Study of innovative 3D-printed steel production for Structural Engineering applications

Vittoria Laghi

Yearly assessment, SEHM2 PhD program, XXXIII Cycle, Bologna

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Co-Advisors: Prof. Ing. Giada Gasparini
Dott. Ing. Michele Palermo

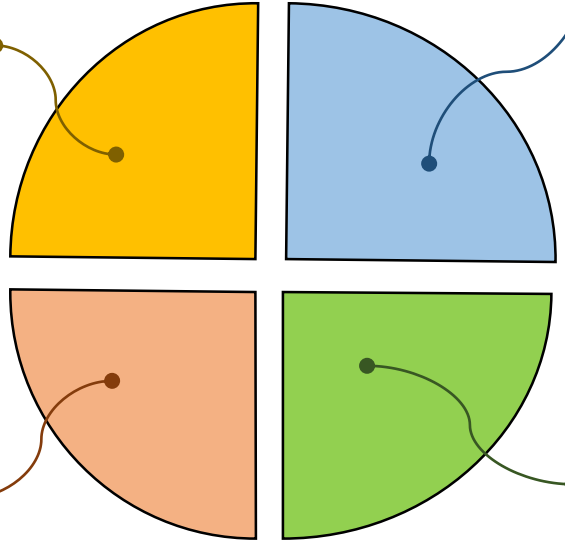
OUTLINE

- PhD proposal
- Overview of the 1st year of research
- 2nd year of research
- Outcomes of the 2nd year of research
- Further studies

PhD proposal

PART A
WAAM materials (main properties and structural behavior)

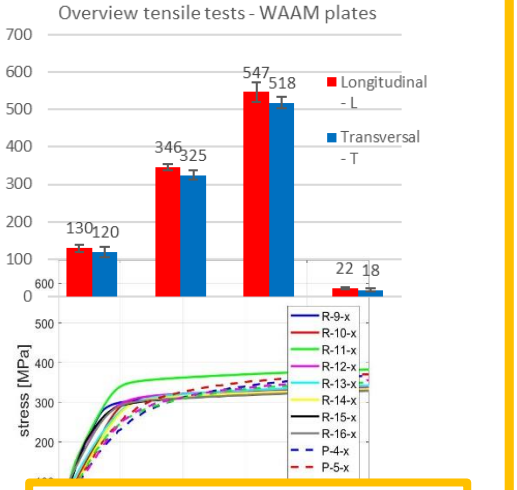
PART B
Preliminary structural design of WAAM elements



PART C
Numerical models of WAAM elements

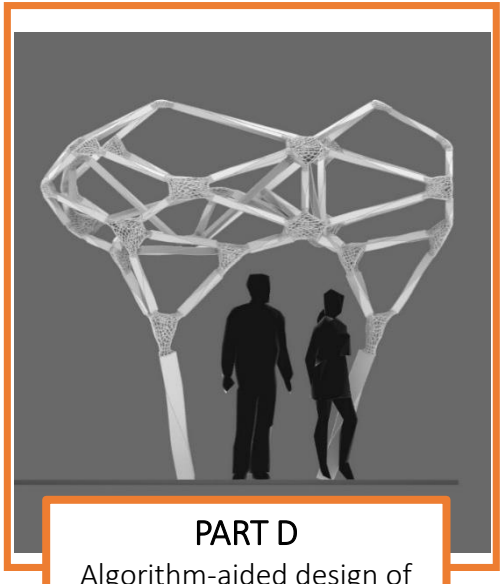
PART D
Algorithm-aided design of WAAM structures

PhD proposal



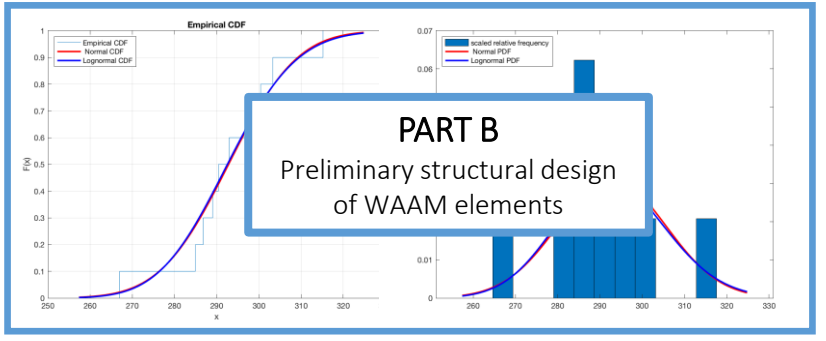
PART A

WAAM materials (main properties and structural behavior)



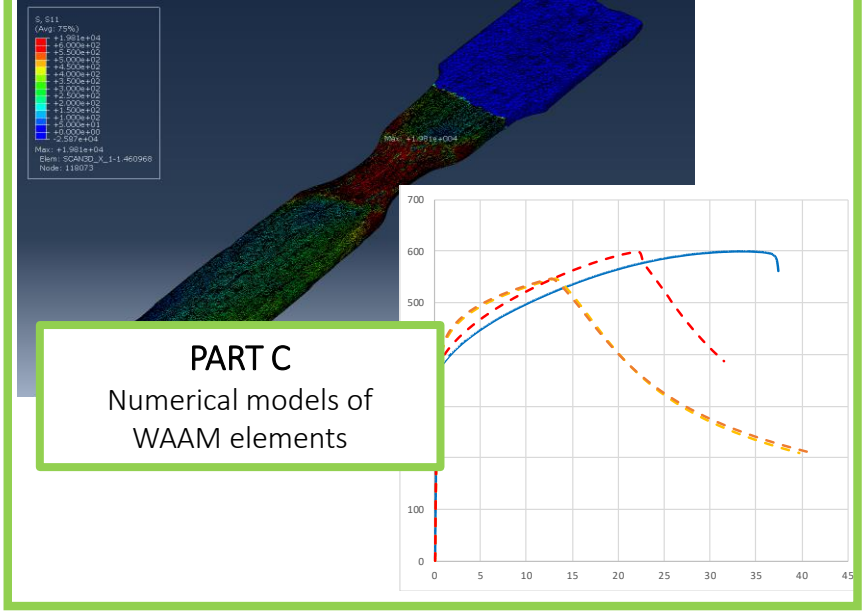
PART D

Algorithm-aided design of WAAM structures



PART B

Preliminary structural design of WAAM elements

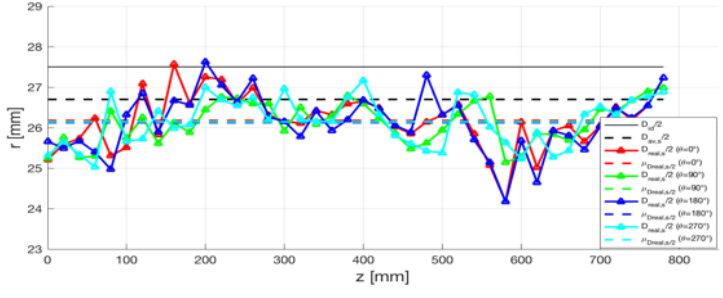


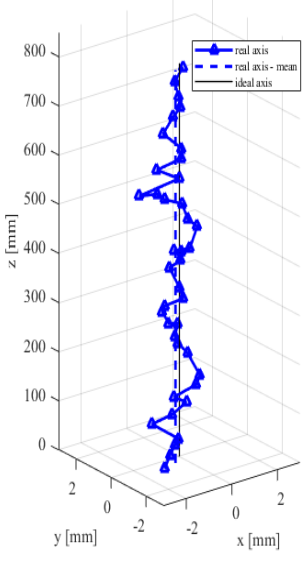
PART C

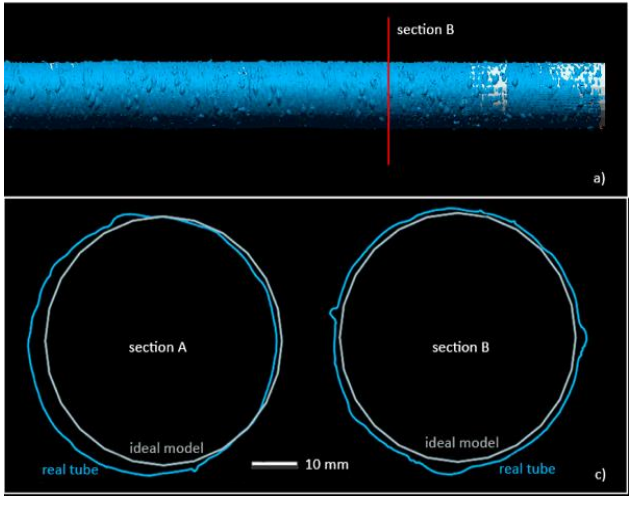
Numerical models of WAAM elements

1st year of research

- **Geometrical characterization** of WAAM 308LSi stainless steel elements
  - Evaluation of the geometrical discrepancy between digital model and real printed outcome (manual measurements, volume-based measurements, 3D scan acquisition)

