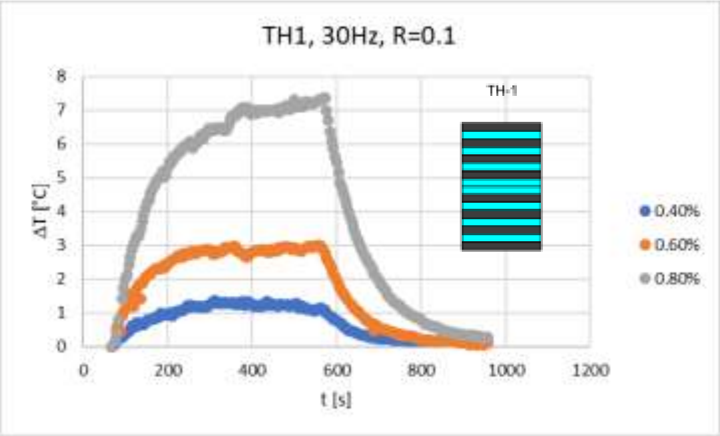


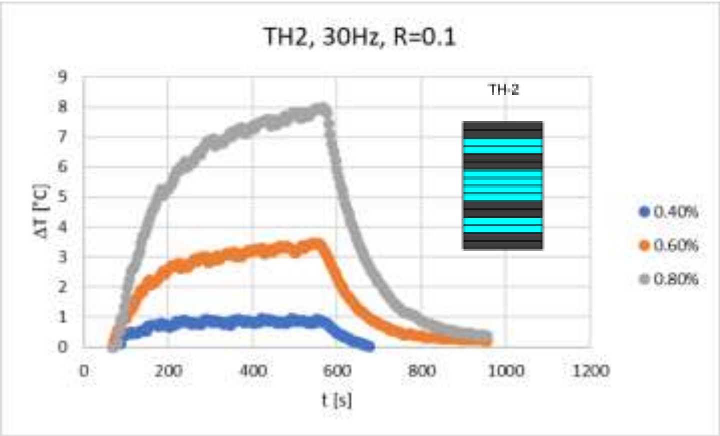


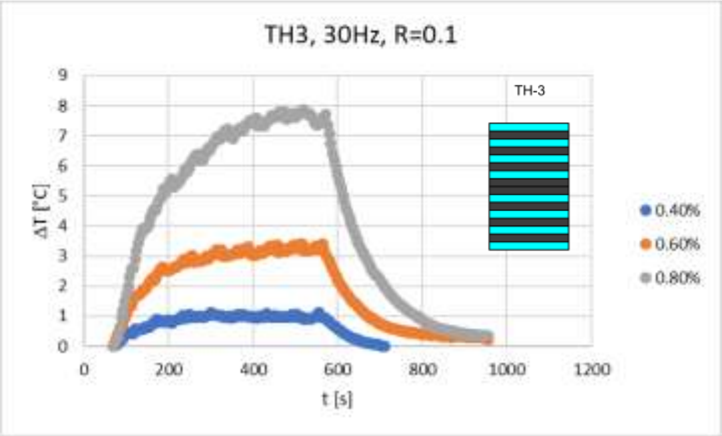


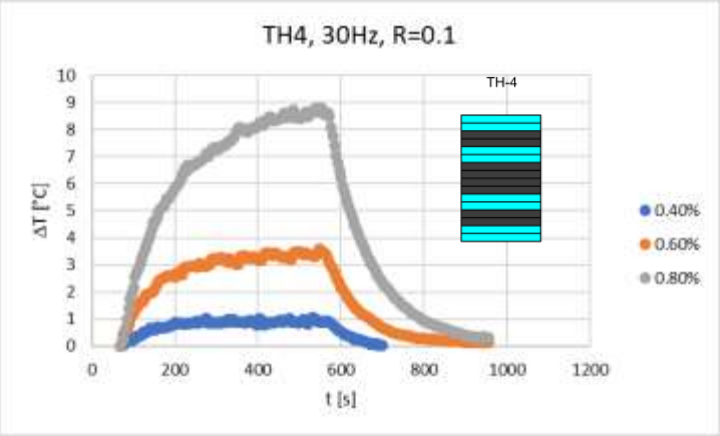
Results: self-heating of laminates

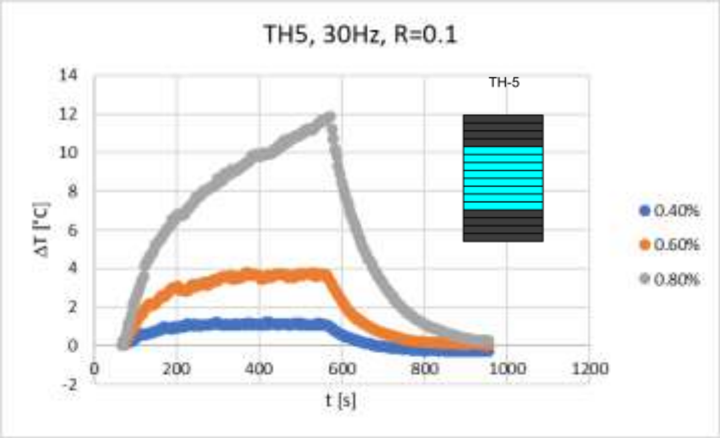
- Typical data: Self-heating effect in hybrid thin-ply laminates, 30Hz, R=0.1

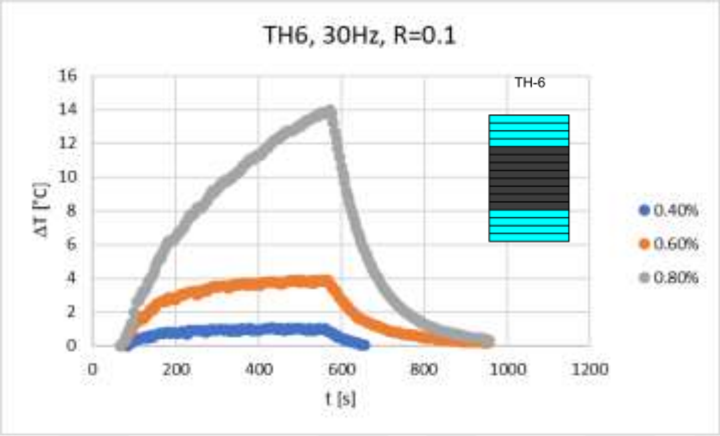






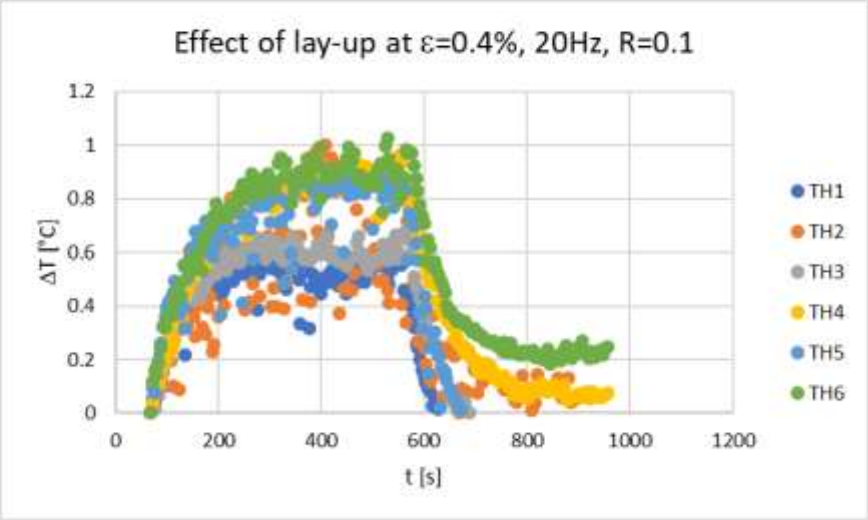


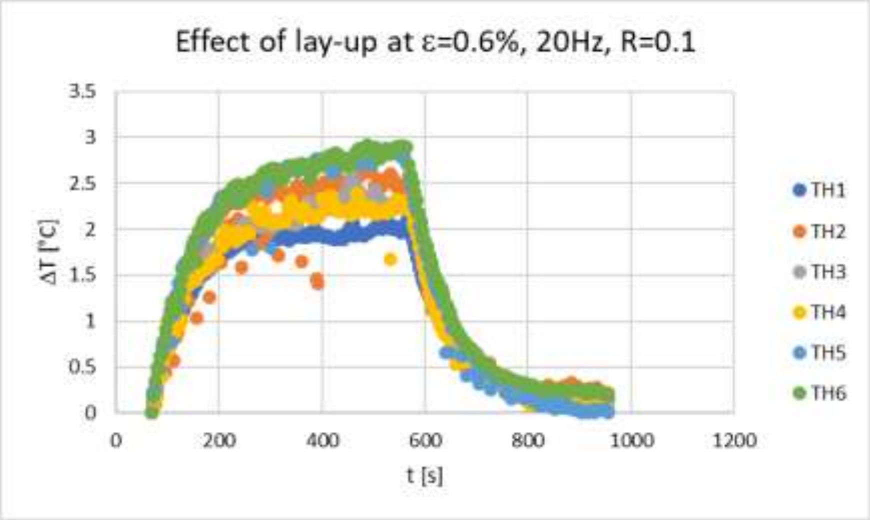


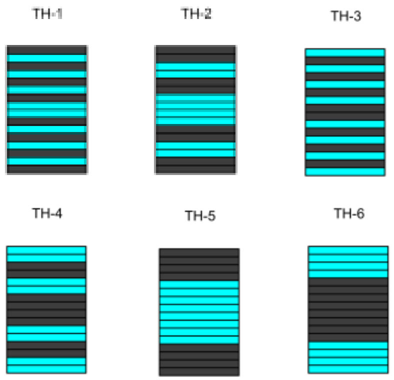


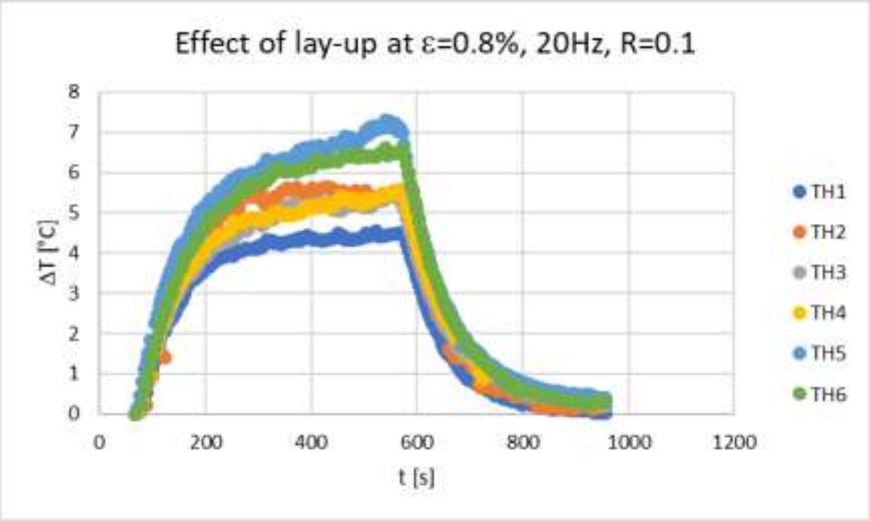
Effect of laminate lay-up

- Laminates with different lay-ups subjected to identical loading conditions, 20Hz



