Immersed finite element analysis of laser powder bed fusion process: Modeling and experimental validation

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OBJECTIVES

The capability of correctly predicting part deflections after support removal is important to assess the quality of a final artifact produced by laser powder bed fusion (LPBF) technology. Due to the high flexibility of LPBF additive manufacturing, most of the components produced by means of such a technology have an optimized shape and **complex geometrical features**. Consequently, the process of generating an analysis suitable mesh starting from the original 3D virtual model turns out to be a non-trivial task. **Immersed boundary methods** represent a possible solution to perform accurate process simulation without the meshing burden. In this work an ***in-house* developed immersed finite element framework** suitable to perform **thermo-mechanical part-scale analysis** is experimentally validated by means of part deflection measurements obtained for a single-cantilever structure after support removal.

EXPERIMENTAL SETUP

To experimentally validate the numerical method presented in this work, we compare the simulated part deflection with experimental data obtained for the AMBench2018 challenge [1] proposed by the National Institute of Standards and Technology (NIST).

For this benchmark, an EOS M270 LPBF machine is used. Measurements of part deflection after plate removal are reported for the eleven ridges present on the upper surface of the structure as depicted in Figure 1.

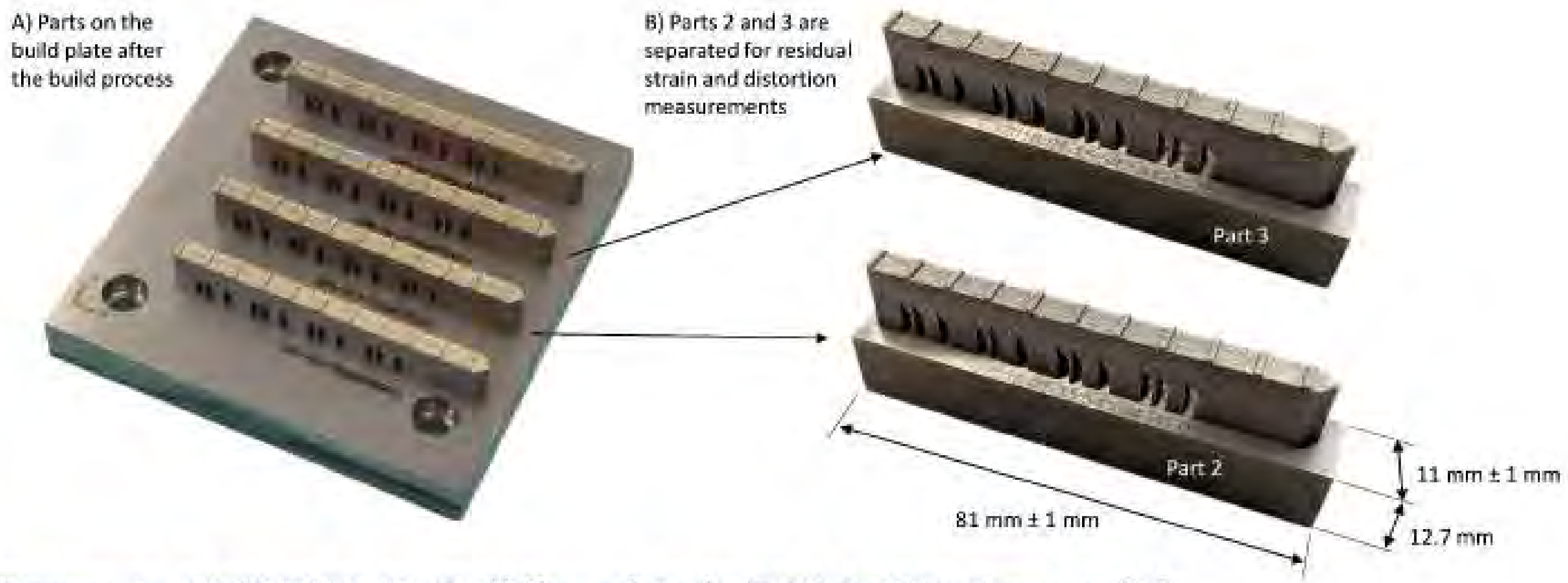


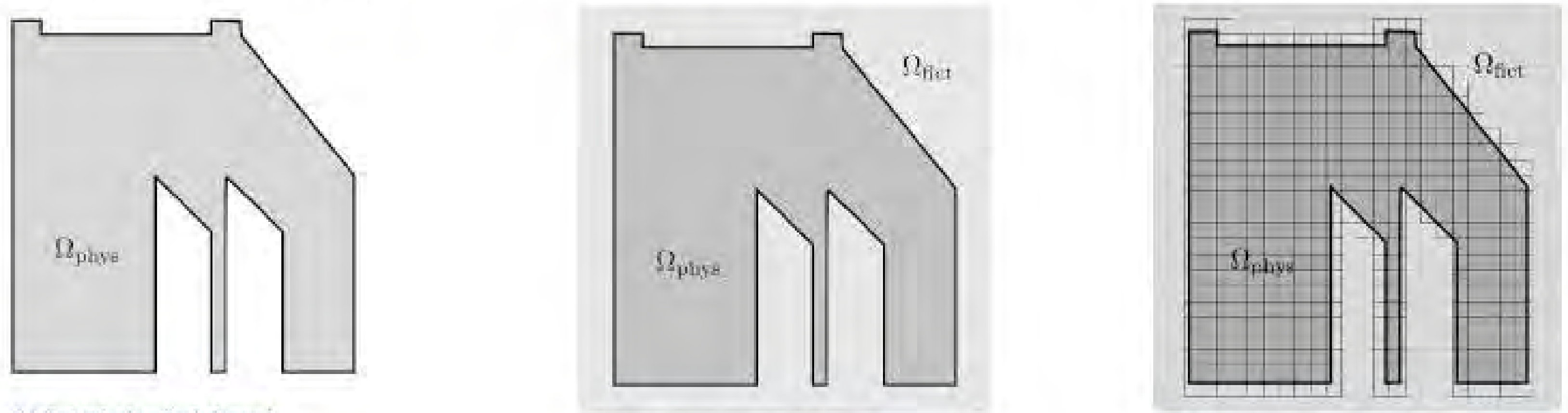
Figure 1: AMB2018-01 Building plate in EOS M270. Source: [1].

NUMERICAL MODEL

We employ the **Finite Cell Method (FCM)** [2] - an immersed boundary finite element method - to solve the following thermo-mechanical problem:

Thermal model	Mechanical model
$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$ $Q = \frac{\eta P}{\mathrm{HAV}}$ $q^{loss} = h^{loss}(T - T_e)$	$\nabla \cdot \boldsymbol{\sigma} = \mathbf{0}$ $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{th} + \boldsymbol{\varepsilon}^{e} + \boldsymbol{\varepsilon}^{p}$ $\boldsymbol{\varepsilon}^{th} = \alpha \Delta T \mathbf{I}$ $\Phi = \sigma_{vm} - \sigma_y(\gamma) \leq 0$ $\dot{\boldsymbol{\varepsilon}}^{p} = \dot{\gamma} \frac{\partial \Phi}{\partial \boldsymbol{\sigma}}$

As shown in Figure 2, thanks to its immersed nature, FCM allows to solve physical problems on complex geometries avoiding time consuming conforming mesh generation processes. The actual geometry of the physical domain is then reconstructed only at the element integration level by means of an **adaptive quadrature rule** [3].