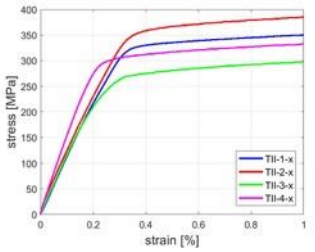


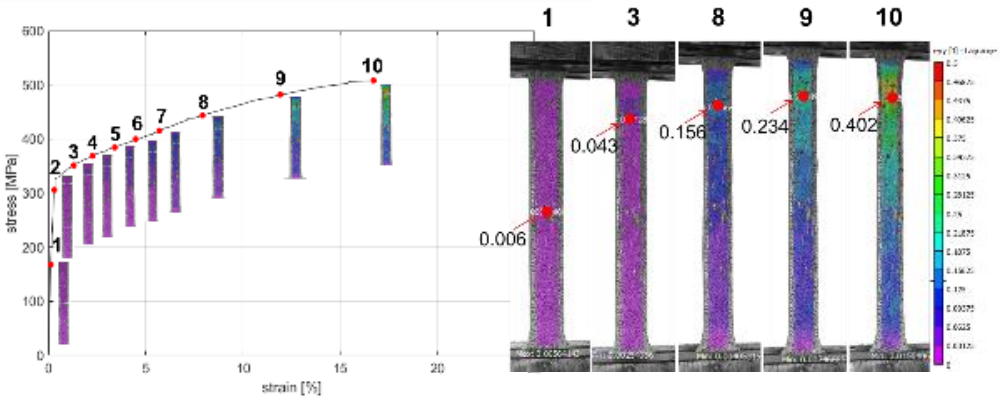




1st year of research

- **Mechanical characterization** of WAAM 308LSi stainless steel elements
  - Evaluation of the mechanical response of WAAM planar and tubular elements tested under tension, compression and buckling





1st year outcomes

- **Geometrical characterization**: the current 3D-printing process requires specific geometric factors to adapt the geometry taken from the digital model to the real outcome.

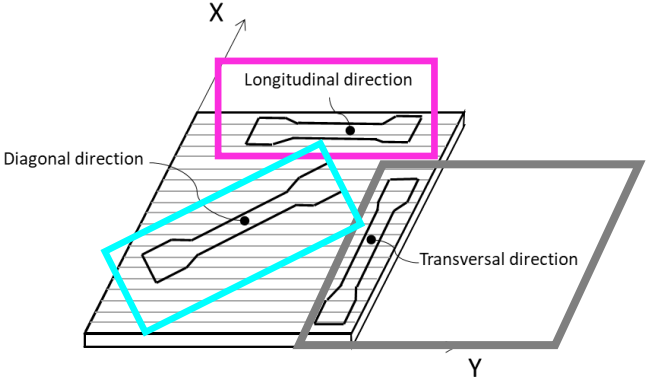
- **Mechanical characterization**: the 3D-printed stainless steel presents in general different characteristics with respect to the traditionally-manufactured one (half value of elastic modulus E, higher yielding point and higher ductility)

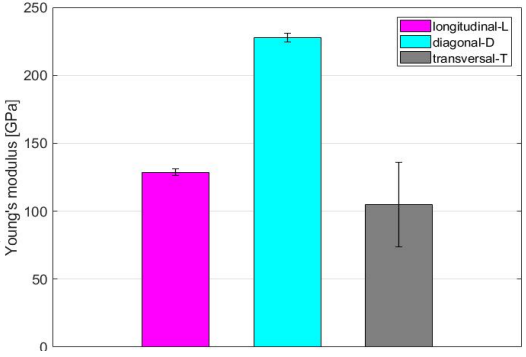
2nd year of research

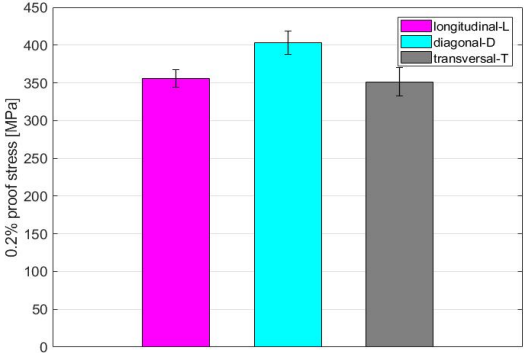
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel
  - Evaluation of the response of WAAM elements under tensile loading depending on:
    - the orientation of the specimen with respect to the deposition layer
    - the printing strategy ("continuously" printed or "dot-by-dot" printed)
    - the surface texture (either "polished" or "rough", i.e. as printed)

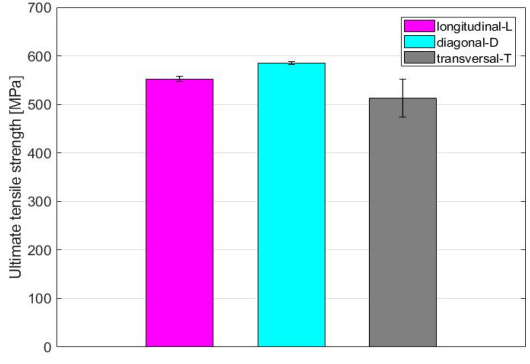
2nd year of research

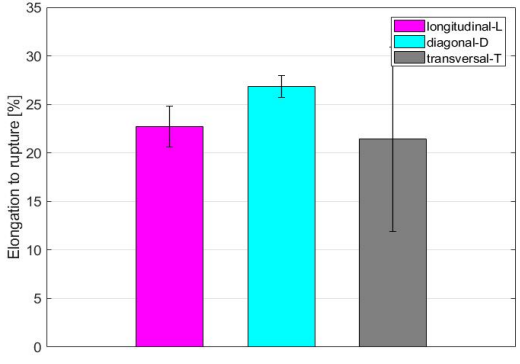
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel





