A REVIEW OF WELDING MODELLING APPROACHES FOR NUCLEAR INDUSTRY

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ABSTRACT

In the nuclear industry, welding process is widely used to assemble components. As a manufacturer, Framatome has developed over the years specific tools and approaches to answer the needs of our welders. Indeed, for an industrial use, welding modelling must be efficient, robust and reliable but unfortunately no approach can achieve all these goals, so choices must be made. Many approaches exist in the literature to model residual stresses and distortions. This paper will focus only on thermomechanical approaches of welding by finite element analysis such as: moving heat source, thermal cycle, inherent strain, ... Each of these approaches has advantages and disadvantages such as computation time or accuracy of results. In this paper we propose to make a comparison between these approaches and to define the assumptions and limits for each of them in the context of welding and Wire Arc Additive Manufacturing modelling for nuclear industry. First, the paper will present a review of each approach capabilities and then their applications on a specific mockup designed as an Additive Manufacturing wall are described. The distortions and residual stresses results are compared for each approach with experimental data with the goal to give limits and guidelines for each application.

Keywords: Distortions, 18MND5, TG10, Welding Simulation

INTRODUCTION

The Wire Arc Additive Manufacturing (WAAM) process comes directly from arc welding, an industrial process that has been mastered for over a century. This connection brings several advantages such as the ability to use existing welding equipment and proven methodologies like numerical simulation. However, it also introduces specific challenges related to the sequential nature of material deposition, such as weld bead overlapping and new geometric possibilities that significantly reduce material waste but also create new challenges.

In the development of welding processes, the nuclear industry has long relied on numerical simulation to complement experimental observations, virtually test configurations, optimize process parameters, and reduce the time and cost of mock-up testing. Over time, this approach has become a valuable tool for improving lead times and weld reliability.

For WAAM, however, achieving the same synergy between experimental and numerical methods is more challenging due to the complexity of the models involved. Therefore, it is essential to develop faster simulation techniques that can accurately reproduce the effects of the process while remaining compatible with industrial constraints.

NUMERICAL METHODS FOR WAAM MODELLING

In the literature on welding and additive manufacturing modelling, two main approaches are commonly identified:

- A local-scale approach, which focuses on simulating complex fluid flow within the melt pool [1].
- A weldment-scale approach, which aims to predict the structural effects of welding and additive manufacturing, such as solid-state phase transformations, distortion, and residual stresses [2].

This paper focuses on the second, standardized approach, which is widely used in the nuclear industry. It relies on the Finite Element Method (FEM) but faces the challenge of increasing degrees of freedom (D.O.F.): the more weld beads involved, the larger and more time-consuming the model becomes. Therefore, for high number of beads - such as in additive manufacturing - efficient solutions must be developed to manage computational complexity.

Several authors have already reviewed simplification techniques [3] allowing to simulate large components [4]. For clarity, these techniques can be grouped into three categories: meshing techniques, computational techniques, and simplified approaches.

- Meshing techniques focus on optimizing the choice of finite elements for a given problem. For example, shell or combined shell-solid approaches can significantly reduce computation time [5]. Unfortunately, these methods are more suitable for predicting distortions in large, flat structures.
- Computational techniques aim to enhance efficiency through numerical algorithms. These may involve solver-level improvements, such as leveraging GPU computing power [6] or using technic solvers like superelements. A few authors even tried methods to bypass iterative solving by using data-driven numerical approach [7]. All these methods share the goal of solving the same physical equations without altering the underlying solution. This direction appears promising for the future of numerical modelling, especially with the growing potential of computational power and artificial intelligence.
- Finally, the simplified approaches consist in saving time of computation without too much modification of the solution. Many simplifications are possible with the difficulty to master the error of simplification. In this paper we will concentrates on a few of them described below.