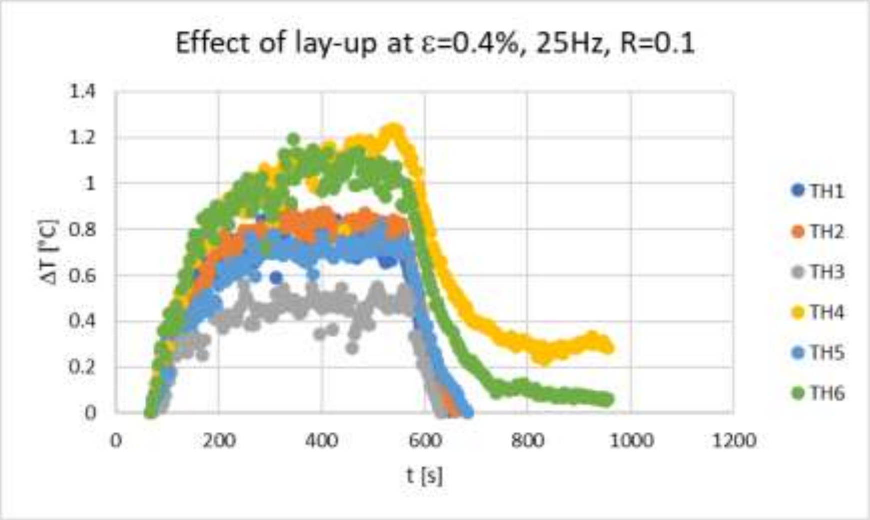


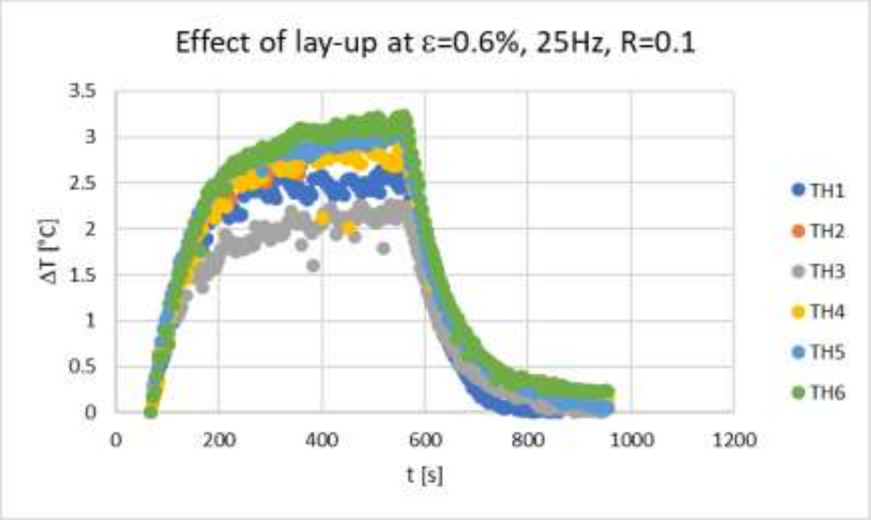


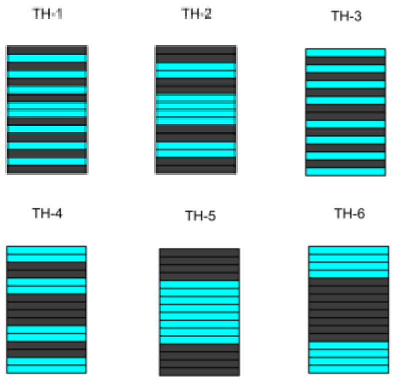


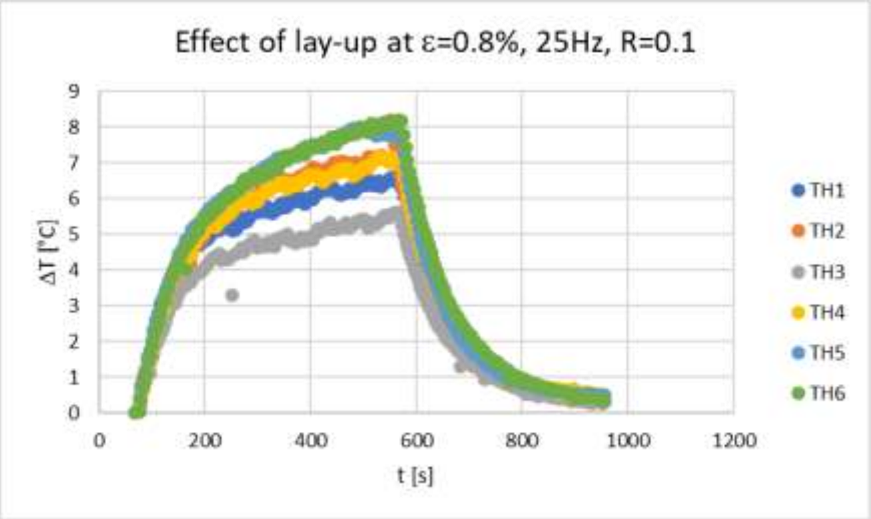
Effect of laminate lay-up

- Laminates with different lay-ups subjected to identical loading conditions, 25Hz



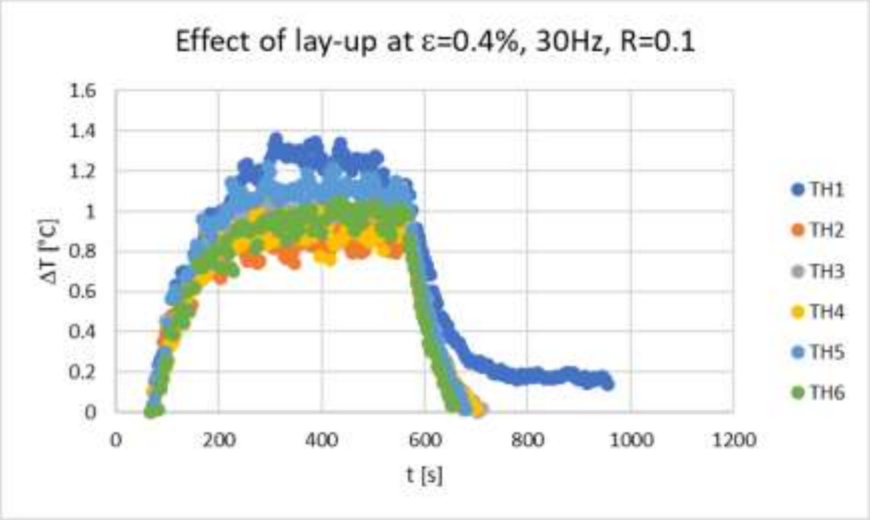


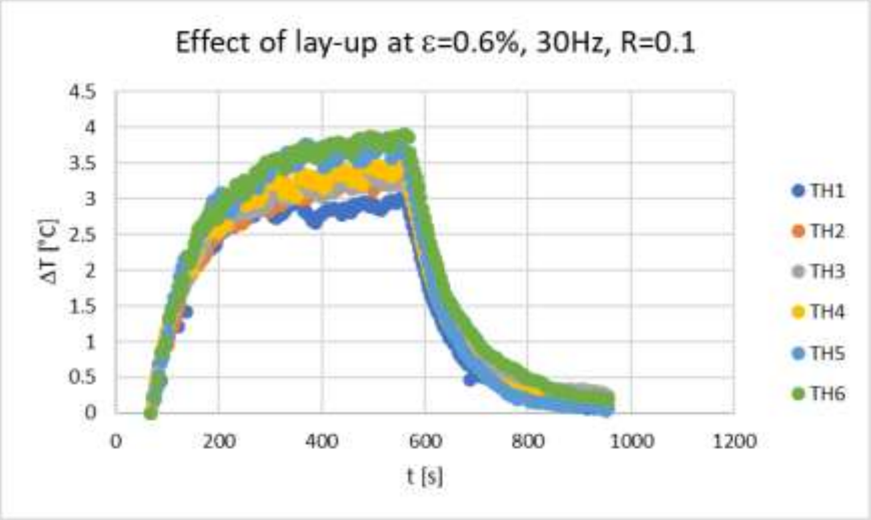


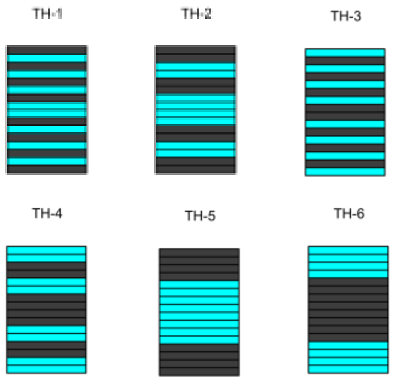


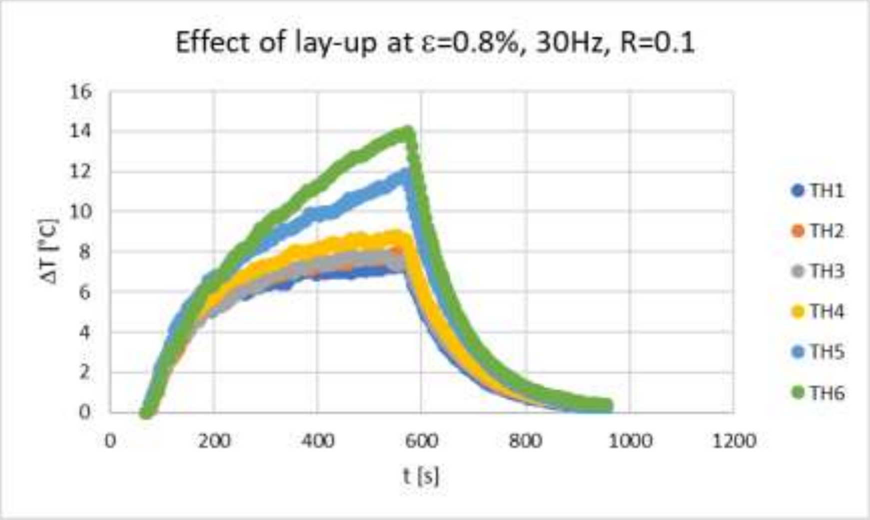
Effect of laminate lay-up

- Laminates with different lay-ups subjected to identical loading conditions, 30Hz