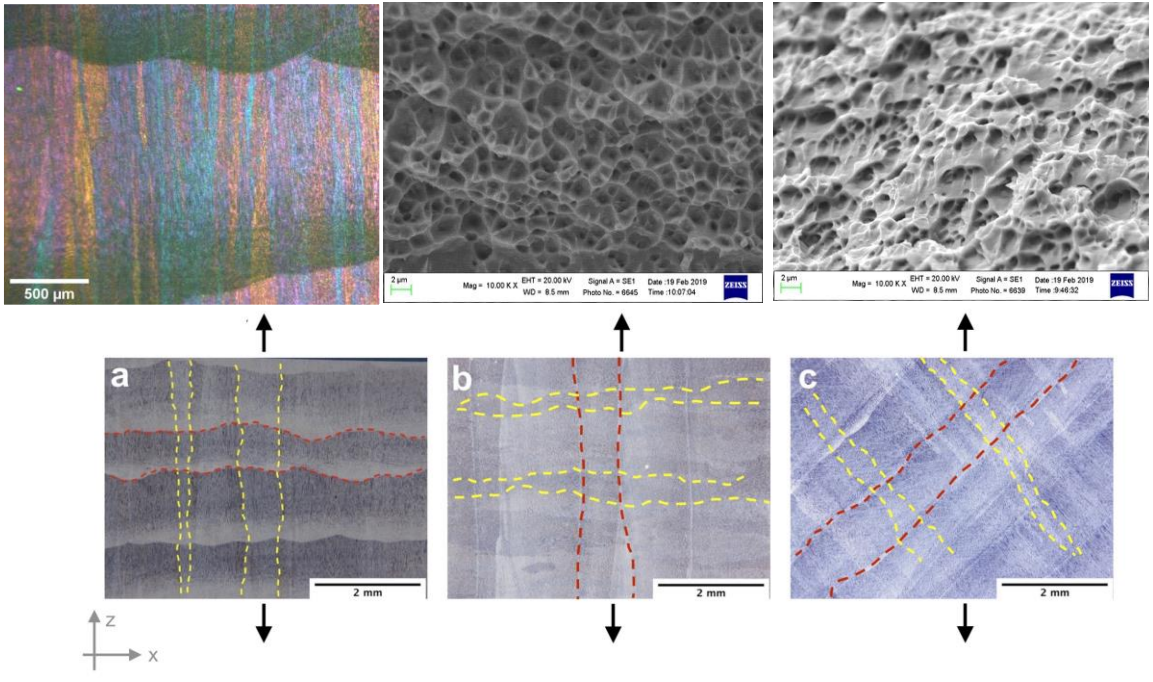


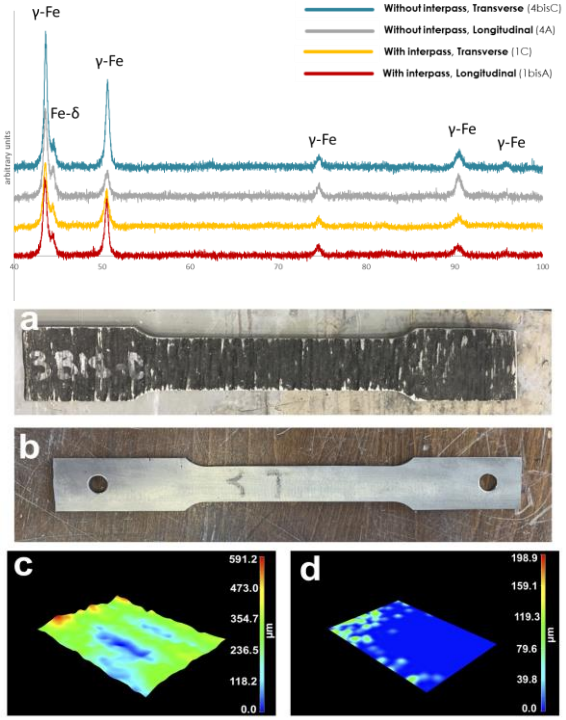




2nd year of research

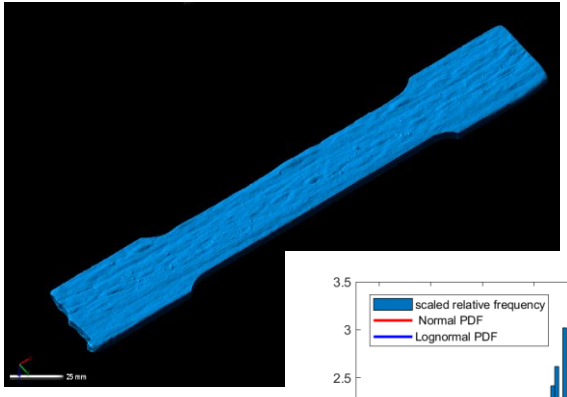
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel
  - Microstructural analysis of the WAAM 308LSi stainless steel in collaboration with the Metallurgic department at University of Bologna

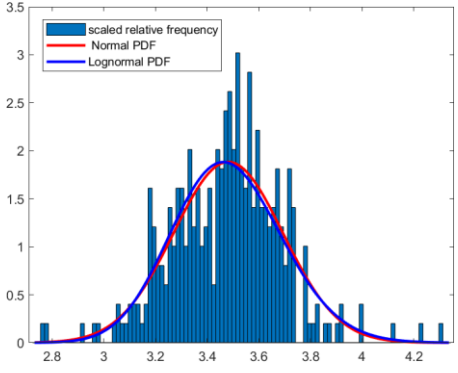


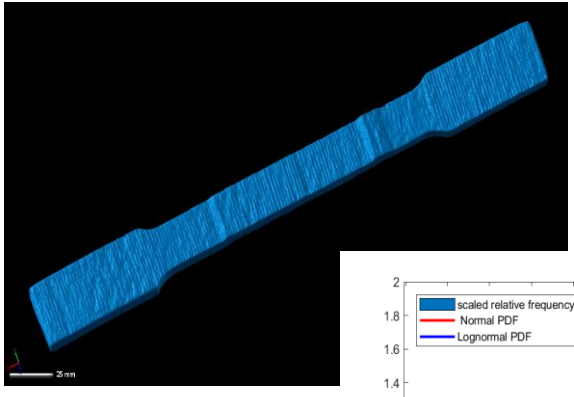


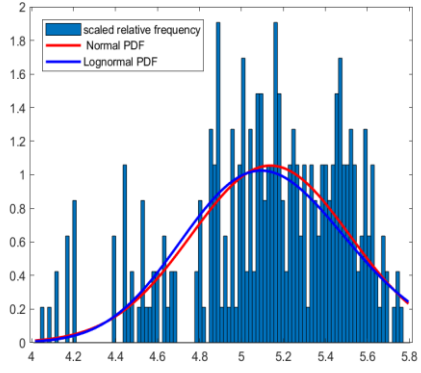
2nd year of research

- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel
  - 3D scan acquisition of planar specimens ("continuous" printing strategy)



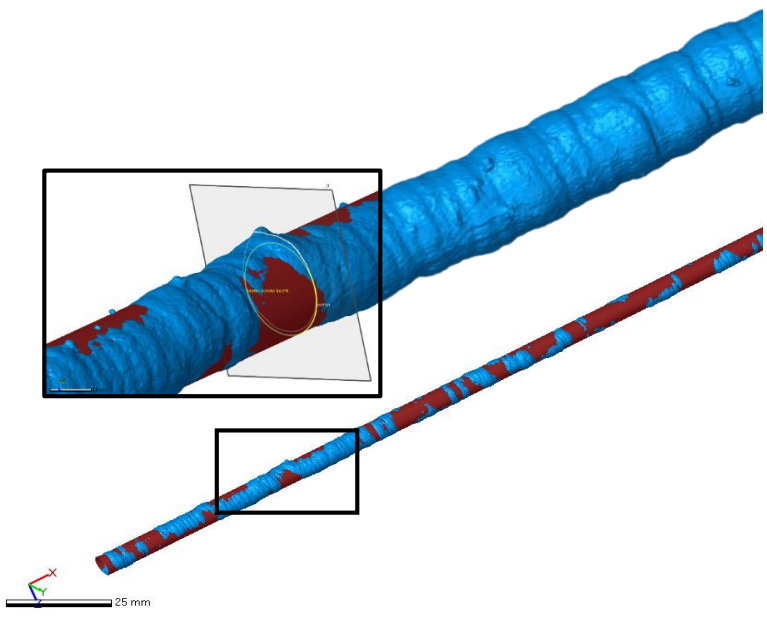


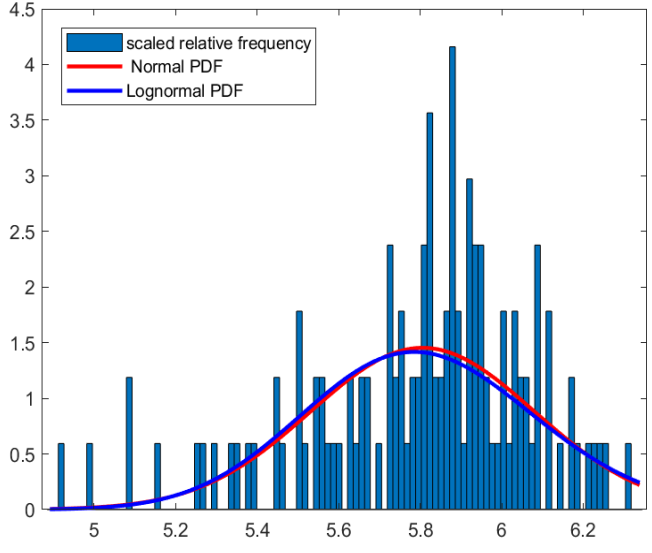




2nd year of research

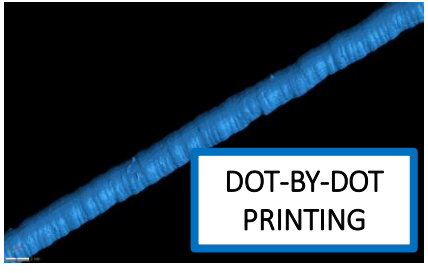
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel
  - 3D scan acquisition of rod specimens ("dot-by-dot" printing strategy)