MOVING HEAT SOURCE APPROACH (MHS)

Among the various existing approaches, the moving heat source method is widely recognized as the most accurate and will be used as a reference in this study. This method is based on the progressive activation of model elements along the welding path by a heat source that represents the energy input into the workpiece. At each time step, a thermal simulation is performed to model the heat input and its dissipation throughout the part. These thermal variations cause local expansions and contractions of the material, generating internal stresses and deformations that are accounted for in the mechanical model. The accuracy of the simulation depends on several factors, including material properties - which must be temperature- and phase-dependent - and the mesh, which must be fine enough to capture steep thermal and stress gradients. Additionally, heat source parameters such as welding speed, shape, and heat input density must be accurately defined and validated through experimental [8].

LUMP BEAD THERMAL CYCLE APPROACH (TCY)

Another approach developed for welding simulation - and applicable to the WAAM process - is the lumped bead method [9], which aims to accelerate simulations while maintaining representative thermal evolution and distribution. In this method, a thermal cycle is applied either sequentially or simultaneously to each bead during its deposition. The results of this thermal analysis are then directly integrated into the mechanical model, which accounts for the thermal effects on stress and deformation before solving the mechanical equilibrium of the structure.

A key aspect of this approach lies in the relevance of the thermal cycle, which can be extracted from a preliminary reference model. In this study, we use data derived from the moving heat source reference case. One limitation of the lumped bead method is its insensitivity to welding direction when the thermal cycle is applied to the entire bead at once. An improvement to this method involves dividing each bead into multiple segments - typically two or three - to better capture directional thermal and mechanical effects.

FAST HEAT SOURCE (FHS)

This method is based on the assumption of a stabilized thermal zone away from the start and end of the weld beads [10]. The principle involves using a conventional 3D moving heat source for the start and end regions, while applying an equivalent 2D heat source to the intermediate section - referred to as the "acceleration zone." The goal is to reduce computation time by simplifying the simulation of the homogeneous and stabilized region.

The advantage of this hybrid method is that it can be combined with the reference moving heat source approach, but it introduces new parameters that must be calibrated: the lengths of the start, acceleration, and stop zones, as well as a multiplier coefficient for the 2D heat source in the acceleration zone.

3D/2D APPROACH (3D/2D)

The so-called 3D/2D methodology, developed by Framatome [11], is an hybrid approach designed to optimize simulation accuracy while significantly reducing the computational costs associated with full process modelling. It relies on a two-step decomposition of the problem, combining the detailed representation of thermal and metallurgical phenomena through a three-dimensional state model with the computational efficiency of two-dimensional model for thermomechanical analysis.

In the first step, a steady-state thermo-metallurgical 3D simulation is performed for each weld bead. This simulation captures the temperature distribution induced by an equivalent heat source representative of the process, producing both a thermal field and a map of metallurgical phases. In the second step, the 3D thermal results are transposed into 2D data, which are then used in a 2D thermo-metallo-mechanical simulation. This enables the evaluation of residual stresses, plastic deformations, and shrinkage effects associated with bead deposition, while accounting for the complex thermomechanical interactions specific to the WAAM process.

The 3D/2D method offers an effective compromise between physical fidelity and computational performance. Its main limitation lies in the difficulty of representing complex geometries within a 2D cross-sectional framework.

INHERENT STRAIN METHOD (IS)

The Inherent Strain method is one of the most used approaches in additive manufacturing modeling. Its principle is based on simplifying the simulation process by not directly accounting for thermal effects. Instead, a strain tensor is applied to each bead to reproduce distortions. This results in a single mechanical computation step per bead, enabling very fast simulations. However, this method only provides distortion results and is dependent on the applied loading. Two main loading strategies exist:

1. Applying the full strain tensor, including all three components. In this case, a partial reference model - such as the moving heat source method - may be required to define the strain accurately.
2. Applying a reduced strain tensor, primarily in the welding direction, which governs the final deformation. This approach can be calibrated using an iterative inverse method to fit experimental data [12].