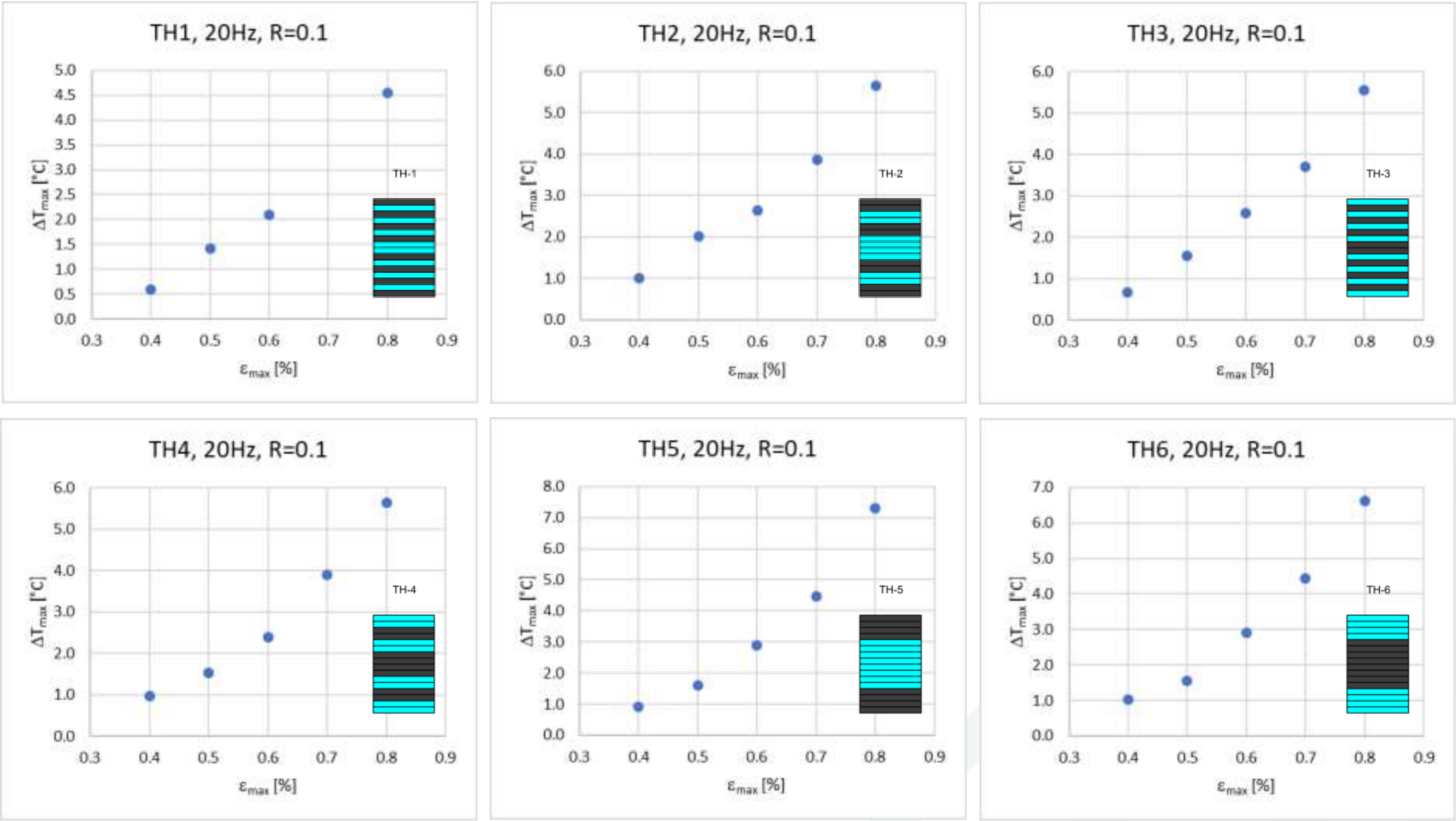






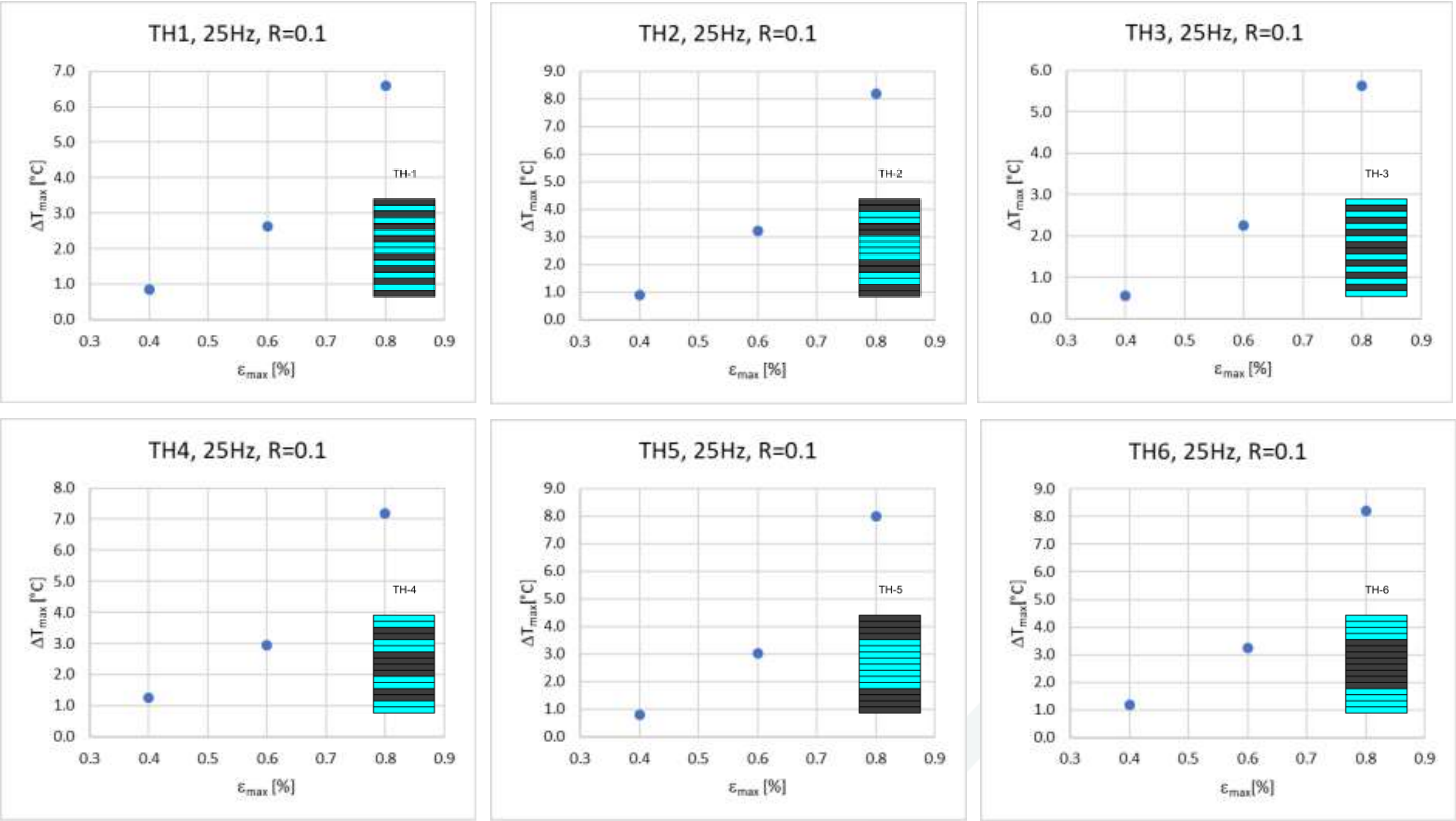
Results: effect of strain level

- Maximum temperature increase ΔT_{max} vs maximum applied strain level ε_{max}, 20Hz



