Towards a design approach for Wire-and-Arc Additively Manufactured stainless-steel elements

Summary

Study objectives

This project, as its title suggests, revolves around the pursue of a new design approach for the application and use of WAAM-produced stainless-steel structural elements. This can be reached on two levels:

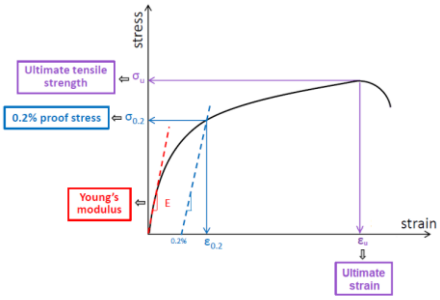
1. The most general design method involves characteristic and design values of some basic variables, as well as the employment of partial safety factors; this corresponds to the semi-probabilistic approach used in the Eurocodes;
2. A deeper evaluation can be carried out through Finite Element Analyses, which allow to fully characterize the material's non-linear behavior and its consequent performance.

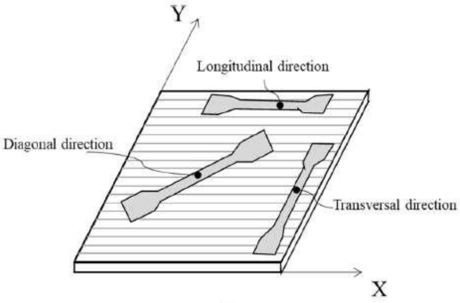
The need for this is directly linked to the production technique utilized: in fact, Wire-and-Arc Additively Manufacturing delivers a material that is anisotropic and characterized by geometrical imperfections and a superficial roughness, which influence the material's behavior as well.

Method

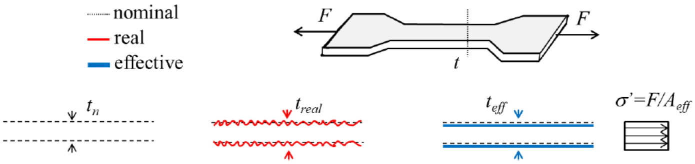
Regarding the adjustment and calibration of partial safety factors, the steps listed here below have been followed:

1. Material characterization: research activities previously carried out at the University of Bologna involved tensile testing on milled specimens (oriented in the direction parallel to the deposited layers – L, as well as orthogonal – T – and inclined of 45° – D), and provided the full strain fields for each of them by means of Digital Image Correlation.

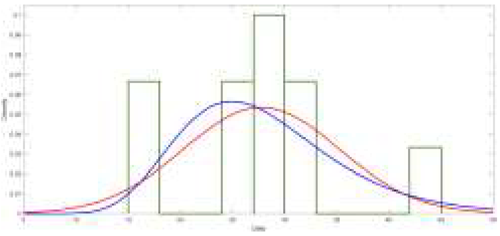


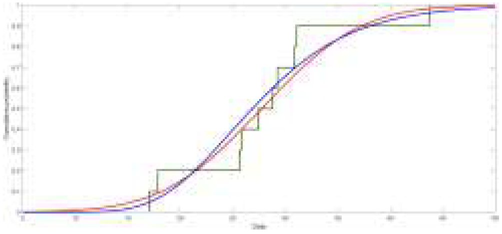


2. Geometrical characterization: additional research previously conducted at the University of Bologna on rough specimens provided effective dimensions of L and T specimens through volumetric measurements.



3. Statistical analysis of basic variables: focusing on the main mechanical and geometrical properties, the best-fit distributions (Normal and Lognormal) related to each of them were identified, and, through Kolmogorov-Smirnoff tests, the best fit out of the two distributions was found.





The main basic variables analyzed are:

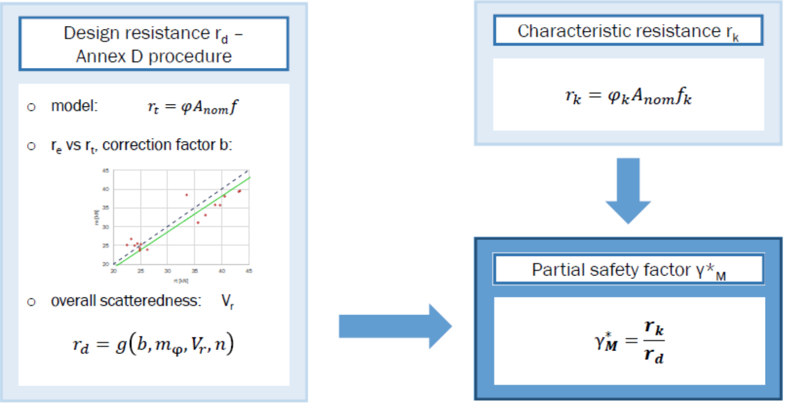
- Mechanical properties: Young's modulus E, 0.2% proof stress $\sigma_{0.2\%}$, ultimate strain ε_u and ultimate stress σ_u;
- Geometrical properties: effective thickness t_{eff}, which, normalized with respect to the nominal value t_{nom}, becomes a calibrating coefficient named geometrical corrective factor φ.