THE TG10 MOCKUP

An experimental mock-up has been designed in order to collect useful data for modelling. This mock-up is inspired by the previous TG9 configuration [13] but uses a low alloyed steel [14] subject to solid state transformations These transformations locally alter the material microstructure, affecting mechanical properties such as hardness, distortions, or residual stresses. The mock consists of a thin plate of 8 mm onto which five beads were deposed as presented Fig. 1. Five similar mock-ups were produced using the same welding parameters for each bead as detailed in Table 1.

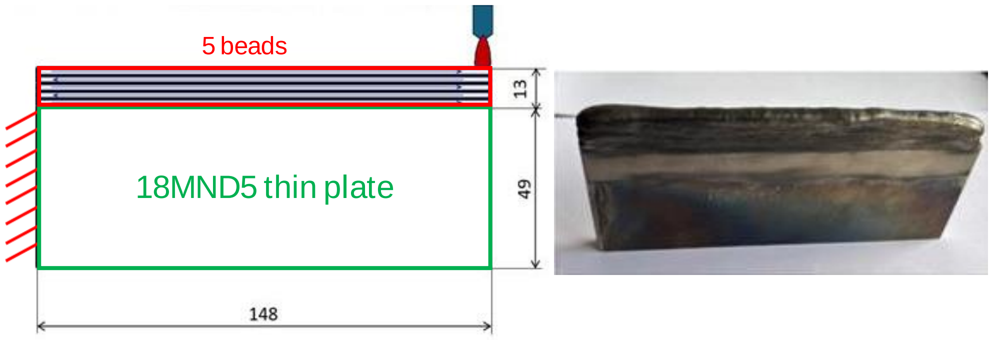

Fig. 1 The TG10 mockup

Table 1 Welding parameters

Parameter	Preheating [°C]	Welding speed [mm/s]	Voltage [V]	Current [A]	Wire feed speed [mm/s]	Wire diameter [mm]	Interpass temperature [°C]
Experimental Value	175	10	18.5	225	30	3.2	250

Several measurements were performed on the mock-up, both in-situ and postmortem. These included temperature monitoring using an infrared camera and thermocouples, as well as macrographic analysis to examine the molten zone and the heat-affected zone. From a mechanical perspective, residual stress measurements are still ongoing within the European network NET [15]. For the purpose of this paper, we primarily focus on distortion measurements taken at the extremities of each mock-up, as shown in Fig. 2. Temperature data were not recorded for intermediate beads, so some variation is expected; however, the final distortion values were measured at room temperature. For comparison purposes, we will mainly refer to the final average distortion value of 0.43 mm.

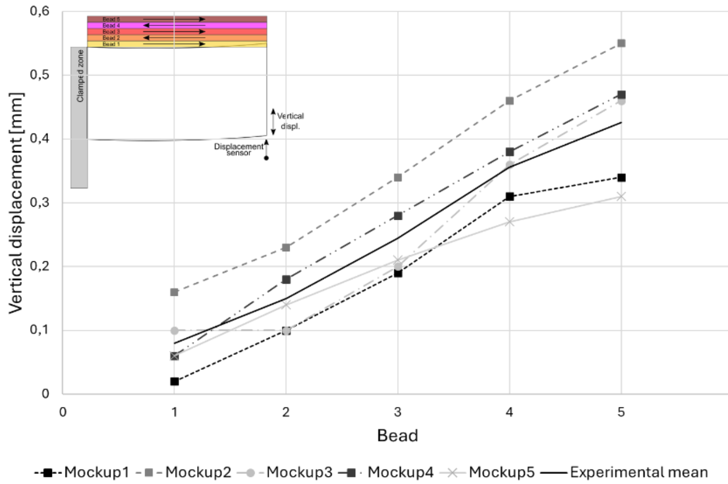

Fig. 2 Distortion measured on each TG10 mockup

NUMERICAL MODEL OF TG10

The simulations were carried out using the software SYSWELD™ [16] along with internal tools and databases. The mesh consists of linear hexahedral elements, which are preferred for nonlinear mechanical calculations. The boundary conditions, illustrated on Fig. 3 include:

- A heat exchange coefficient accounting for both convection and radiation losses on the surface area of the mock-up. This surface is updated after the deposition of each bead.
- Mechanical constrains applied in all three directions on the left face of the model, consistent with the clamping conditions of the experimental setup.