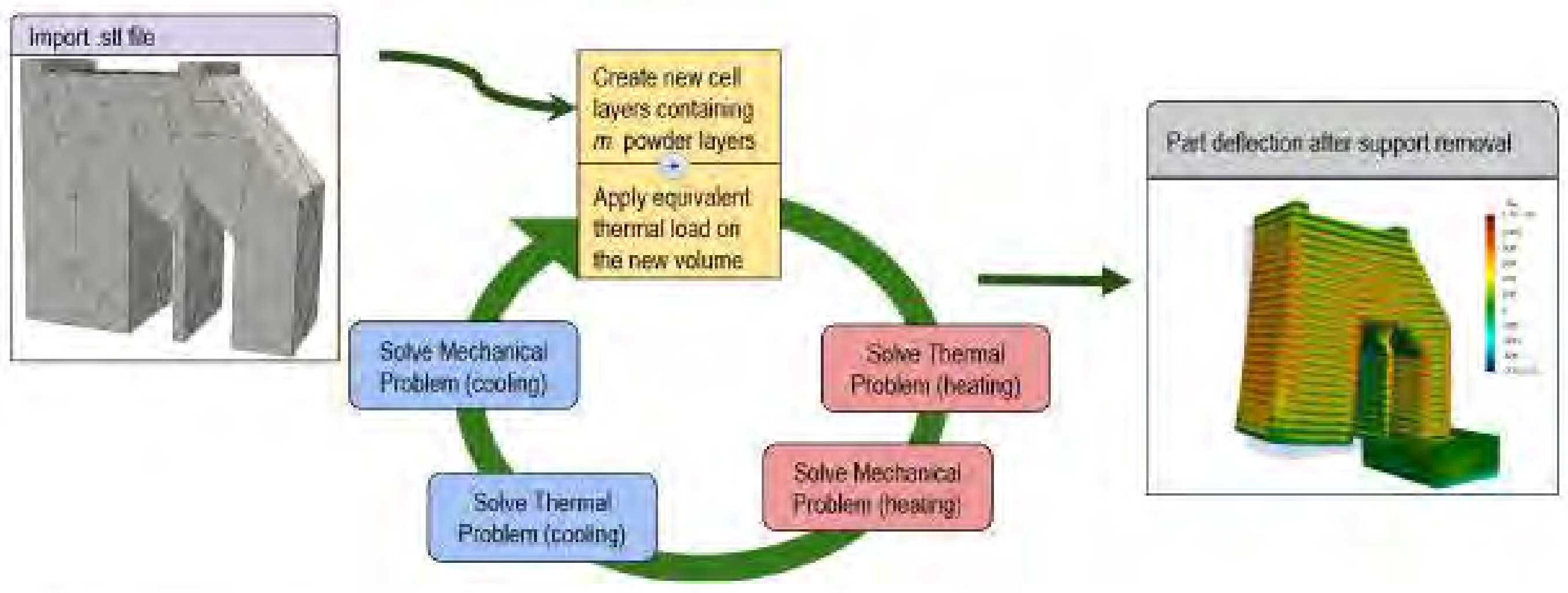
(a) Initial physical domain

(b) the physical domain is immersed into a ficticious domain of much simpler shape

(c) A cartesian grid of so-called finite cells can be easily generated to discretize the ficticious domain

Figure 2: Finite Cell Method for LPBF part-scale analysis.

As depicted in Figure 3, an **agglomerated layer activation strategy** is employed to simulate the LPBF process [4].


Import .stl file

Create new cell layers containing m powder layers

Apply equivalent thermal load on the new volume

Solve Thermal Problem (heating)

Solve Mechanical Problem (heating)

Solve Thermal Problem (cooling)

Solve Mechanical Problem (cooling)

Part deflection after support removal

Figure 3: Thermo-mechanical part-scale model flowchart.

RESULTS

Two simulations are performed using a different number of powder layers activated at each thermo-mechanical cycle (m parameter). In the first coarser analysis 125 powder layers are activated at each new cycle (m=125), while in the second one we set m=*25*.

The approximated upward deflections measured at the mid-point of each grounded ridge are reported in Figure 5 together with the corresponding simulated results. The coarser analysis delivers an **error on the maximum deflection of 4.72%,** while - in the refined analysis - this error drops down to approximately 1%. Both analyses show **an excellent (almost perfect) correlation with respect to the measured data**.

The computational speed up obtained by means of the coarse analysis is very significant, dropping from more than 8 hours to **less than 90 minutes** (factor 5.5), whereas the accuracy of the predicted results is practically not affected.

Figure 6 shows the von Mises stress distribution at the end of the last cooling time step for the case m=25. During the support removal stage, the residual stresses are relieved generating an upward deflection of the final structure (see Figure 5). In Figure 6, we can observe how, thanks to the immersed nature of FCM, the method is able to compute stresses directly on the .stl geometry employing a relatively small numbers of degrees of freedom.