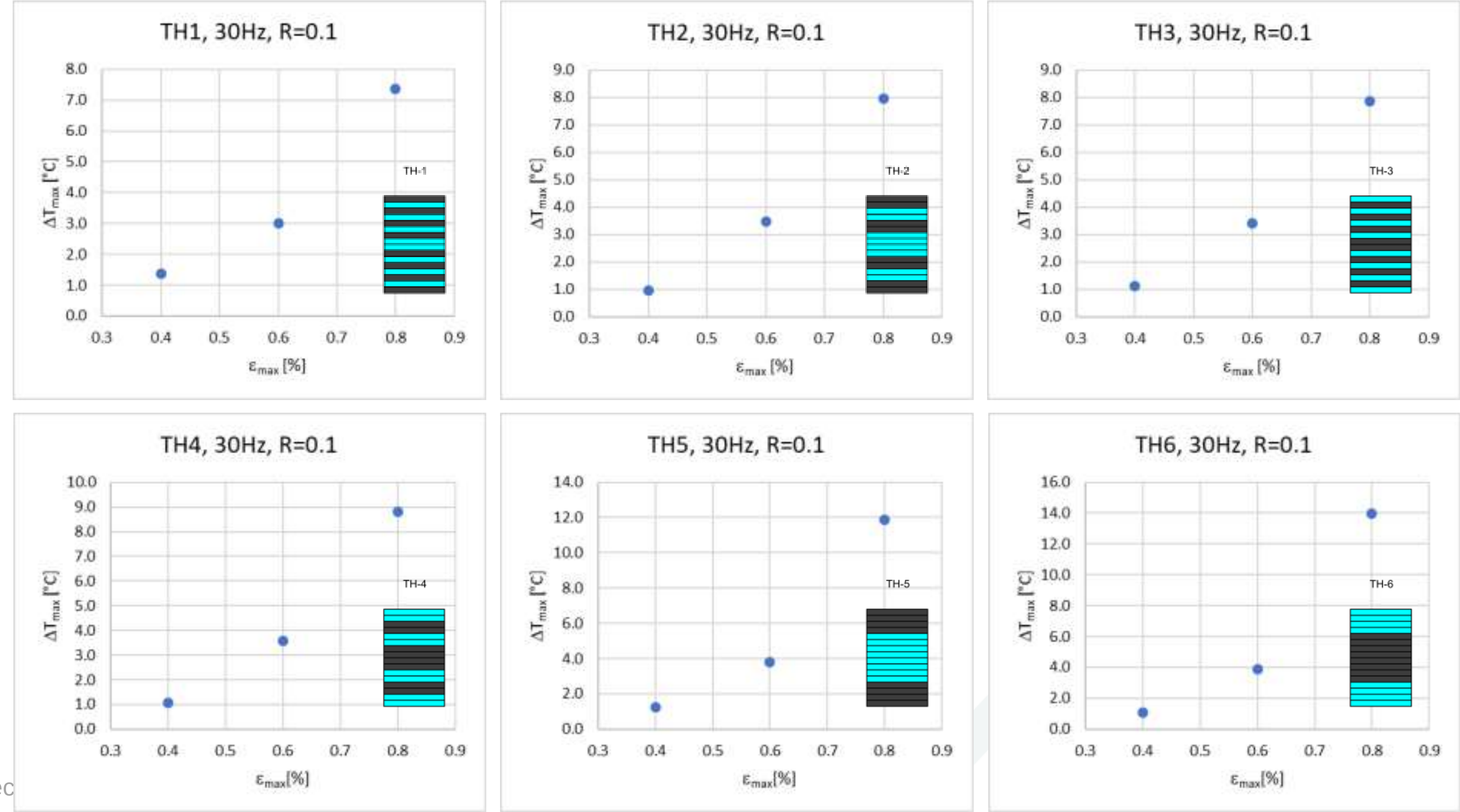
Results: effect of strain level

- Maximum temperature increase ΔT_{max} vs maximum applied strain level ε_{max}, 25Hz



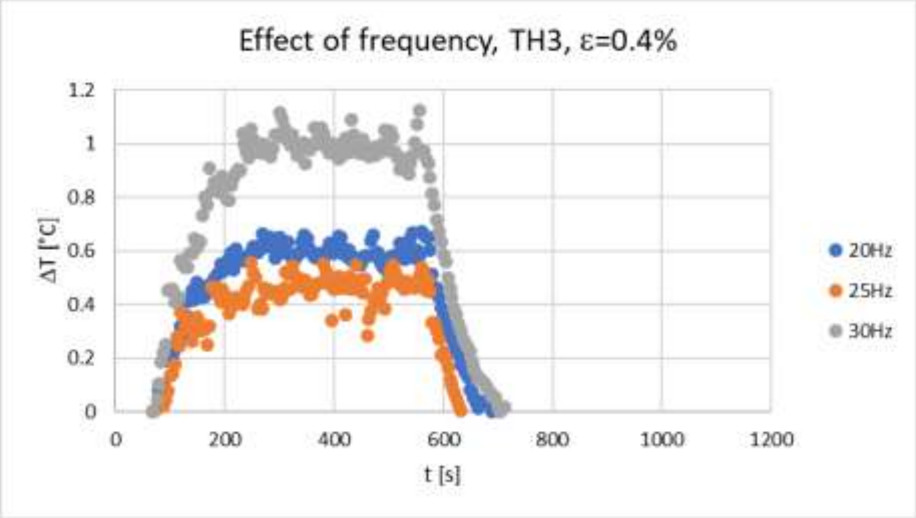
Results: effect of strain level

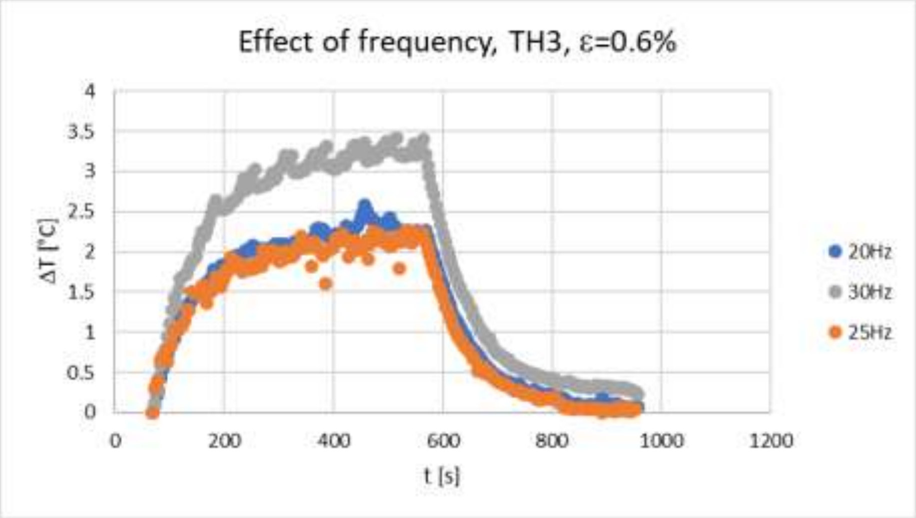
- Maximum temperature increase ΔT_{max} vs maximum applied strain level ε_{max}, 30Hz



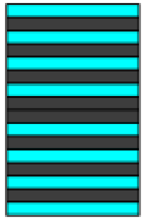
Results: effect of loading frequency

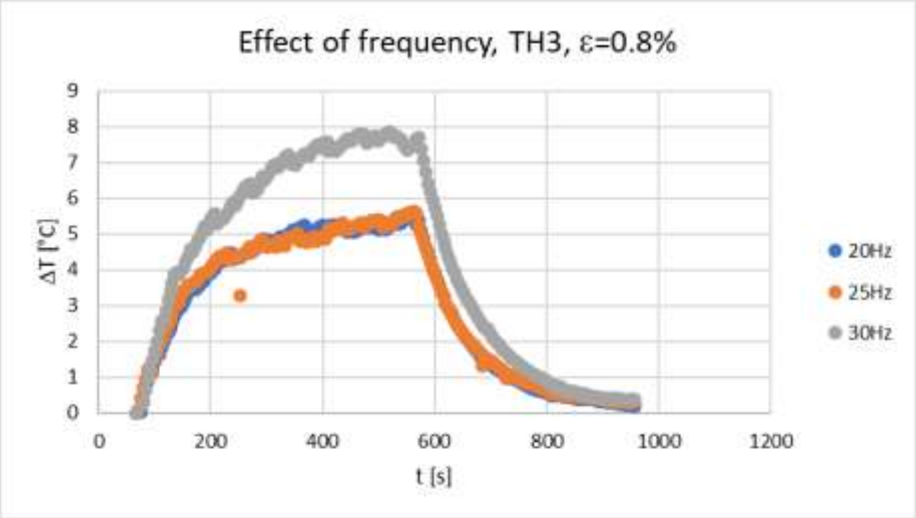
- Laminates subjected to loading with frequency 20Hz, 25Hz, 30Hz