The heat source used in the reference moving heat source simulation is a Goldak-type model [17] calibrated to reproduce the same fusion zone as observed in the experimental mock-up. Solid-state phase transformations are incorporated using the Leblond model [18] with parameters fitted for the same material [11]. All numerical assumptions, including mesh configuration and boundary conditions, are consistently applied across all modelling approaches.

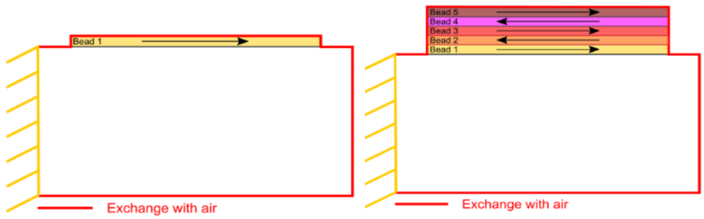

Fig. 3 Thermal and mechanical boundary conditions

COMPARISON OF METHODS

In this study, each modelling approach was tested on the industrial use case to assess its relevance and performance. No assumptions or simplifications were introduced beyond those inherent to each method, allowing for both qualitative and quantitative comparisons. The focus is primarily on thermometallurgical and mechanical results. Additionally, computation times are compared to evaluate the efficiency of each numerical approach.

THERMOMETALLURGICAL COMPARISON

Fig. 4 presents the thermal cycles extracted at the midpoint of the structure, 3 mm below the top surface, for each simulation approach during the five bead depositions. It is important to note that the inherent strain method, being purely mechanical, does not produce thermal results and is therefore excluded from this analysis.

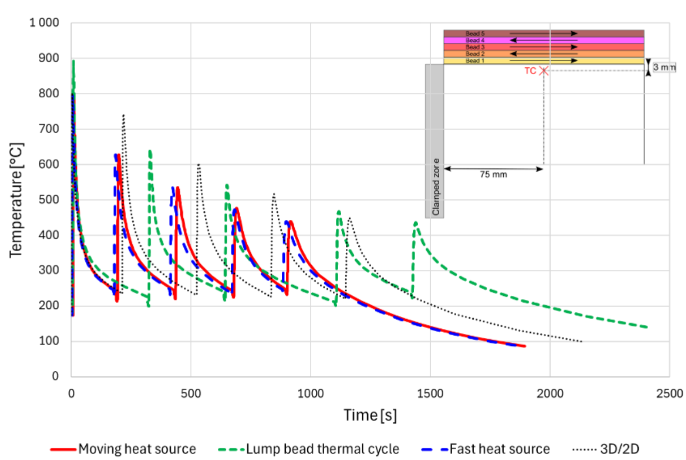

Fig. 4 Temperatures evolution obtained by TG10 simulations

The overall thermal profiles remain consistent across simulations: as the extraction point moves further away with each successive bead deposition, a decrease in peak temperature is observed. However, differences in timing between methods emerge, primarily due to the way interpass temperature is handled: in all approaches, each bead is deposited after the previous layer cools to the target interpass temperature of 250 °C. Therefore, most methods tend to overestimate the actual deposition time during interpass cooling - especially simplified approaches that do not preserve global energy consistency. For example, the thermal cycle method overestimates the time required to reach the interpass temperature by approximately 50% for the final bead.

For a closer look on the potential impact on mechanical results, Fig. 5 highlights the thermal cycle observed during the deposition of the first bead.