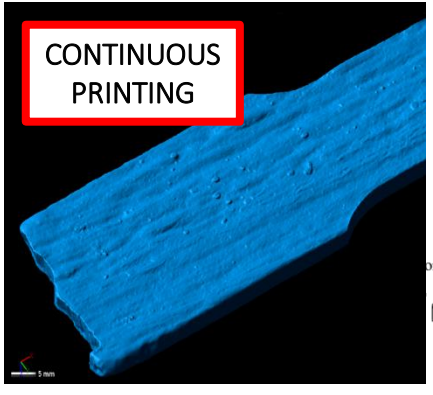


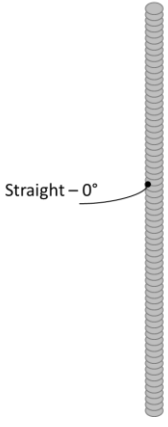


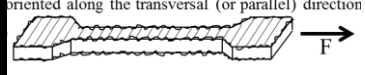
2nd year of research

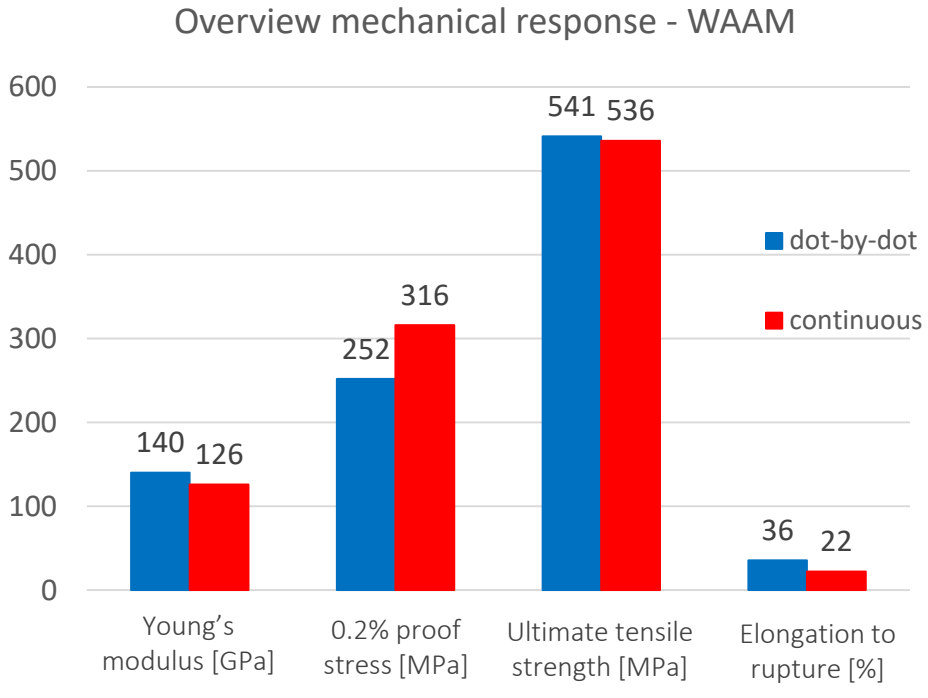
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel





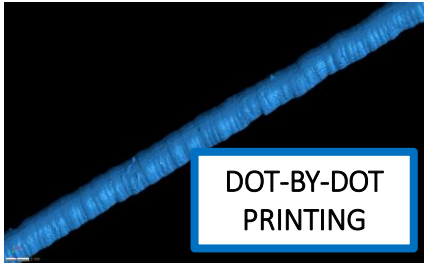


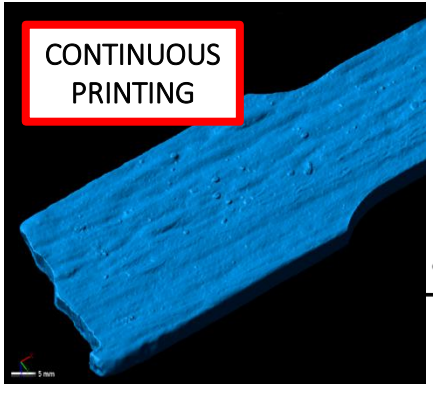


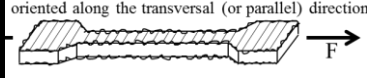


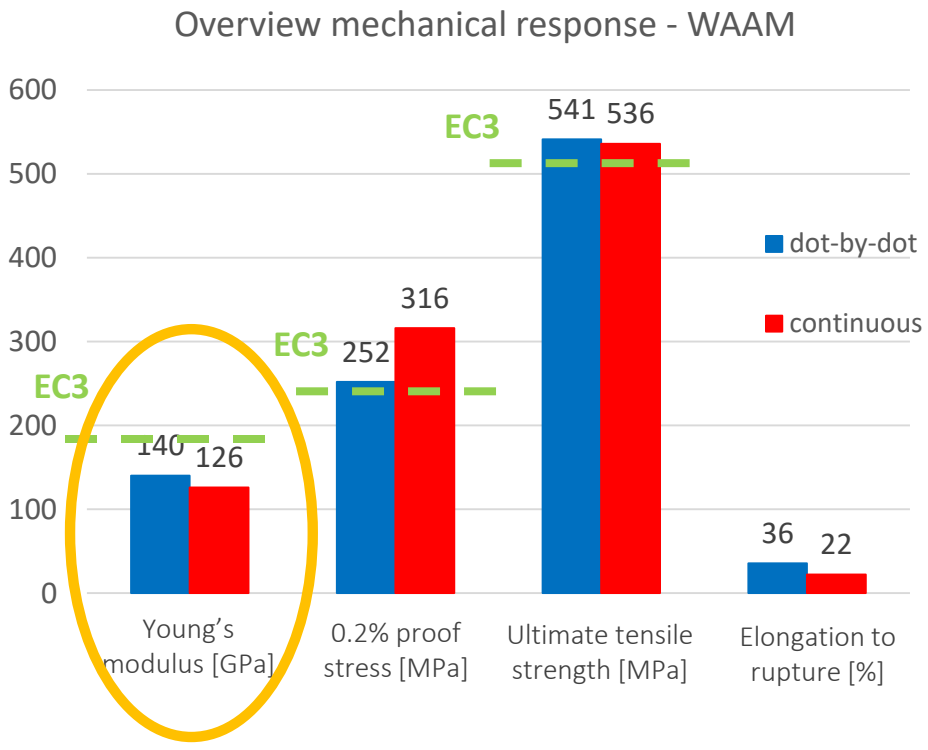
2nd year of research

- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel







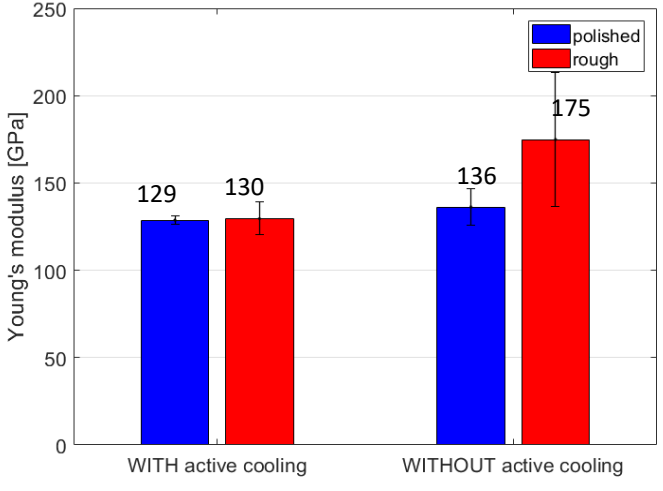


2nd year of research

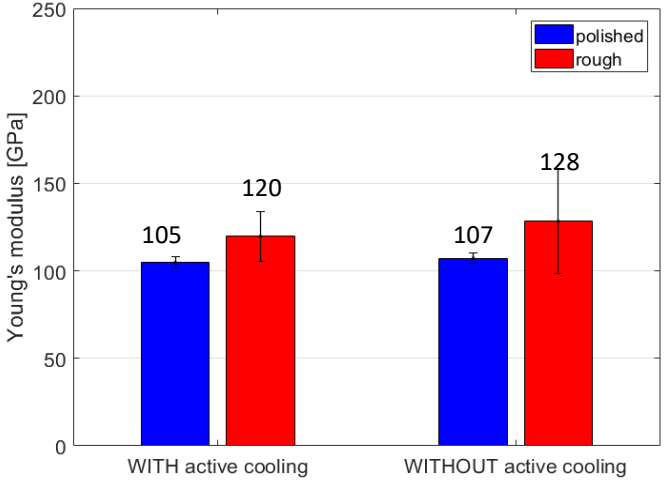
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel

POLISHED

ROUGH



Longitudinal (L)