4. Application of procedures outlined in Annex D of EC0: Annex D of Eurocode 0 provides procedures for the determination of characteristic values of single basic variables, provided that they follow either a Normal or Lognormal distribution.

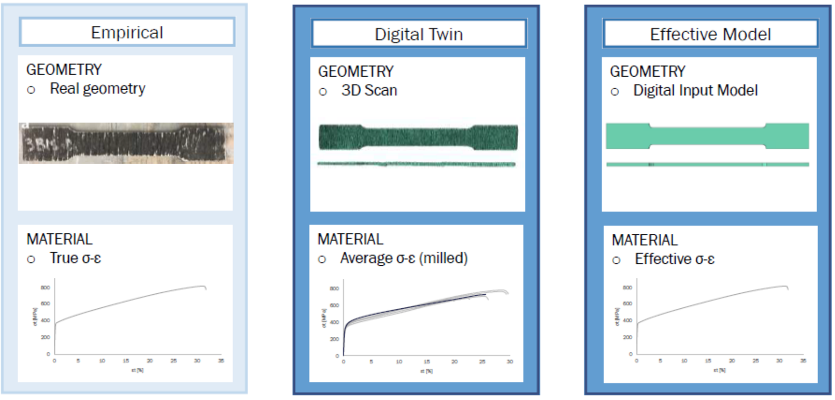
   Normal: $X_{k(n)} = m_x(1-k_nV_x)$

   Lognormal: $X_{k(n)} = e^{m_y - k_n s_y}$

5. Determination of resistance function and partial safety factors: in general, the exact value of the tensile resistance can be found as R = A · f (where f can be the strength at yielding f_y or at the ultimate state f_t). For WAAM, though, some assumptions are made: regarding stresses, they are taken from milled specimens, in order not to have the influence of geometrical imperfections; while effective values are taken for areas, hence the average dimensions instead of the exact ones point-by-point. Both assumption carry an error (η), and, therefore: $R = (A_{eff} \cdot f) \cdot \eta$ (where $A_{eff} = \varphi \cdot A_{nom}$, making φ a random variable). Annex D provides a procedure also for the determination of design resistance r_d, as shown in the figure below: combining that with the characteristic value of the resistance r_k, partial safety factor γ^*_M can be computed.



Regarding part B, i.e. advanced numerical modeling and in-depth analysis of the influence of geometrical irregularities on the mechanical behavior of the material, the approach was the following:

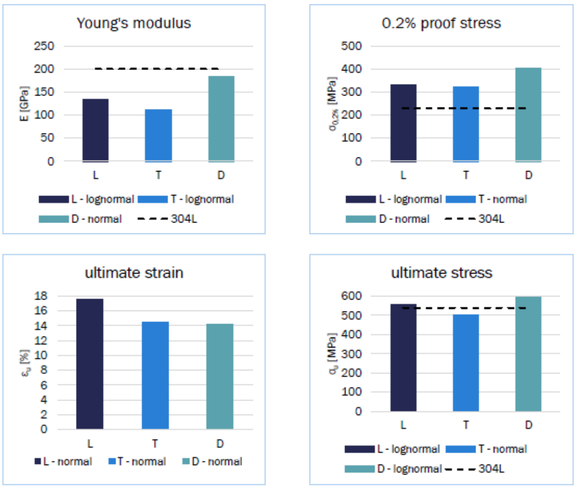


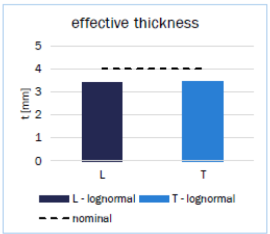
Namely, three different models were accounted for:

1. Empirical (reference response): the material's behavior is characterized by the true stress-strain model obtained from testing on the actual rough specimen;
2. Digital Twin: the geometry is taken form a 3D scan of the exact same rough specimen, while the mechanical behavior of the material is taken on average from that of milled specimens – the geometry carries the influence of geometrical imperfections;
3. Effective Model: the geometry is defined from effective dimensions and a Digital Input Model is created, while the material's behavior is the effective one from the rough specimen – in this case, the influence of geometrical imperfections is carried by the mechanical behavior of the rough material.