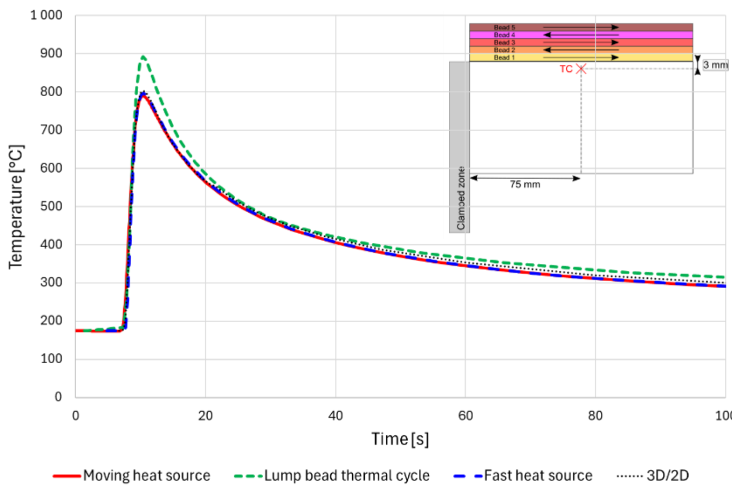

Fig. 5 Temperatures evolution obtained by TG10 simulations – zoom on deposit 1

Despite some variations, the overall trends remain consistent across all approaches, with a rapid temperature rise followed by a gradual cooling phase. Notably, the cooling rates are similar, which is crucial for accurate microstructure prediction. However, differences in peak temperature values are observed, likely due to variations in heat input modeling. In the Moving Heat Source and 3D/2D approaches, the heat input is directly derived from welding parameters, ensuring consistency. In contrast, the Lumped Bead method applies a uniform average thermal cycle to all beads, resulting in higher cumulative heat input into the workpiece. Post-processing reveals that the effective heat input in the Lumped Bead approach is approximately 3.3 kJ/cm, compared to the reference value of 3.0 kJ/cm.

Fig. 6 shows the final metallurgical state at the end of welding in a cross section in the middle of the plate.

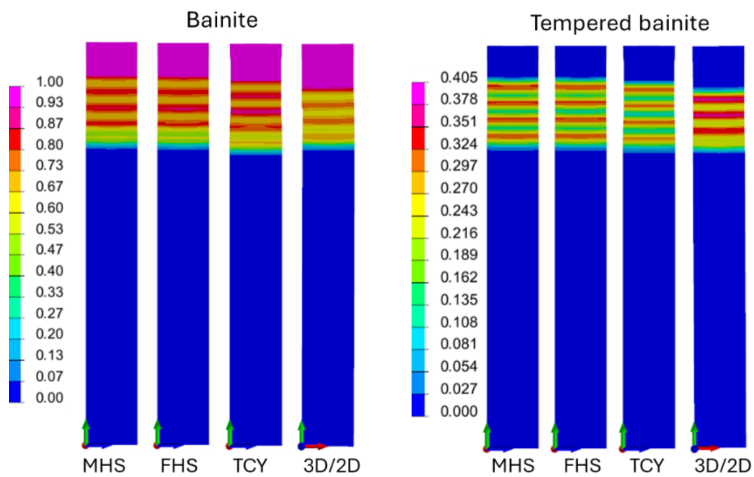

Fig. 6 Metallurgical phase proportions

The same bainite distribution is observed in both the moving heat source and fast simulation approaches. In the thermal cycle method, a vertical offset of approximately 0.8 mm is noted, which aligns with the applied thermal cycle and the associated heat input. In contrast, the 3D/2D method shows a lower proportion of bainite compared to the other approaches. Since phase proportions in this method are derived from a steady-state computation, this difference suggests that steady-state conditions were not fully achieved and it slightly affects the cooling rate, even though the thermal cycle at the thermocouple location appears to be in good agreement with experimental data.