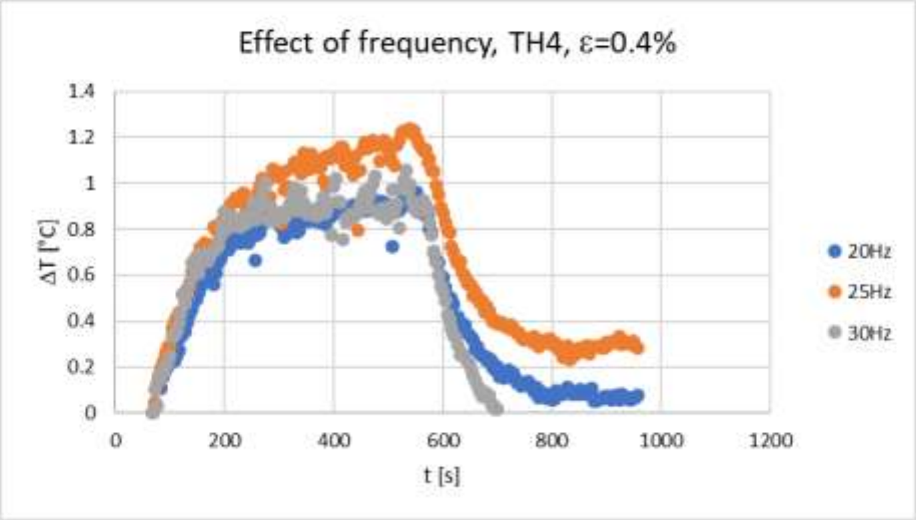
TH-3

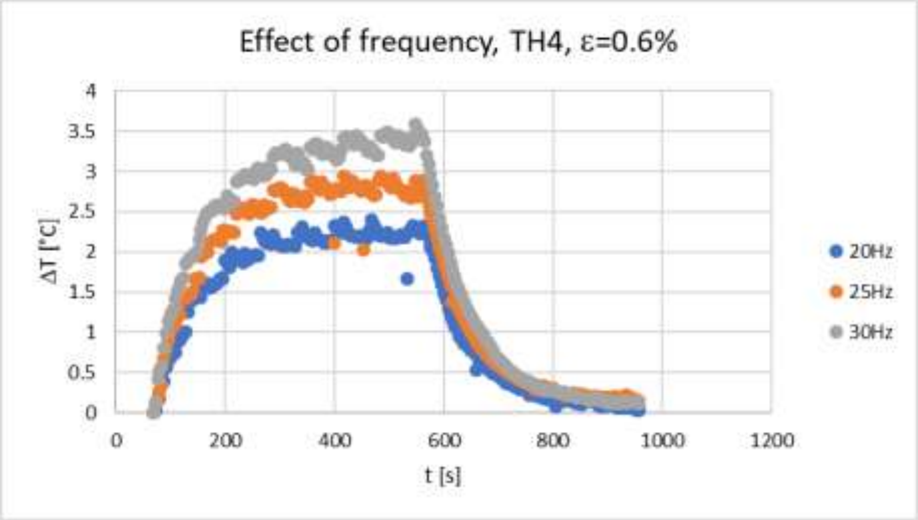


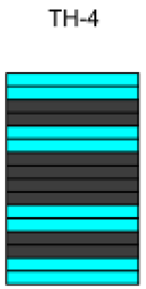


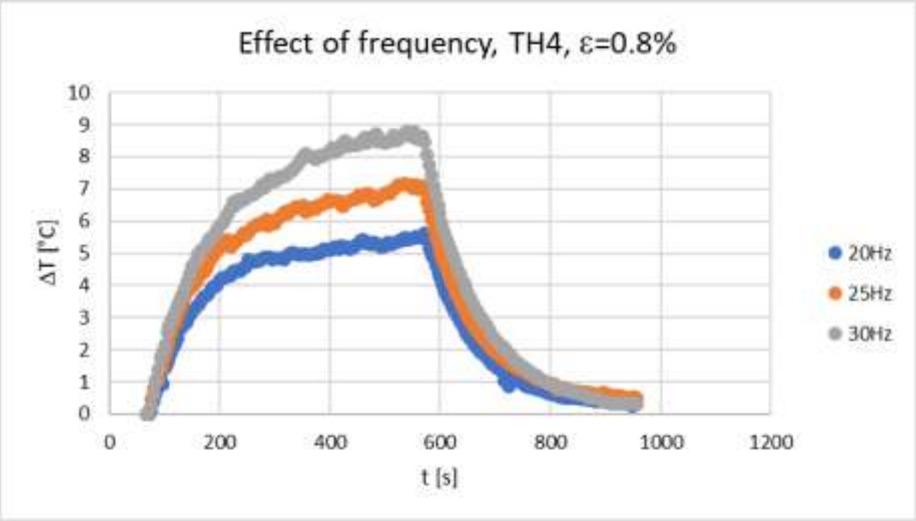
Results: effect of loading frequency

- Laminates subjected to loading with frequency 20Hz, 25Hz, 30Hz



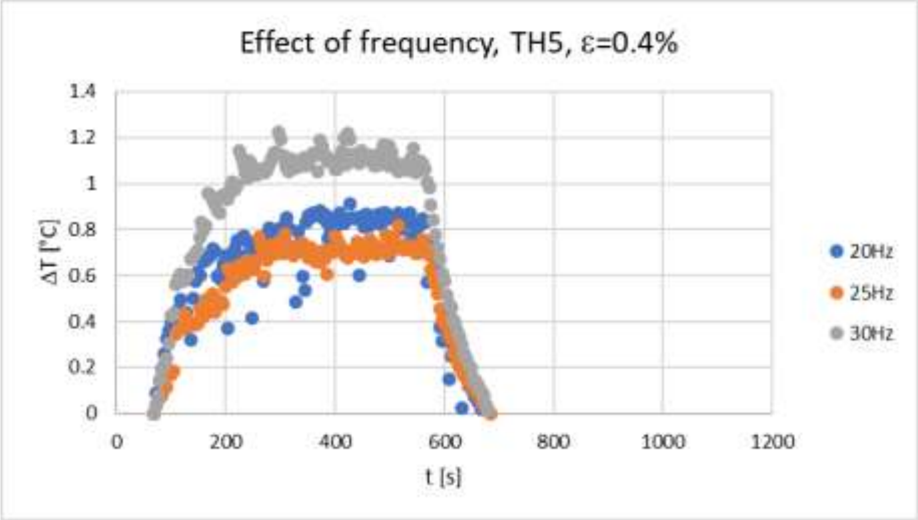


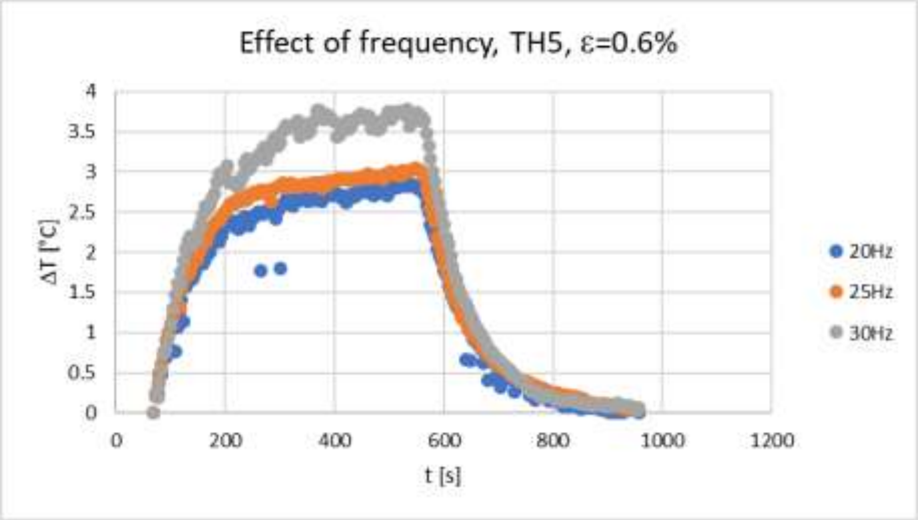


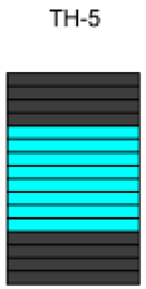


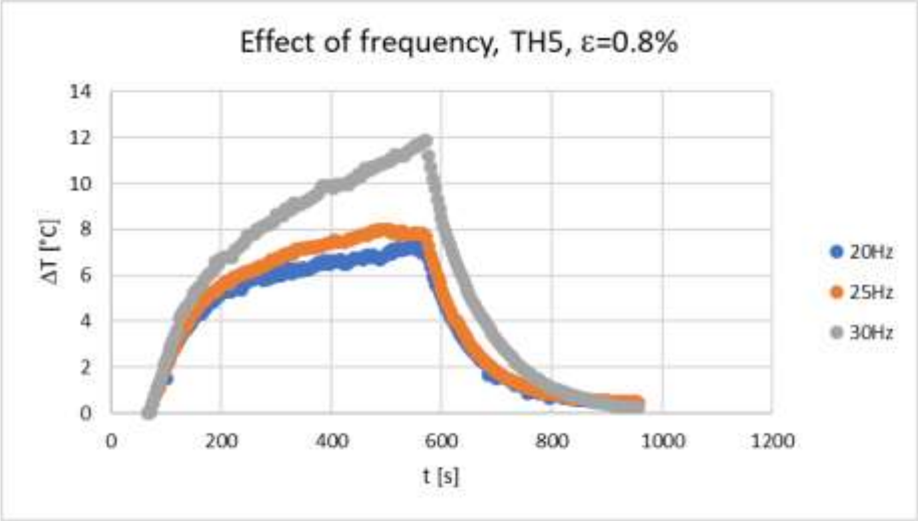
Results: effect of loading frequency

- Laminates subjected to loading with frequency 20Hz, 25Hz, 30Hz



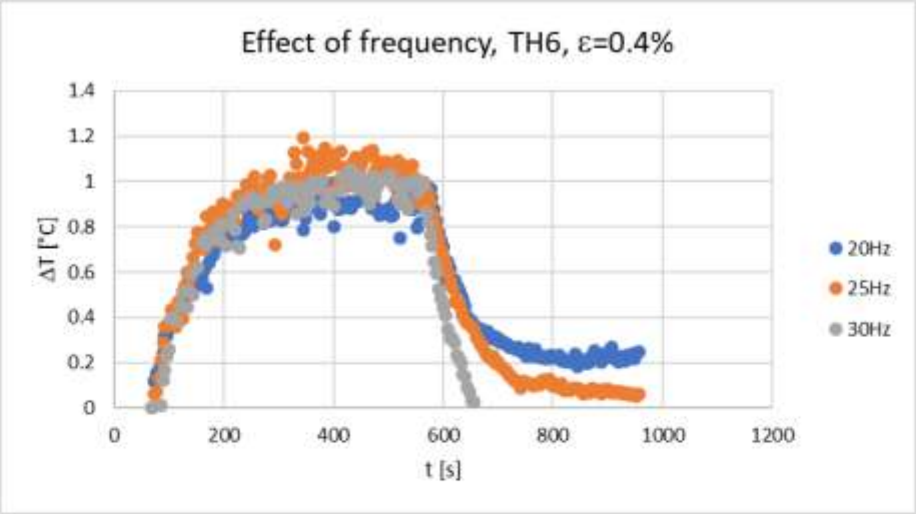


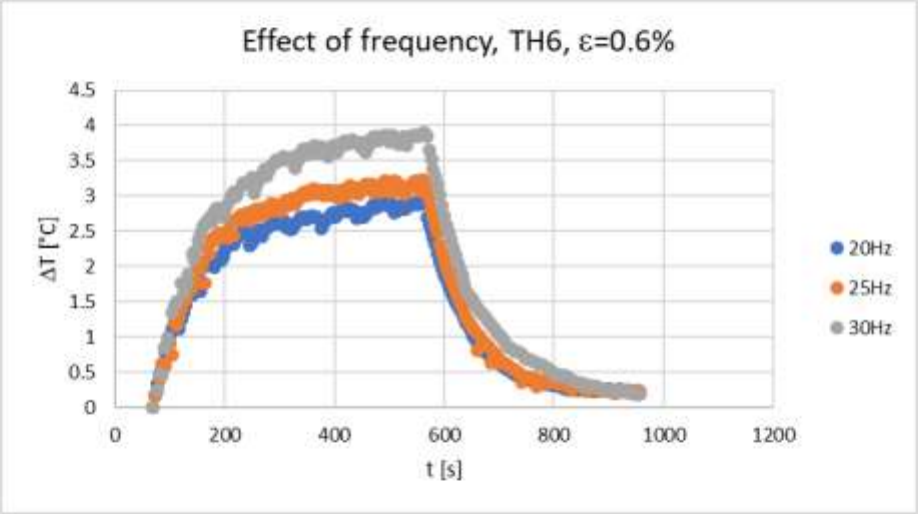


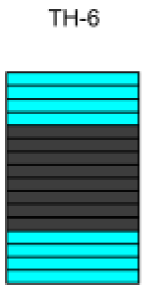


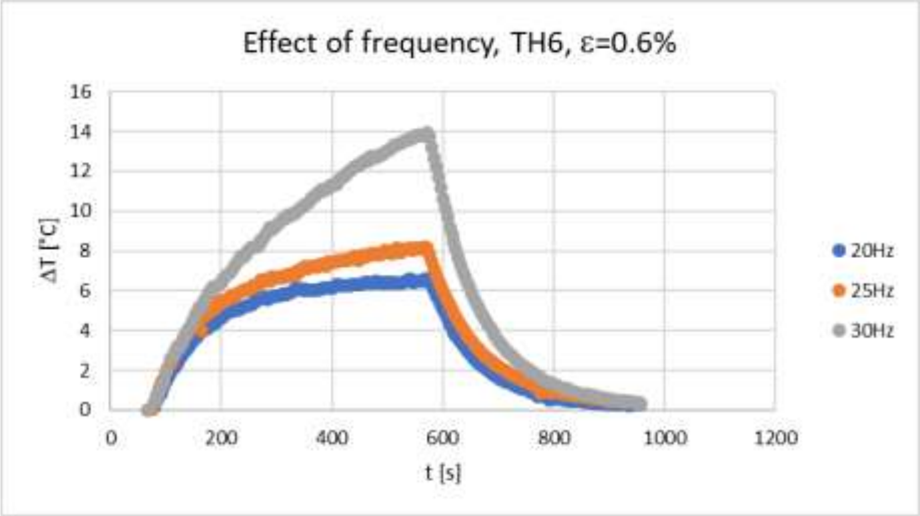