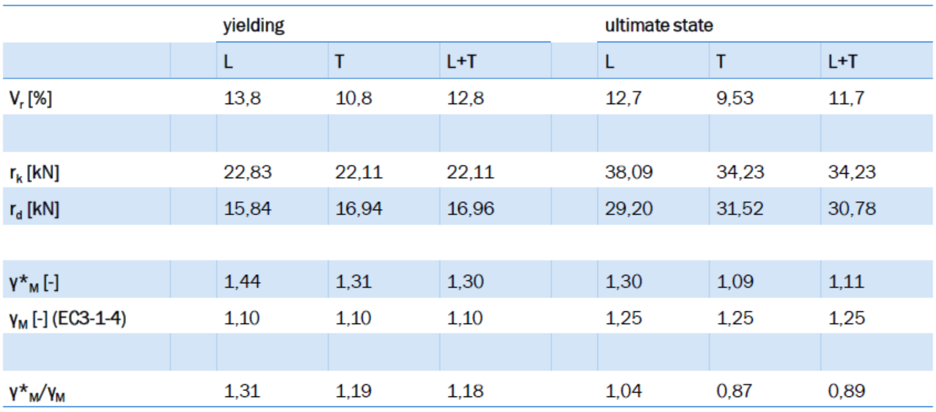
Results

Regarding the definition of characteristic values of basic variables, the following was observed:





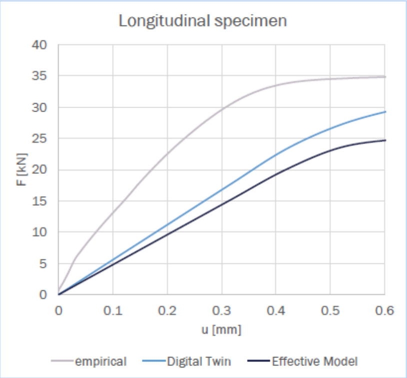
Concerning mechanical parameters, the elastic behavior of the WAAM-produced material is generally scarce with respect to the traditional material, especially for longitudinal and transversal specimens; yielding occurs at higher strengths, especially for diagonal specimens; ultimate stresses are comparable in all three directions, as well as against the traditional material; longitudinal specimens present a higher ductility than the other two orientations. Regarding geometrical parameter t_{eff}, it presents similar values both for L and T directions, which are smaller than the nominal value.

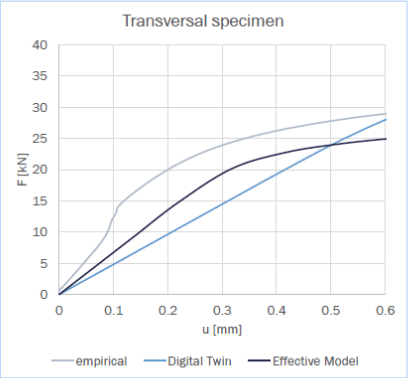


	yielding			ultimate state		
	L	T	L+T	L	T	L+T
V_r [%]	13,8	10,8	12,8	12,7	9,53	11,7
r_k [kN]	22,83	22,11	22,11	38,09	34,23	34,23
r_d [kN]	15,84	16,94	16,96	29,20	31,52	30,78
γ^*_M [-]	1,44	1,31	1,30	1,30	1,09	1,11
γ_M [-] (EC3-1-4)	1,10	1,10	1,10	1,25	1,25	1,25
γ^*_M/γ_M	1,31	1,19	1,18	1,04	0,87	0,89

The results in the table above show that partial safety factors should be increased at yielding, while their traditional values are still valid at the ultimate state. It also highlights the dependency of the design value of the resistance, and consequently of the partial safety factors, on the variability related to the model and the basic variables: to a higher variability V_r corresponds a higher value of γ^*_M.

The results of part B, where the attention is mainly on the elastic phase, are expressed in terms of reaction force vs displacement: both for the longitudinal and transversal specimen, and for both models, the elastic stiffness is quite lower than the empirically observed one, hence they require calibrations.





Future objectives and applications

Concerning the semi-probabilistic approach for WAAM-produced stainless-steel elements, in the future, some goals might be:

- For producers to be able to assure certain levels of variability related to the roughness of the printed material;
- For researchers to widen this study employing larger statistical populations, and then be able to associate values of γ^*_M to the levels of variability assured by the manufacturers.

Regarding advanced numerical modelling, surely the study can be deepened in order to define generalized calibrating factors, both for the elastic and plastic phases, in order to be able to carry out reliable Finite Element Analyses.

The results of this study can be helpful to carry out further research on the matter, which would allow to finally be able to safely design structural elements to be produced using WAAM, without having to actually manufacture the element and test it first, as has been done so far.