MECHANICAL COMPARISON

The Fig. 7 and Fig. 8 illustrate the longitudinal and transverse residual stresses in the welding direction at the end of the process, evaluated across two cross-sections. The results from the 3D/2D approach are also included, shown for one section cut and one cross-sectional view. Finally, Fig. 9 presents a stress profile along a defined cutting line, allowing for a quantitative assessment of stress variation.

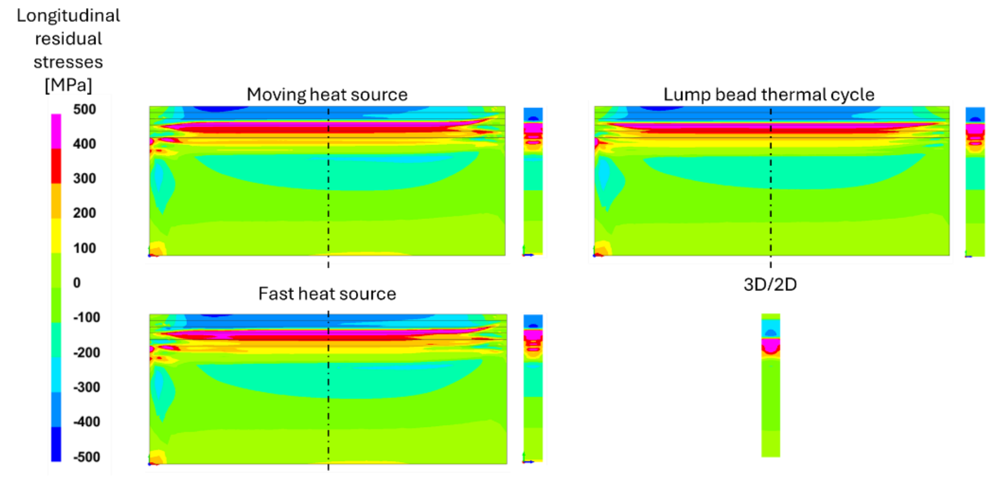

Fig. 7 Longitudinal residual stresses

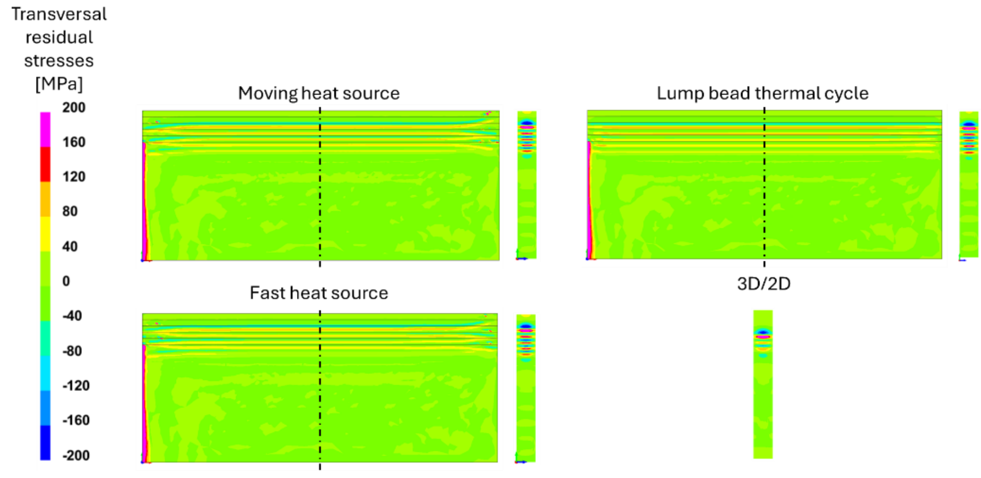

Fig. 8 Transverse residual stresses

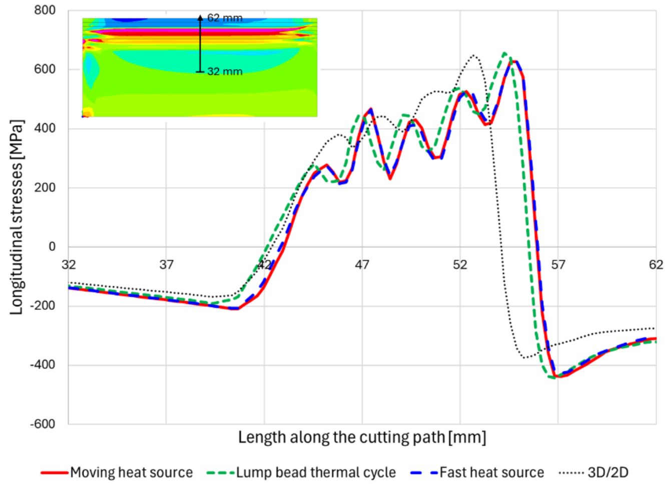

Fig. 9 Residual Stress along a cutting line in the middle

No experimental measurement have been performed yet but residual stress predictions indicate that the moving heat source method, considered as the reference, provides a highly detailed and localized stress distribution, accurately capturing transient thermomechanical effects. The fast heat source method also delivers very good stress predictions, particularly in the so-called acceleration zone. In contrast, the 3D/2D approach yields smoother and less precise stress profiles, which aligns with the corresponding metallurgical observations.

DISTORTIONS

This section examines the distortions induced by the welding process, as predicted by various simulation approaches. Fig. 10 presents a comparison between numerical predictions and experimental measurements at a point located at the bottom of the mock-up, following the completion of