Results: effect of loading frequency

- Laminates subjected to loading with frequency 20Hz, 25Hz, 30Hz



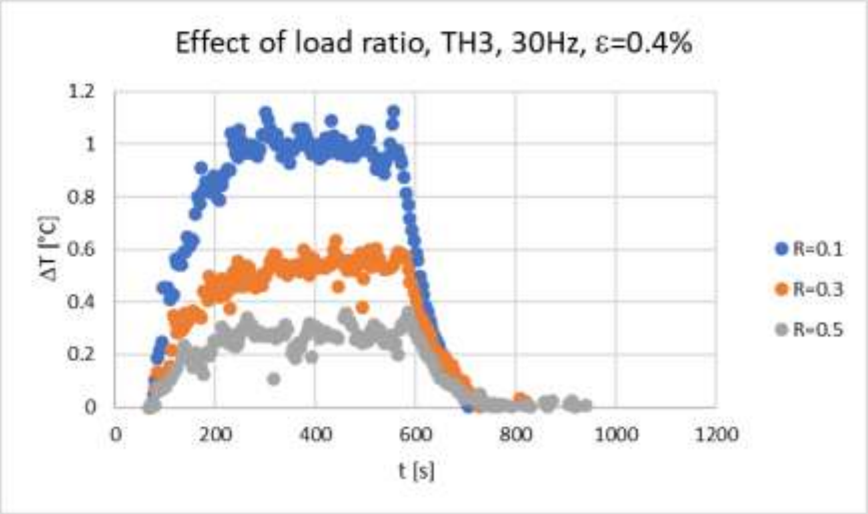


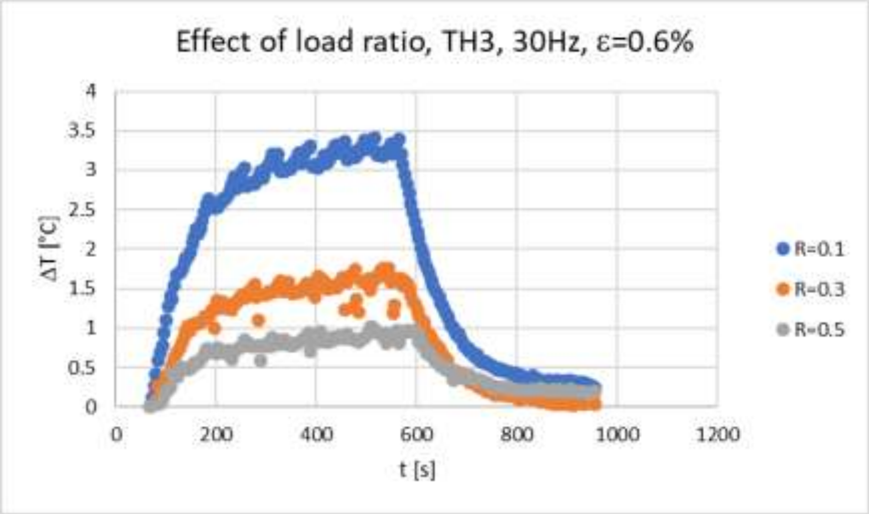




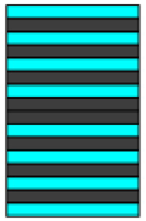
Results: effect of load ratio

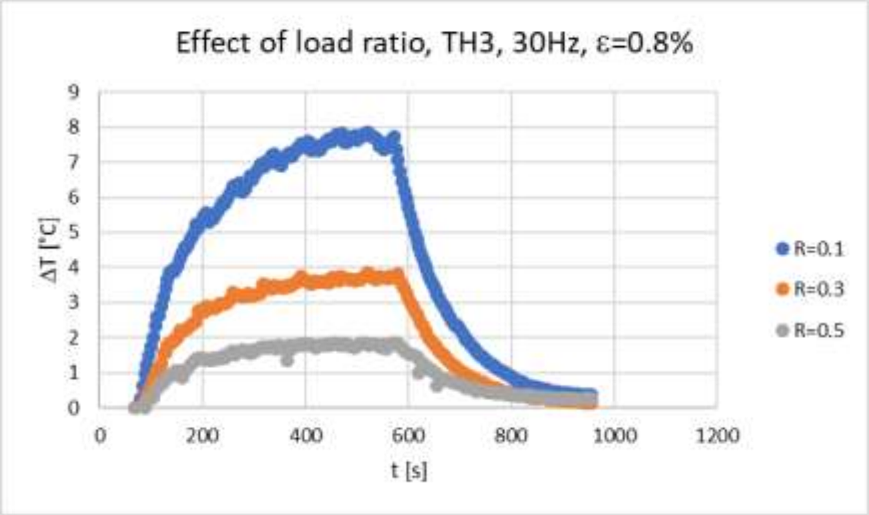
- Self-heating of laminates loaded with ratio $R = \varepsilon_{min}/\varepsilon_{max} = 0.1, 0.3, 0.5$





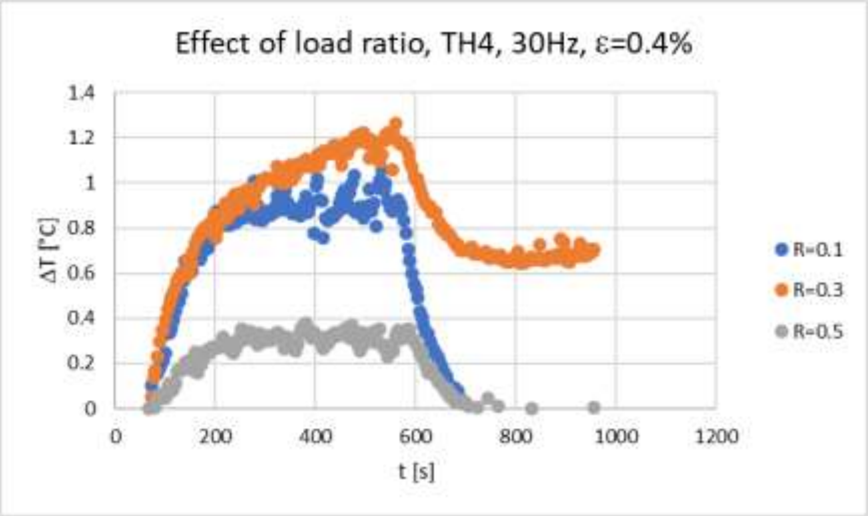
TH-3

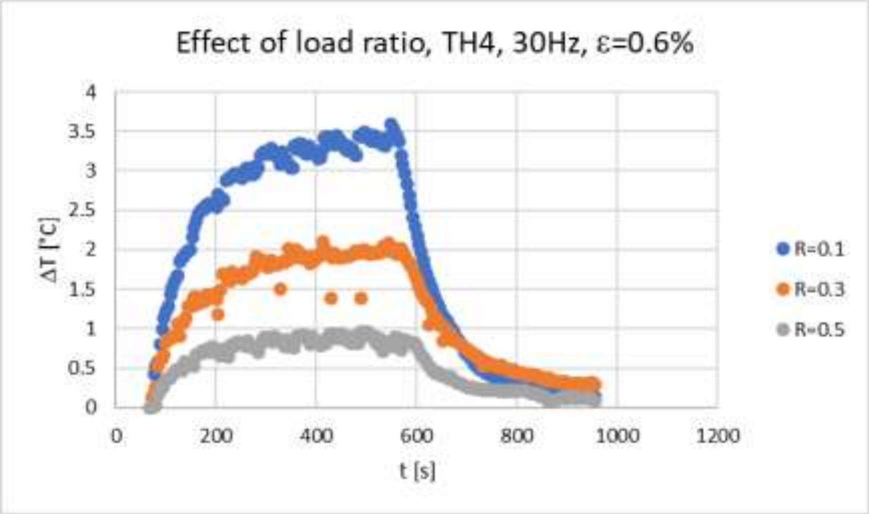




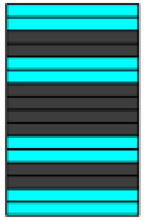
Results: effect of load ratio

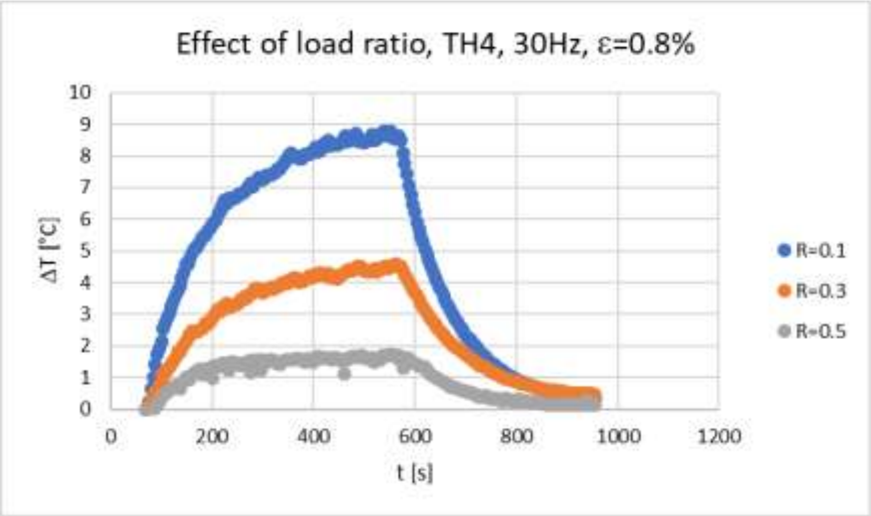
- Self-heating of laminates loaded with ratio $R = \varepsilon_{min}/\varepsilon_{max} = 0.1, 0.3, 0.5$