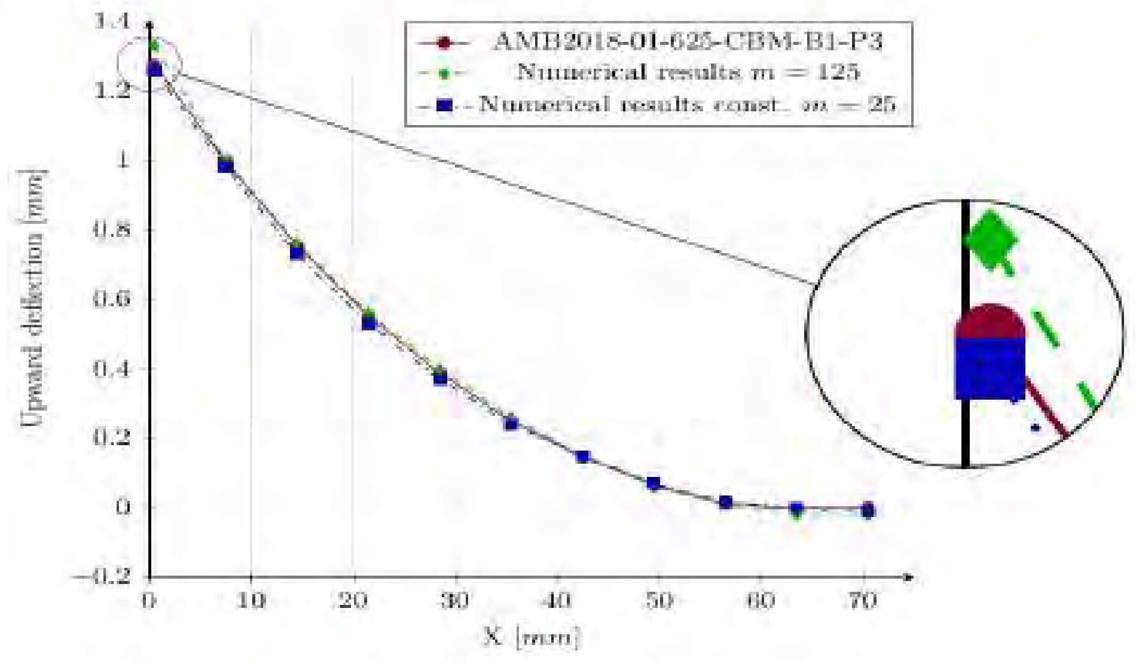


Figure 5: Part deflection after support removal. Experimental measurements Vs. Numerical results.

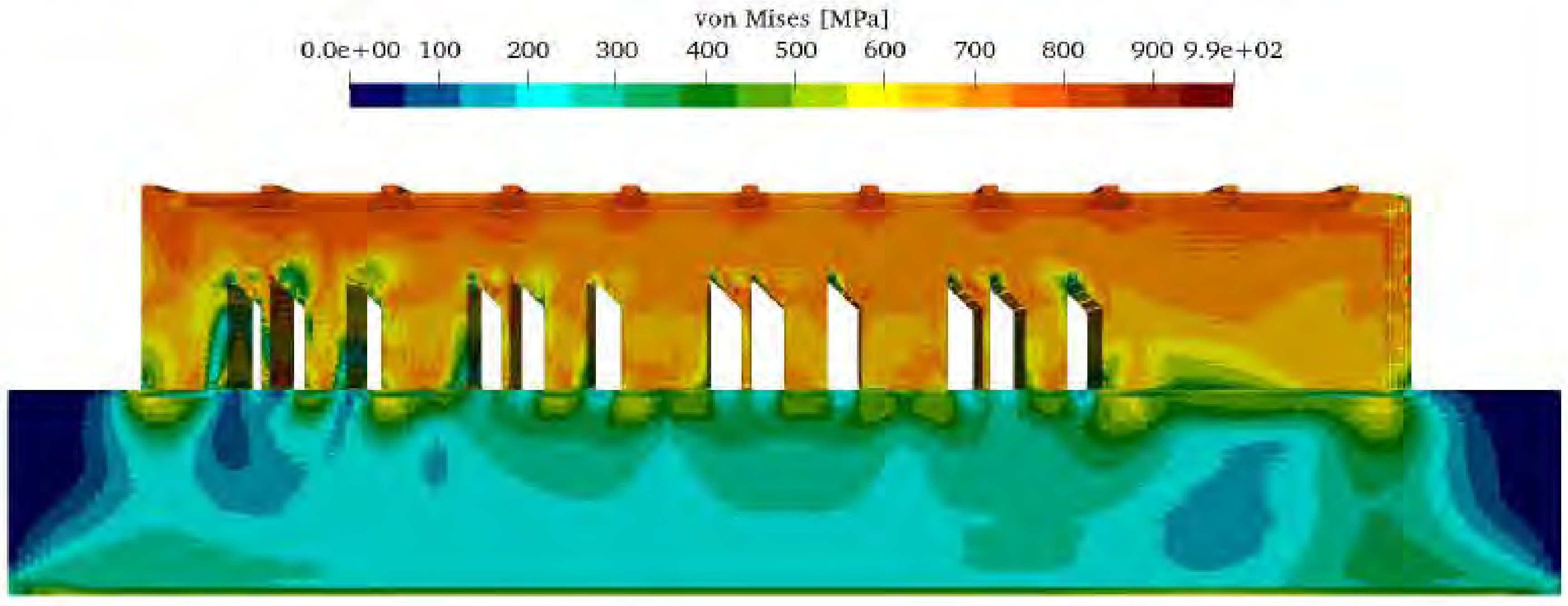


Figure 6: von Mises stress distribution.

CONCLUSIONS

Combining FCM and a simple yet effective part-scale model, we are able to accurately capture experimental measurements of part deflection after support removal.

The immersed nature of FCM allows to employ a very coarse discretization, able to perform the entire calculation in less than 90 minutes on a standard desktop computer, delivering at the same time results with a **very accurate correlation with experimental measurements**. The possibility to rapidly **estimate part deformation directly within a CAD environment** can be very attractive in the industrial practice.

OUTLOOK

Possible further developments of the present work can include an extension of the numerical scheme to allow **local refinement**. Moreover, the computational time could be further reduced by means of **HPC computation and code parallelization**.

REFERENCES

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