welding. The 3D/2D method is excluded from this analysis due to its limitation to in-plane deformation only. For the Inherent Strain method, a constant strain tensor - extracted from the third bead of the 3D model - is applied sequentially across all deposited beads.

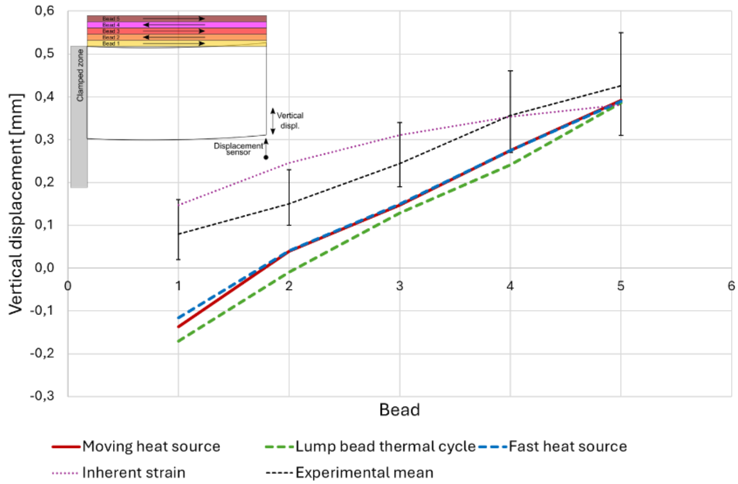

Fig. 10 Distortion evolution

A noticeable variation is observed between the evolution of numerical and experimental distortion results, most likely due to differences in interpass temperature. For the first four beads, the measurements were taken while the workpiece was still cooling resulting to a non-uniform temperature distribution. As cooling progresses, the measurement point shifts upward, transitioning from negative to positive values. The deviations observed in these initial beads can therefore be attributed to differences in timing and temperature conditions between the experiments and the simulations.

Despite this, the analysis of simulated displacements shows consistent trends across the different modelling approaches. This indicates that all methods are capable of capturing general distortion behaviour, making them suitable for design-oriented applications - especially fast approaches like the inherent strain method. However, it is important to note that the inherent strain method is not reliable for quantitative predictions, as its results deviate significantly from those using more physically detailed models. Moreover, its accuracy strongly dependent on the strain tensor values used in the simulation.