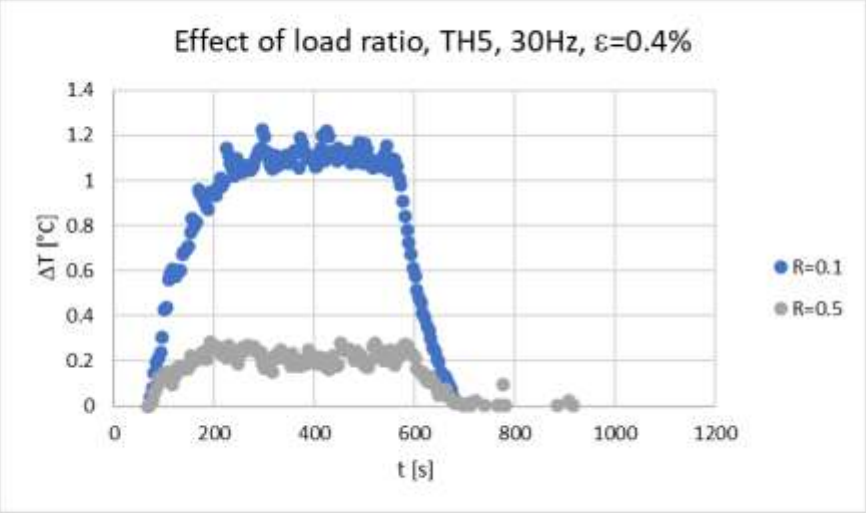
TH-4

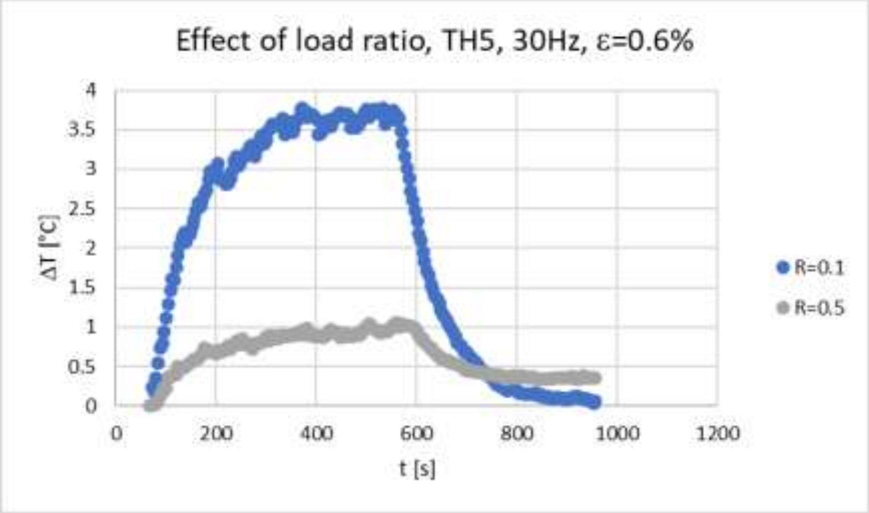


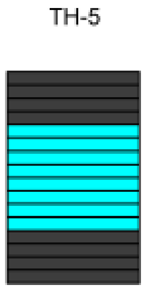


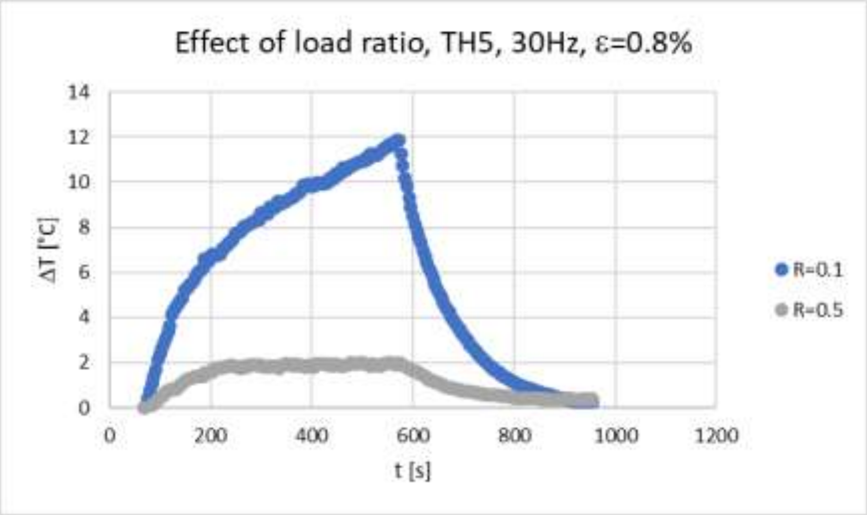
Results: effect of load ratio

- Self-heating of laminates loaded with ratio $R = \varepsilon_{min}/\varepsilon_{max} = 0.1, 0.3, 0.5$



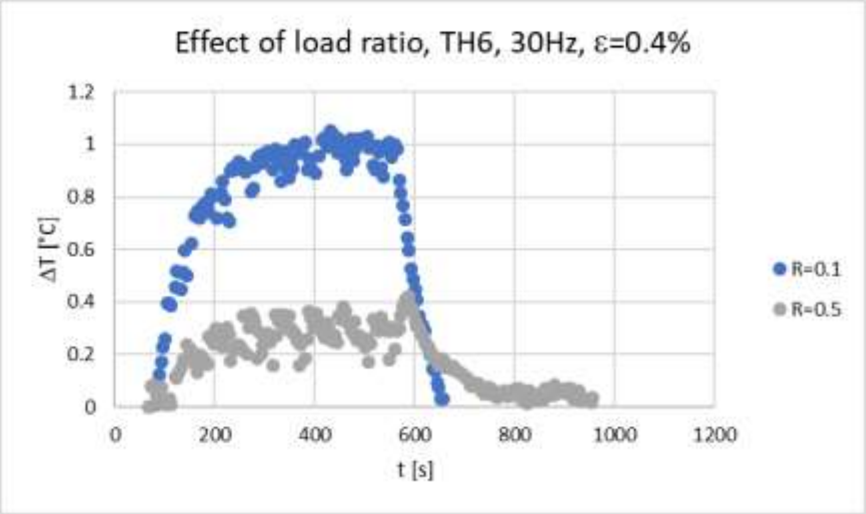


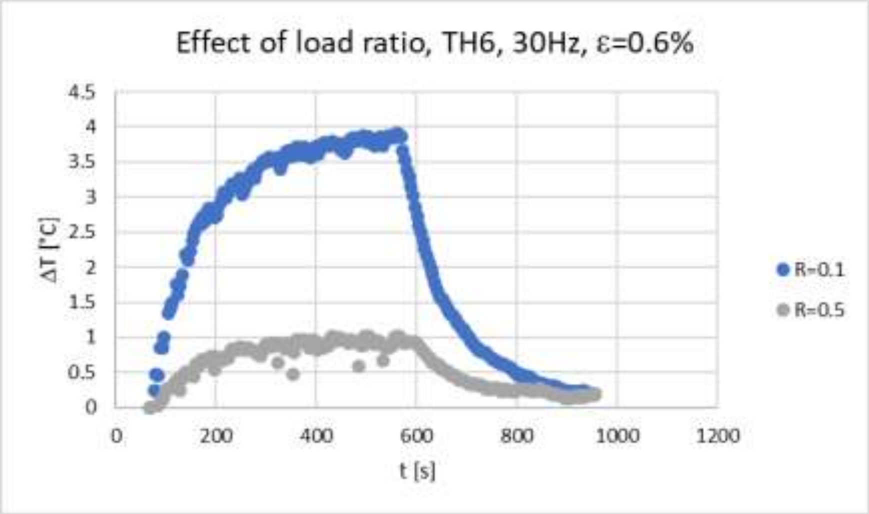


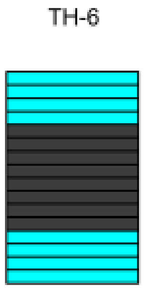


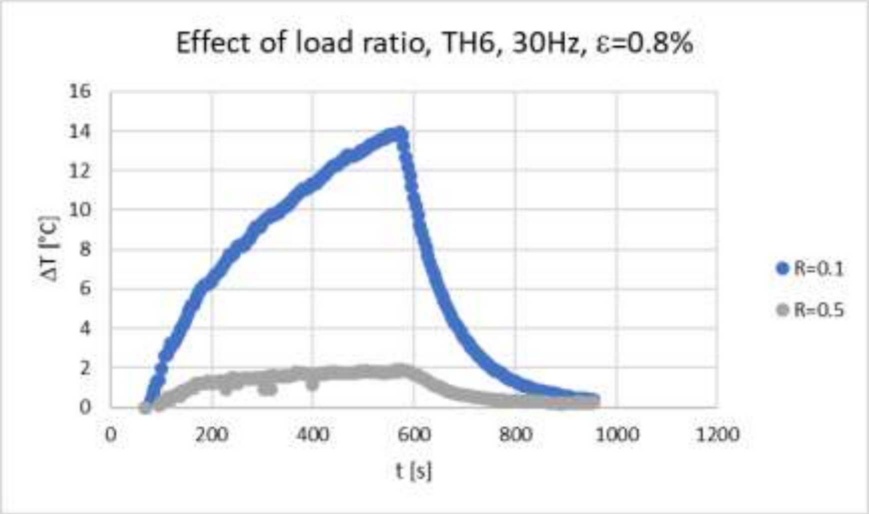
Results: effect of load ratio

- Self-heating of laminates loaded with ratio $R = \varepsilon_{min}/\varepsilon_{max} = 0.1, 0.3, 0.5$