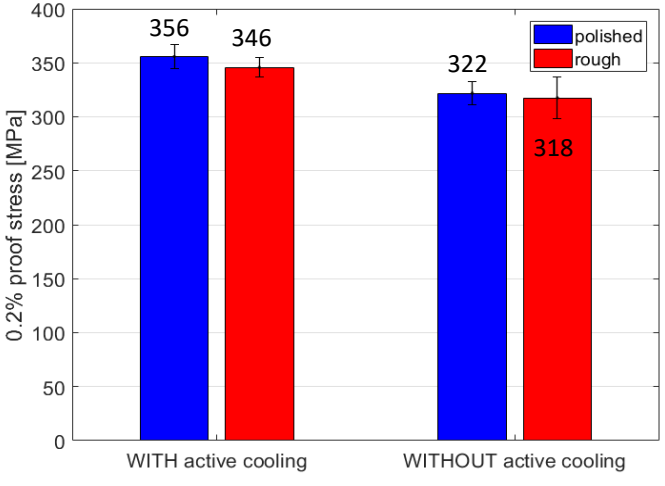
Transversal (T)

2nd year of research

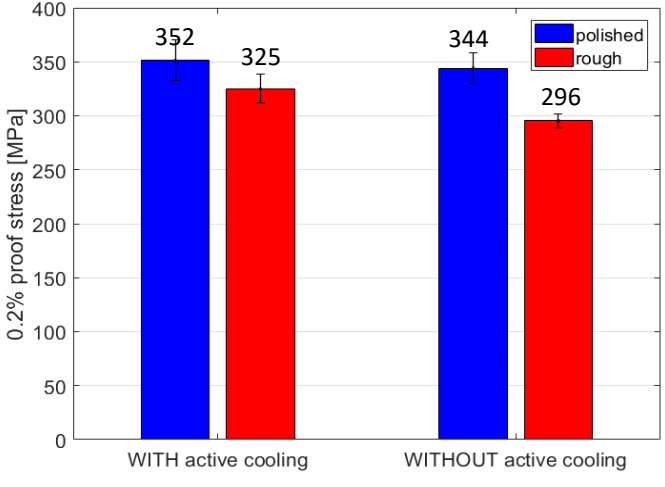
- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel

POLISHED

ROUGH



Longitudinal (L)



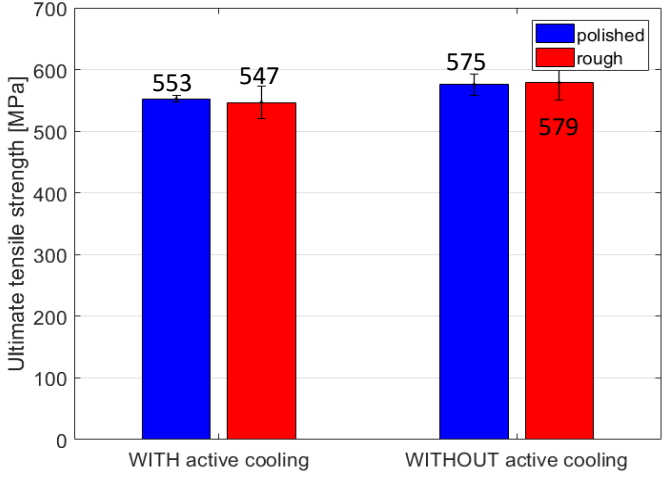
Transversal (T)

2nd year of research

- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel

POLISHED

ROUGH



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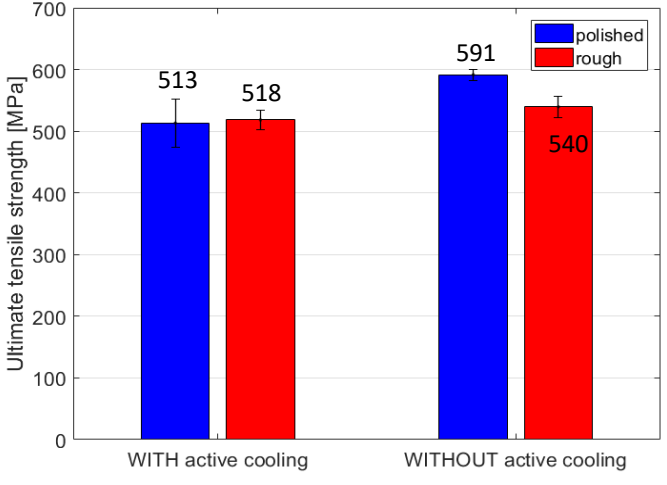

Transversal (T)

2nd year of research

- **PART A: Mechanical characterization** of WAAM 308LSi stainless steel

POLISHED

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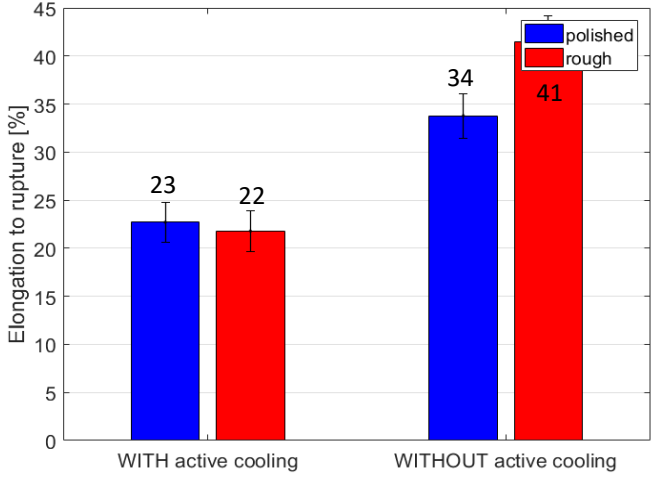
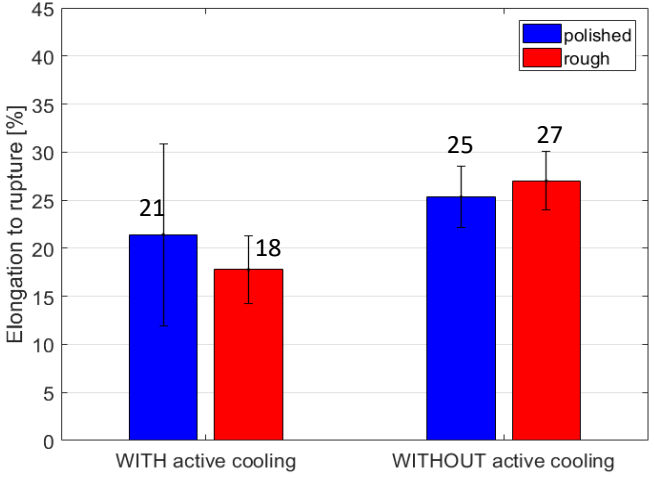


Longitudinal (L)

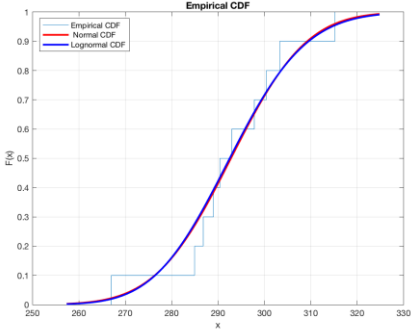


Transversal (T)

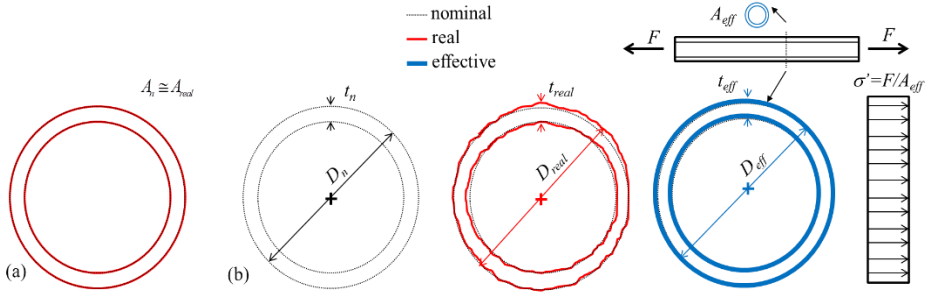
Research period abroad

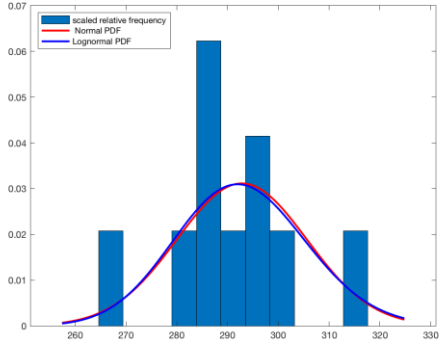
- **PART B: Calibration of design values** of WAAM 308LSi stainless steel