TIME OF COMPUTATION

The Fig. 11 shows a comparison of computation times for each method. For both the thermal cycle and inherent strain approaches, an initial simulation of a single weld bead is required to generate input data. As the number of weld beads increases, the impact of this preliminary simulation on the total computation time becomes less significant. This is because the initial simulation is performed only once, while its results can be reused in the simplified simulations, thereby improving overall computational efficiency for complex models.

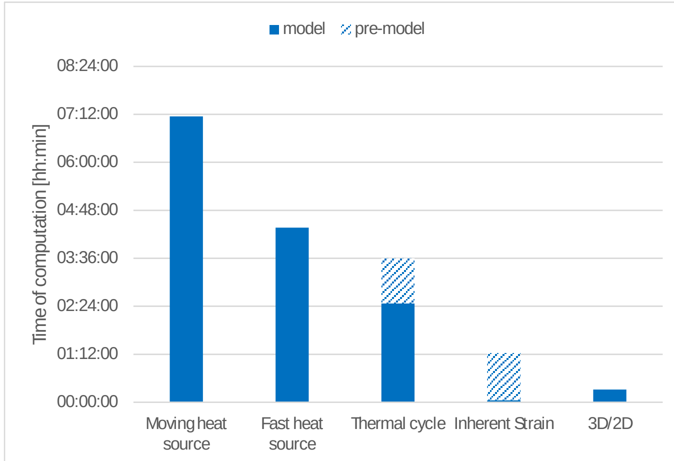

Fig. 11 Computation time for each approach

The analysis of computation times highlights notable differences between the various simulation methods. The moving heat source approach remains the most computationally intensive. In contrast, the fast heat source and thermal cycle methods offer a balanced compromise, particularly advantageous as weld bead length increases. These methods leverage thermal cycle data or geometric simplifications, reducing the need for full recalculations at each step. Consequently, their efficiency improves with longer welds. On the other hand, the 3D/2D and inherent strain methods deliver exceptionally short computation times, making them well-suited for modelling large structures with thousands of weld beads.

DISCUSSION

This study was conducted as part of an effort to assess and compare various simulation methods for the WAAM (Wire Arc Additive Manufacturing) process, using a simplified experimental setup. The simulations performed revealed the respective strengths and limitations of each approach. The moving heat source method demonstrated the highest accuracy - particularly in predicting thermal and mechanical fields - but required significantly longer computation times. In contrast, the thermal cycle, fast heat source, and 3D/2D methods provided faster alternatives, altering sometimes physical accuracy. The inherent strain method proved especially suitable for predictive purposes, though less appropriate for detailed validation. Ultimately, the choice of simulation method depends on the desired balance between accuracy, computational cost, and industrial applicability.

To support industrial applications in the nuclear sector, a summary of these findings is presented in Table 2, providing practical guidelines for future users in selecting the most appropriate simulation method.

Table 2 Sum-up of approaches limitations and difficulties

Method	Moving heat source (MHS)	Fast moving heat source (FHS)	Thermal cycle (TCY)	3D/2D	Inherent strain (IS)
Limitation	Non-industrial time of computation	Requires stationary phase	No directional effects	Requires stationary phase - Only one main direction	No phase transformation prediction
Difficulty	Mesh	Mesh and computation time	Energy consistency	None- use in welding	Choosing appropriate strain tensor
Reliability	Perfect if enough data	Good, especially for interpass time	Good	Good for microstructure and stresses	Trend-level accuracy only

Beyond this evaluation, this work opens several perspectives for future research and development:

- Scaling up the models: Future simulations should target geometries that more closely look like industrial components, incorporating a greater number of weld beads deposited side by side and across multiple layers. This will enable better representation of thermal and mechanical interactions between successive passes.
- Extended experimental validation: Conducting measurement campaigns on more complex mock-ups will enhance model robustness and help refine simulation assumptions.
- Development of hybrid tools: Integrating fast and accurate methods through multi-scale or adaptive approaches could provide an optimal balance, facilitating the industrial deployment of WAAM technologies.

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