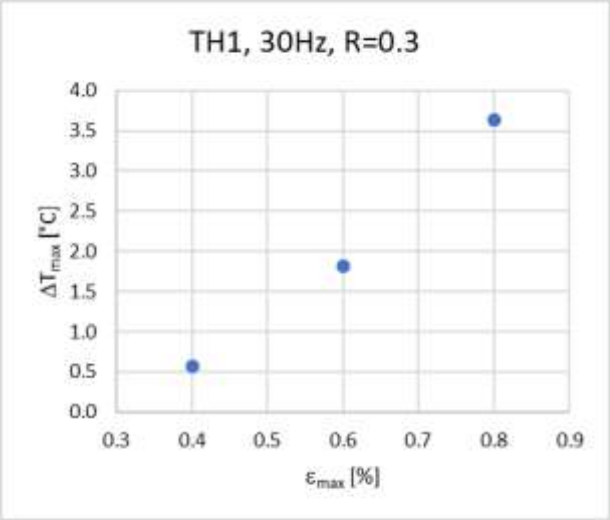


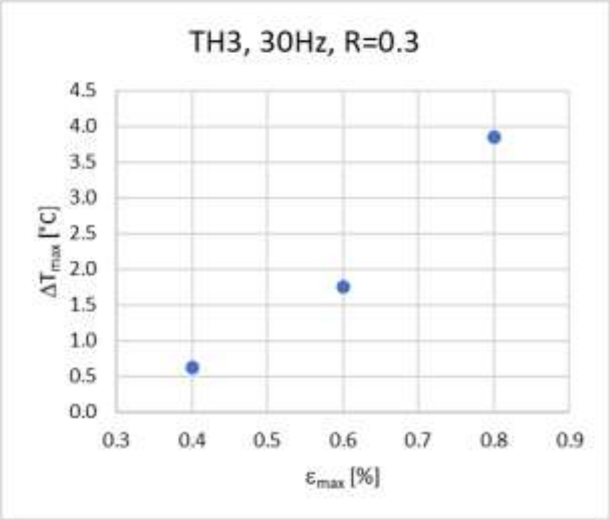


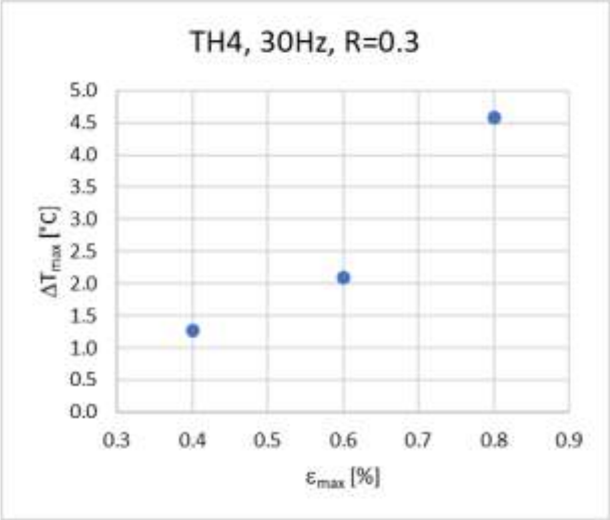


Results: effect of load ratio

- Maximum temperature increase ΔT_{max} vs maximum applied strain level ε_{max}, at $R = 0.3$

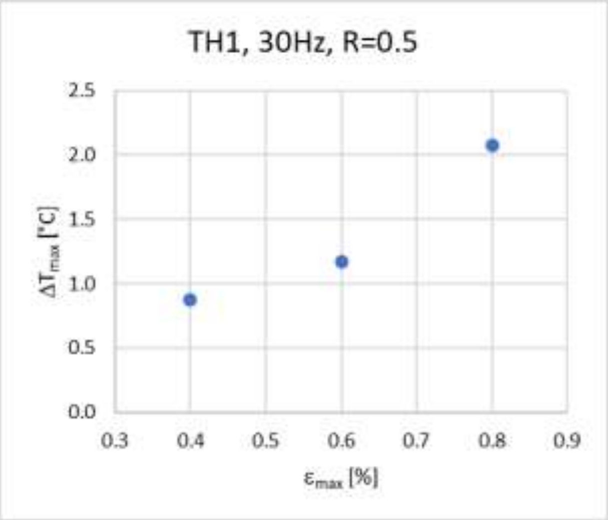


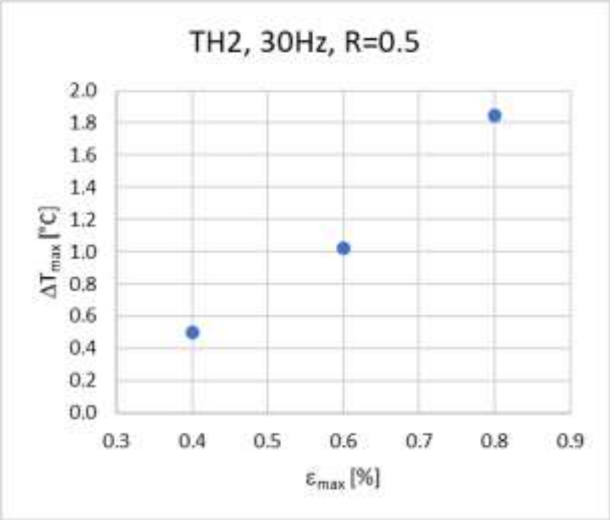


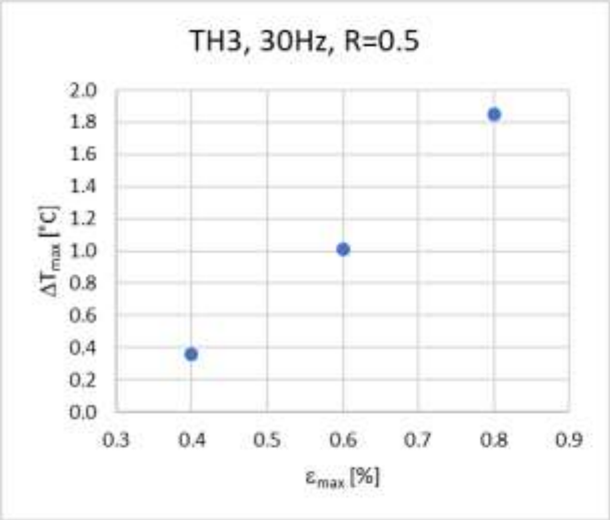


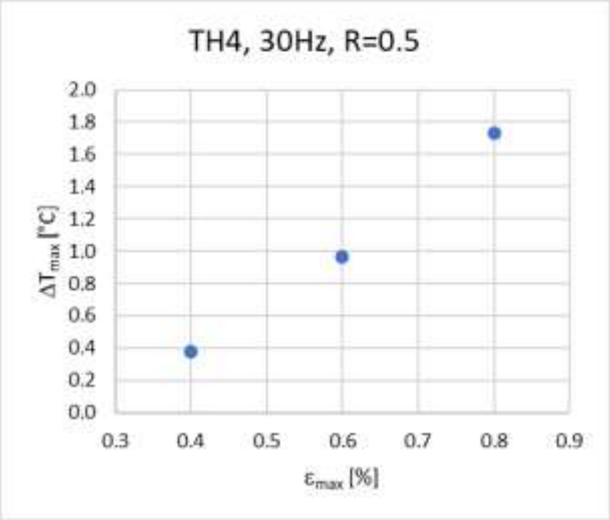
Results: effect of load ratio

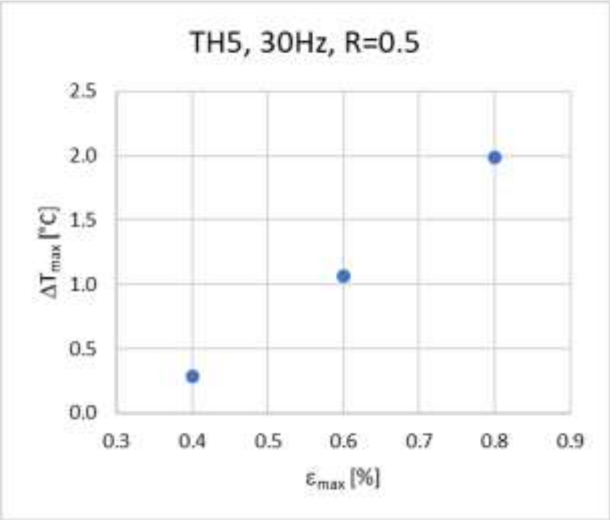
- Maximum temperature increase ΔT_{max} vs maximum applied strain level ε_{max}, at $R = 0.5$

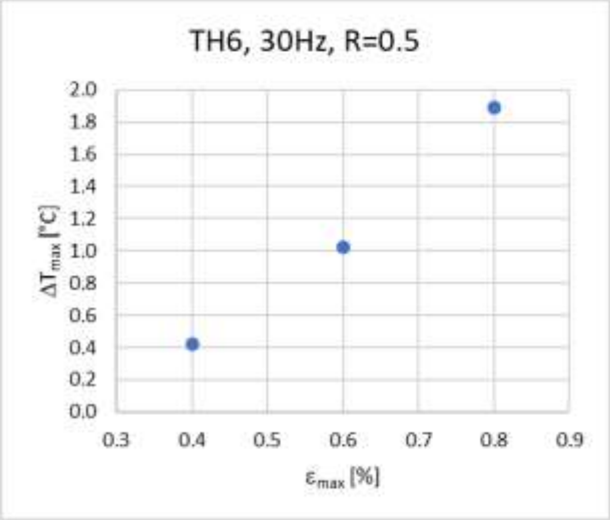












Conclusions

- Self heating of hybrid thin-ply glass/carbon composite laminates was studied experimentally.
- Proposed methodology using high resolution thermal imaging camera was able to capture detailed differences in self-heating behavior.
- As expected, visible dependency on maximum strain level, loading frequency and load ratio was found.
- Notable dependency on laminate lay-up was found – in particular laminates with thickest external glass fiber layers were found to have highest temperature increase.
- Notable deviation from linear self-heating temperature increase was found at loading frequency 30Hz at ε_{max}=0.8%, R=0.1

Future work

- Validation: comparison of self-heating behavior trends with micro-damage state in laminates.
- To quantify the material property dependency on temperature and evaluate contribution of time-dependent behavior.
- To perform analysis of temperature distribution in laminate layers.
- To develop analytical and numerical models for prediction of self-heating behavior.

Acknowledgement

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Thank you for your attention!