  - 4 main basic variables to be calibrated:
    - 0.2% proof stress - f_y
    - Ultimate tensile strength – f_t
    - Young's modulus – E_0
    - Equivalent geometry factor - φ



$$R = f_y \cdot A_{eff} = f_y \cdot \varphi \cdot A_{nom}$$





Research period abroad

- **PART B: Calibration of design values** of WAAM 308LSi stainless steel
  - 0.2% proof stress – f_{yk} , f_{yd} , γ_{m1} → Equivalent to γ_{M0} (=1.10 according to EN1993:1-4)
  - Ultimate tensile strength – f_{tk} , f_{td} , γ_{m2} → Equivalent to γ_{M2} (=1.25 according to EN1993:1-4)
  - Young's modulus – E_{0k} , E_{0d} , γ_{m3} → Equivalent to γ_{M1} (=1.10 according to EN1993:1-4)
  - Equivalent geometry factor – $\varphi_k, \varphi_d, \gamma_\varphi$

Resistance of cross-sections to excessive yielding including local buckling	γ_{M0}
Resistance of members to instability assessed by member checks	γ_{M1}
Resistance of cross-sections in tension to fracture	γ_{M2}
Resistance of bolts, rivets, welds, pins and plates in bearing	γ_{M2}

γ_{M0} = 1,1
γ_{M1} = 1,1
γ_{M2} = 1,25

Research period abroad

- **PART B: Calibration of design values** of WAAM 308LSi stainless steel
  - 0.2% proof stress
    - f_{yk} = 320 MPa
    - f_{yd} = 300 MPa

γ_{m1} = 1.10
(=1.10 according to EN1993:1-4)

  - Ultimate tensile strength
    - f_{tk} = 495 MPa
    - f_{td} = 460 MPa

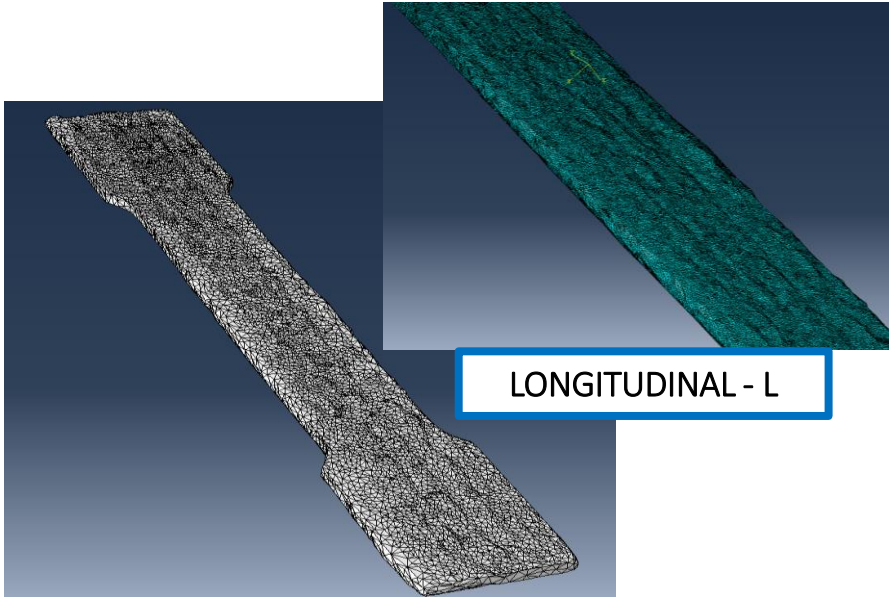
γ_{m2} = 1.10
(=1.25 according to EN1993:1-4)

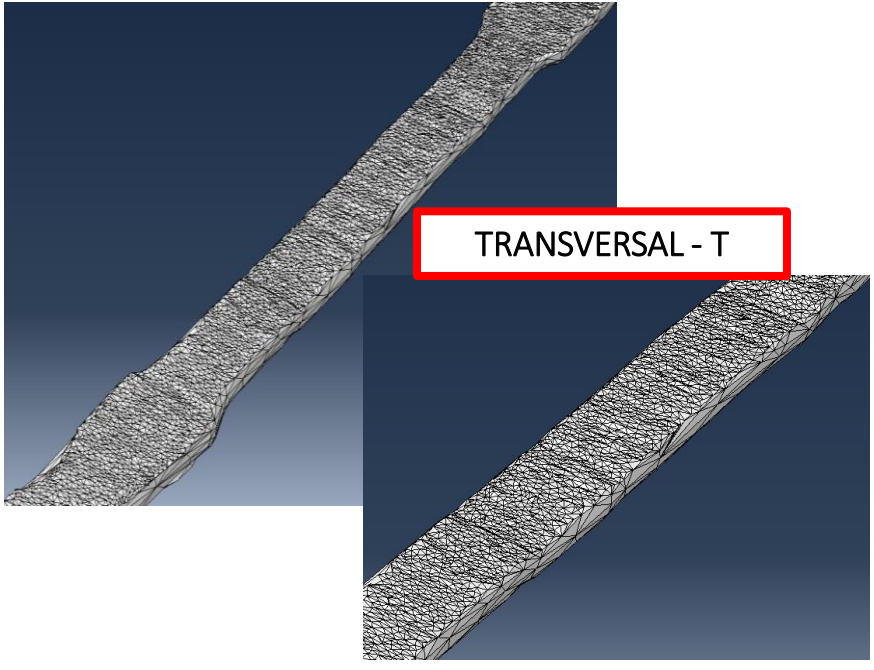
  - Young's modulus
    - E_k = 150 MPa
    - E_d = 120 MPa

γ_{m3} = 1.10
(=1.10 according to EN1993:1-4)

Research period abroad

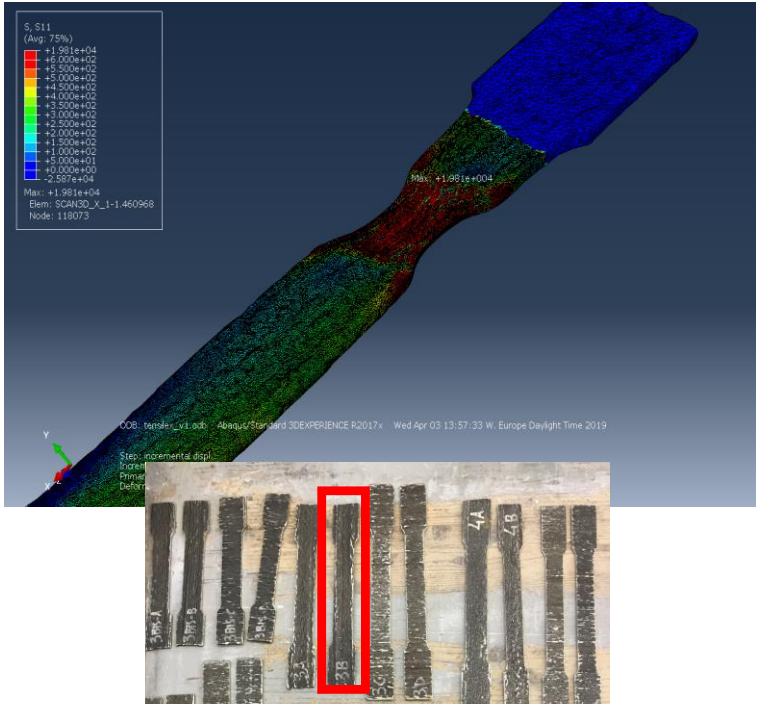
- **<u>PART C:</u> Numerical modeling** of WAAM 308LSi stainless steel

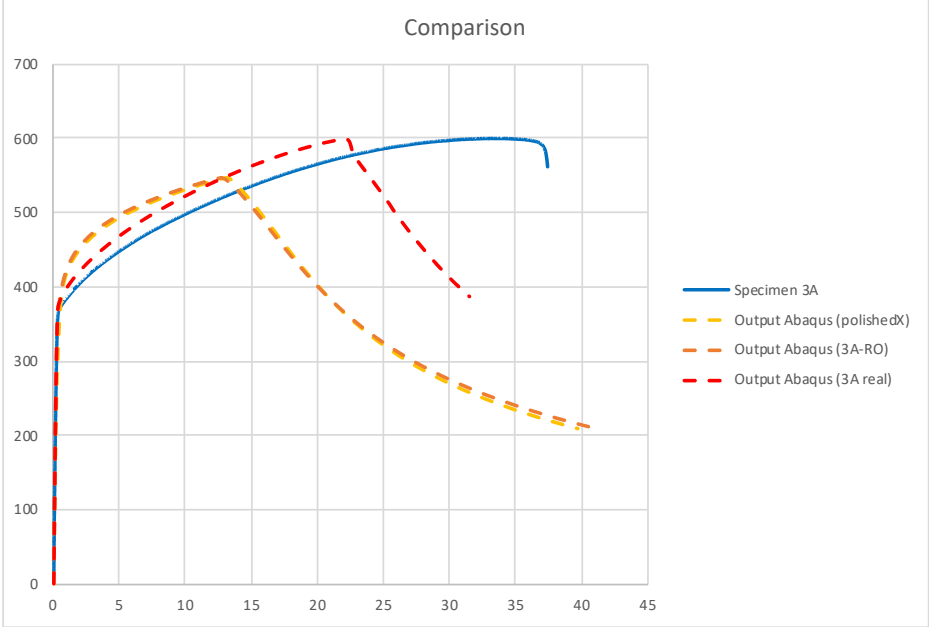




Research period abroad

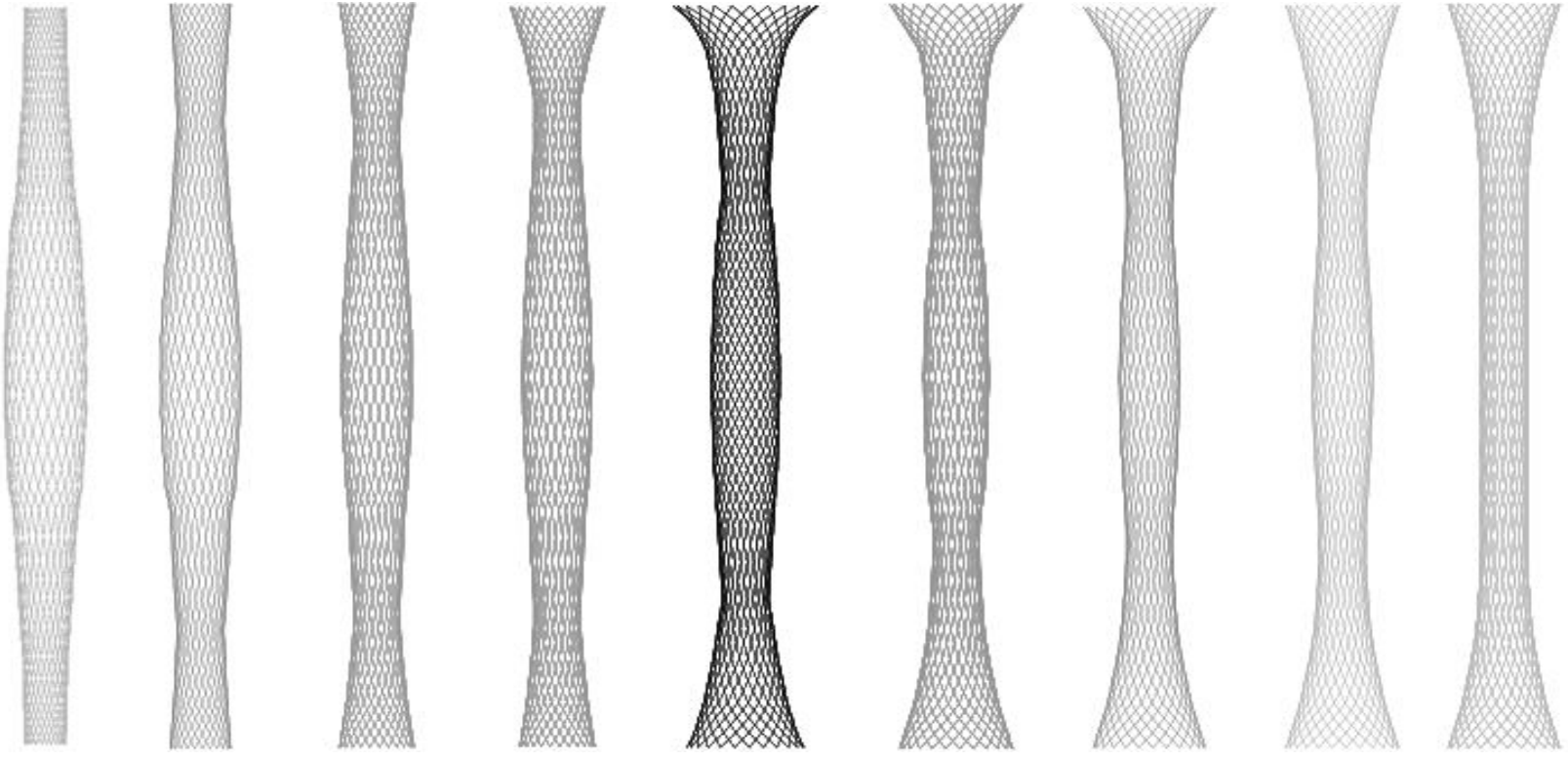
- **PART C: Numerical modeling** of WAAM 308LSi stainless steel





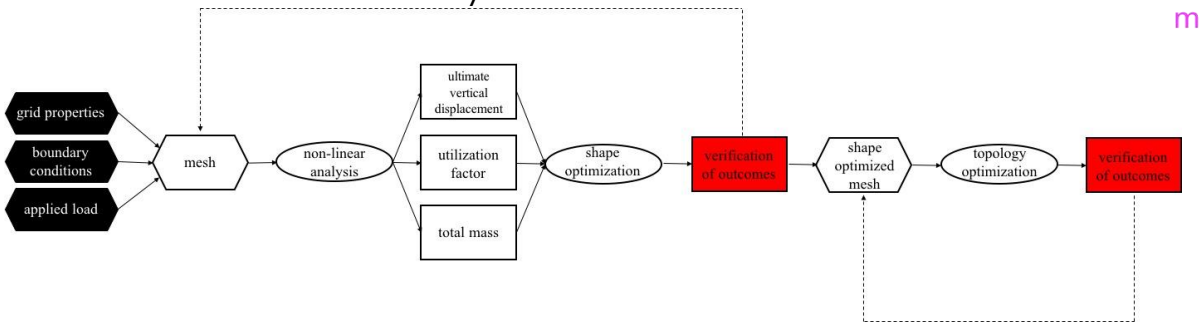
Research period abroad

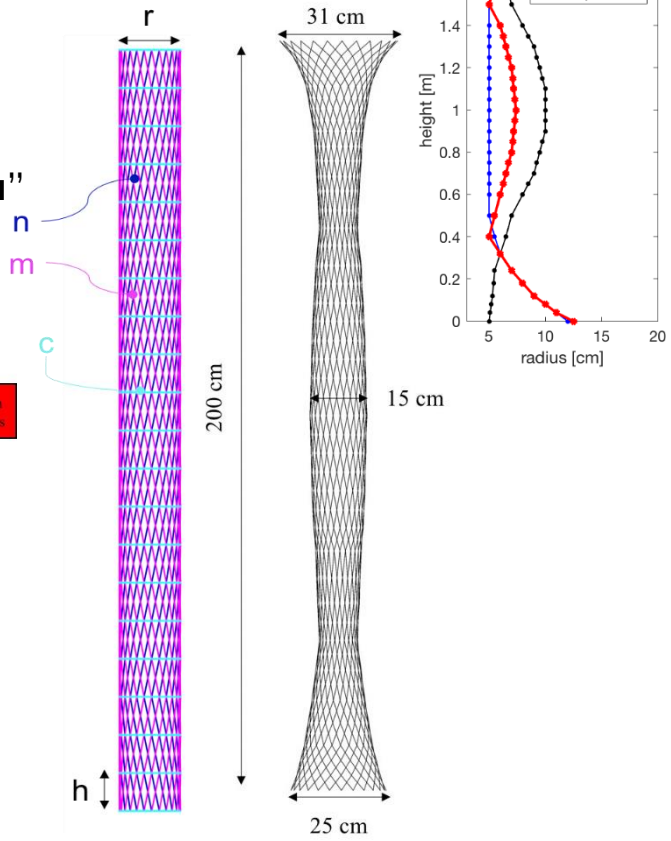
- **PART D: Algorithm-aided design** of WAAM structures



Research period abroad

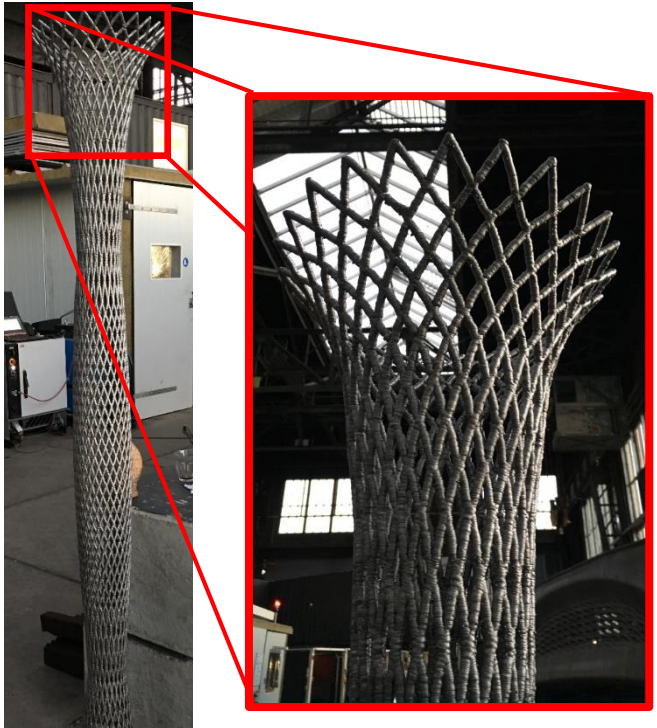
- **PART D: Algorithm-aided design** of WAAM structures
  - **Shape optimization** through Grasshopper's "**Galapagos**" genetic algorithm
  - **Preliminary design check** through Grasshopper's "**Karamba**" solutor for structural analysis





Research period abroad

- **PART D: Algorithm-aided design** of WAAM structures



2nd year outcomes

SIGNIFICANT PUBLICATIONS:

Laghi, V., Palermo, M., Tonelli, L., Gasparini, G., Ceschini, L., Trombetti, T., "***Tensile properties and microstructural features of 304L austenetic stainless steel produced by Wire-and-Arc Additive Manufacturing***", Additive Manufacturing, 2019, *in press*.

Laghi, V., Palermo, M., Gasparini, G., Girelli, V.A., Trombetti, T., "***Geometrical characterization of Wire-and-Arc Additive Manufactured steel elements***", Advanced Materials Letter, 10(10): 695-699, 2019.

Laghi, V., Palermo, M., Gasparini, G., Girelli, V.A., Trombetti, T., "***Experimental results for structural design of Wire-and-Arc Additive Manufactured stainless steel members***", Journal of Constructional Steel Research, 2019, *in press*.

Laghi, V., Palermo, M., Gasparini, G., Trombetti, T., "***Optimization studies on diagrid columns realized with Wire-and-Arc Additive Manufacturing process***", Proceedings for 2019 IABSE Congress, New York City, 2019.

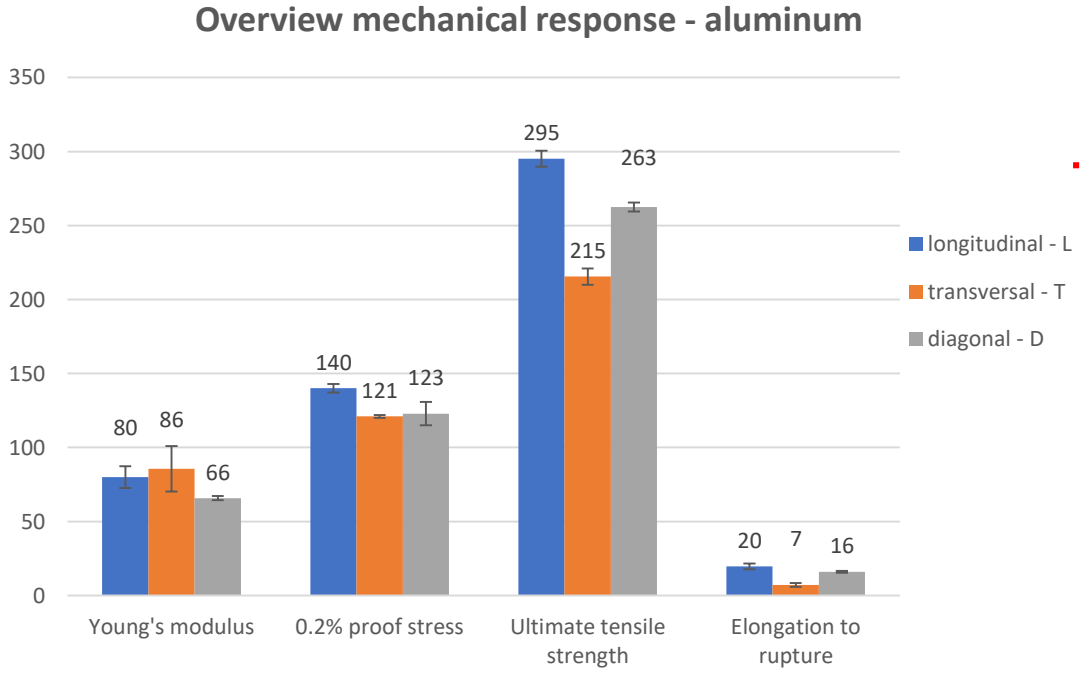
Laghi, V., Palermo, M., Gasparini, G., Silvestri, S., Trombetti, T., "***The application of weld-based additive manufacturing steel to structural engineering***", Proceedings for 10th ISEC Conference, Chicago, 2019.

Laghi, V., Palermo, M., Pragliola, M., Girelli, V.A., Van Der Velden, G., Trombetti, T., "***Towards 3D-printed steel grid-shells: the main idea and first studies***", Proceedings of the IASS Symposium, Boston, 2018.

2nd year outcomes

EXTRA RESEARCH:

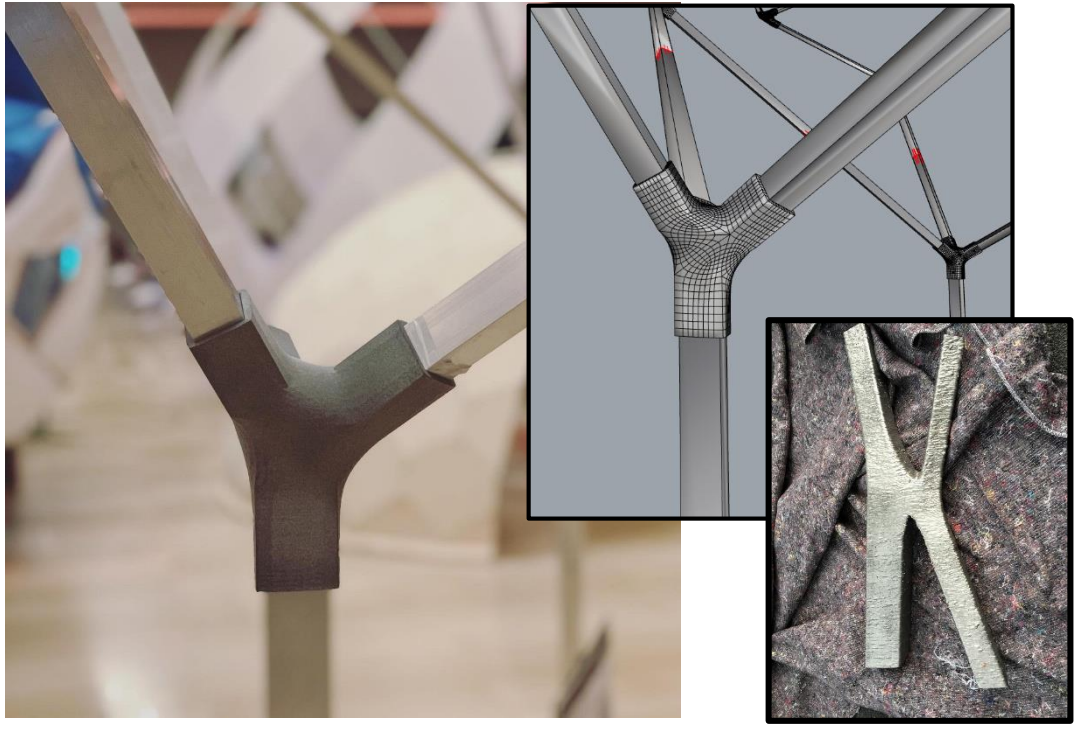
- **PART A: Mechanical characterization** of WAAM AA5183 aluminum



2nd year outcomes

EXTRA RESEARCH:

- **PART D: Pavilion proposal** with ESO nodes realized with 3D-printed technology



3rd year of research

- **Detailed guidelines** for the structural design of WAAM 308LSi stainless steel elements
- **Study of the influence of surface roughness** (and geometrical imperfections in general) on the mechanical response of WAAM elements
- **Structural optimization studies** on free-form shaped structures to be realized with WAAM technology

THANK YOU FOR THE ATTENTION

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